NIGERIAN INSTITUTION OF AGRICULTURAL ENGINEERS

A Division of Nigerian Society of Engineers

26TH INTERNATIONAL CONFERENCE

AND 46TH ANNUAL GENERAL MEETING

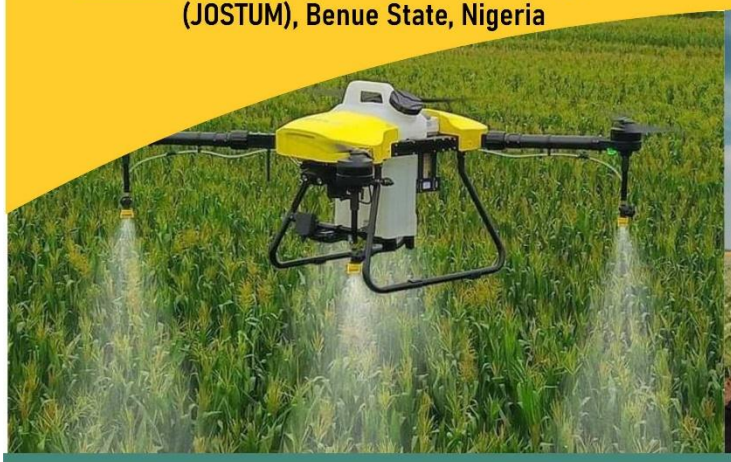
NIGERIAN INSTITUTION OF AGRICULTURAL ENGINEERS (NIAE)

THEME:

ENGINEERING CLIMATE-RESILIENT AND SMART AGRICULTURAL SYSTEMS FOR SUSTAINABLE FOOD SECURITY AND AGRO-INDUSTRIAL GROWTH

DATE: Monday 9th - Friday 13th November, 2026

VENUE: College of Food Science & Ecology Auditorium, Joseph Sarwuan Tarka University Makurdi (JOSTUM), Benue State, Nigeria



CONFERENCE PROCEEDINGS

THE 26TH INTERNATIONAL CONFERENCE AND 46TH ANNUAL GENERAL MEETING OF THE NIGERIAN INSTITUTION OF AGRICULTURAL ENGINEERS (NIAE)

(A DIVISION OF NIGERIAN SOCIETY OF ENGINEERS)

Held at the

College of Food Science and Human Ecology Auditorium, Joseph Sarwuan Tarka University Makurdi, Nigeria.

Theme: Engineering Climate-Resilient and Smart Agricultural Systems for Sustainable Food Security and Agro-Industrial Growth

November 9–13, 2026.

CONFERENCE PROCEEDINGS

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Occasion, Engr. Ali Alimasuya Rabiu, FNSE, FASCE, FAENG, MFR

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The Vice Chancellor, Joseph Sarwuan Tarka University, Makurdi Engr. Prof. Isaac Itodo

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Ladies and Gentlemen,

Good morning.

I feel highly honoured to stand here today to present this address which marks the opening ceremony of the 26th International Conference and 46th Annual General Meeting of our institution, the Nigerian Institution of Agricultural Engineers.

The Institution is the professional body of agricultural engineering practitioners dedicated to the application of engineering principles and technology to render services in the fields of food, agriculture, livestock, rural development, aquaculture and environment, etc. In 1975, it was officially registered as the Nigerian Society of Agricultural Engineers and transformed into the Nigerian Institution of Agricultural Engineers (A Division of the Nigerian Society of Engineers) in 1998.

Since registration, the institution has been holding conferences every year in different states of Nigeria. The last time it was hosted in Benue state and indeed this university, was from September 12th to 15th 1991.

The theme of this year's conference, **"Engineering Climate-Resilient and Smart Agricultural Systems for Sustainable Food Security and Agro-Industrial Growth,"** was carefully chosen to strategically align with Nigeria's drive to modernize agriculture, ensure food security, catalyze rural development, accelerate agro-industrial development and markedly alleviate poverty. It is also timely due to the crises caused by climate change and insecurity. These have led to poor crop yield, low meat production, displacement of farmers, destruction of farms and farm infrastructure, disease outbreak and increased hunger.

From the time of her formal registration to date, the institution has contributed in various ways to the growth of the Nigerian economy. The members have held and are still holding positions of responsibilities such as state governor and deputy governor, vice chancellor, rector and provost of higher institutions, members of national and state assemblies, commissioners, directors general and executive directors, etc. Also, members

of the institution have served as chairmen/members of boards in many government parastatals, governing councils of higher institutions and consultants to many locally and internationally funded agencies such as IFAD, RAAMP, FADAMA, NSPFS, etc. Our members have also headed international and regional professional organizations which include: ISTRO, PASAE, CIGR, AMA, WASAE, etc.

In conclusion, I wish to extend our appreciation to individuals and groups who sacrificed and contributed in different ways to ensure the success of this year's conference. Some of these people are The Executive Governor of Borno State, His Excellency Engr. Prof. Babagana Umara Zulum, the President of the Nigerian Society of Engineers and chairman of the occasion, Engr. Ali Alimasuya Rabiu, the Vice Chancellor, Joseph Sarwuan Tarka University, Makurdi, Engr. Prof. Isaac Itodo, The Vice Chancellor, Federal University Dusima, Engr. Prof. Khalid Othman, the President of COREN, Engr. Prof. Sadiq Abubakar.

Again, we say thank you! and thank you!!

Engr. Prof. Joseph Adama, fniae, mnse, mistro

National Chairman

NIGERIAN INSTITUTION OF AGRICULTURAL ENGINEERS (NIAE)

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Lead Paper I: Engineering Climate-Resilient and Smart Agricultural Systems: The Role of Sustainable Water Resources, Soil and Land Management in Food Security and Agro-Industrial Development

Engr. Prof. G. D. Akpen[1,2] FNSE, FNIWE
[1]Joseph Sarwuan Tarka University, Makurdi, Nigeria
[2]Director General, Bureau for Special Projects and Infrastructure, Government of Benue State, Makurdi

Abstract
Agricultural production in Nigeria must increasingly contend with rainfall uncertainty, damaging floods, dry spells, soil degradation and the uneven performance of irrigation and drainage infrastructure. These problems are often discussed separately from mechanization, automation and digital agriculture, although their effects are closely connected. This study examines climate-resilient and smart agricultural systems and then considers the place of sustainable water resources, soil and land engineering within it. The study argues that resilience depends less on the adoption of individual technologies than on the quality of resource assessment, infrastructure design, operation and long-term stewardship. It discusses integrated watershed planning, dependable irrigation and drainage, groundwater governance, soil-water conservation, erosion control, land suitability assessment and the selective use of geospatial and sensor-based information. Nigerian river basins and irrigation schemes are used to illustrate practical decisions and persistent institutional constraints. An integrated planning framework is proposed, linking catchment diagnosis, farm-level engineering, digital monitoring and accountable asset management. The central implication is that smart agriculture should be judged by measurable improvements in water productivity, soil condition, service reliability, risk reduction and farm livelihoods, not by the sophistication of equipment alone. Conclusively, agricultural engineers can make a more consequential contribution to food security and agro-industrial development when they work across hydrological, soil, land-use and institutional boundaries.

Keywords: Agricultural Engineering, Climate resilience, Irrigation, Water resources, Soil conservation, Land engineering, Nigeria

Introduction

Agricultural production is increasingly exposed to climatic uncertainties that affect not only crop performance but also the reliability of the natural resources and infrastructure upon which farming depends (Prommawin et al., 2024). Delayed rainfall can disrupt planting schedules, intense storms can accelerate soil erosion, while declining groundwater availability may increase the cost of sustaining dry-season agriculture. Similarly, inadequate drainage infrastructure can expose cultivated fields to prolonged waterlogging, resulting in substantial losses despite investments in improved seeds, mechanization and crop management. These challenges demonstrate that advances in agricultural technology do not necessarily translate into greater productivity or resilience unless the underlying physical and environmental conditions are adequately managed. The theme of this conference, "Engineering Climate-Resilient and Smart Agricultural Systems for Sustainable Food Security and Agro-Industrial Growth", therefore calls for a broader understanding of agricultural production as an interconnected system in which technological advancement must be accompanied by sustainable resource management and reliable engineering infrastructure. Within this context, climate resilience extends beyond the capacity to withstand climatic disturbances to include the ability to maintain essential agricultural functions, recover from disruptions and adjust management practices and investments in response to changing environmental conditions. Likewise, the concept of smart agriculture should not be defined merely by the adoption of sophisticated technologies, but by the extent to which reliable information, appropriate technologies and informed decisions improve the efficiency and sustainability of agricultural operations. An irrigation system equipped with automated controls, for instance, may offer limited benefits where groundwater abstraction exceeds available recharge or where poorly maintained distribution infrastructure prevents adequate water delivery to downstream users.

The growing importance of this systems-oriented approach is reflected in international assessments of the pressures confronting agricultural production. The Food and Agriculture Organization (FAO, 2021) documents increasing demands on global land and water resources, highlighting the implications of resource degradation for the

sustainability of food production. Similarly, the assessment of climate change impacts across Africa by Trisos et al. (2022) identifies the vulnerability of agricultural systems to climatic variability, hydrological extremes and constraints on adaptive capacity. These concerns are particularly relevant to Nigeria, where considerable differences in climatic conditions, soil characteristics, water availability and agricultural practices exist across the country's agroecological zones. The humid southern region, the central river basins and the relatively dry northern areas experience distinct patterns of rainfall distribution, flooding, soil degradation and irrigation demand. Consequently, engineering responses to agricultural and environmental challenges cannot be based on uniform technological prescriptions. They must instead reflect the hydrological, ecological and socioeconomic characteristics of each production environment, supported by reliable local data, appropriate design standards and sustainable resource management practices.

Climate-resilient and smart agricultural systems

Climate-smart agriculture is commonly understood as an approach that seeks improvements in productivity and incomes, adaptation to climate change and, where feasible, lower greenhouse-gas emissions (FAO, 2013). These aims do not always move together. A new irrigation development may stabilize yields but increase pumping energy or pressure on an aquifer. A drainage improvement may protect crops while transferring a flood problem downstream. Engineering judgement is required to examine these trade-offs before selecting an intervention. Climate resilience is therefore a property of an entire production system, including its environment and institutions, rather than a label attached to a particular technology. Smart agriculture has the capacity to observe field conditions, estimate future demand and adjust management with better evidence. Soil-moisture sensors, weather stations, remote-sensing products, automated gates, satellite positioning and decision-support models can inform decisions at scales ranging from the root zone to a river basin. FAO (2022) recognizes the potential of automation but also documents barriers associated with affordability, connectivity, skills and infrastructure. Klerkx et al (2019) similarly show why the social organization of digital agriculture cannot be separated from technical development. Data have limited value when no individual or institution is responsible for acting on them.

From an engineering standpoint, the important distinction is between a device and a functioning service. The performance of an irrigation scheme, for example, should be evaluated through the timing, adequacy and reliability of water delivery; the condition and cost of the infrastructure; the distribution of benefits; and the long-term effects on soils and water resources. Telemetry may improve this service, but only when routine maintenance, operating rules and farmers' water requirements have also been addressed. A modest, well-maintained monitoring network can outperform a complex platform that cannot be calibrated or repaired locally.

Climate pressures and implications for Nigerian agriculture

Agriculture is sensitive not only to annual rainfall totals but also to the timing and intensity of rainfall. An apparently satisfactory seasonal total may conceal an extended establishment-stage dry spell followed by storms that generate runoff rather than useful infiltration. Higher evaporative demand can make the same rainfall amount less effective for crops. Where heavy rainfall coincides with flat terrain or inadequate outlets, waterlogging may be as damaging as drought. The **Intergovernmental Panel on Climate Change** (IPCC) assessment reports substantial variability in rainfall and river flows across Africa and identifies sustainable water management and agricultural adaptation as important responses (Trisos et al., 2022). Nigeria's 2025 State of the Climate report provides a current national basis for examining rainfall behaviour, temperature extremes and associated hazards (NiMet, 2026). Its observations should be interpreted by location and season, particularly where they are used for infrastructure planning. The design of a small reservoir in the Sudan savanna, a drainage system in the Benue floodplain and a soil-conservation structure on an intensively farmed hillside will require different rainfall, soil and runoff analyses. National averages cannot substitute for local hydrometeorological records.

Extreme rainfall affects agricultural output through several channels. Runoff can remove seeds, sediment can clog conveyance structures, and prolonged inundation can reduce root-zone oxygen. Flood-damaged farm roads may delay access to markets even when crops survive. Conversely, dry spells can expose the limitations of rain-fed production and create demand for supplementary irrigation. Each response changes the water balance and, in some cases, shifts risk to neighboring farms or other users. This is one reason to connect farm designs with catchment-level assessments. The food-security implications extend beyond crop yields. Agro-processors need consistent supplies of raw materials, predictable delivery periods and adequate quality. Where hydrological shocks regularly interrupt production, milling

and processing equipment may operate below capacity, transport becomes less dependable and farmers carry additional price and storage risks. Engineering improvements in water control, field access and land condition can therefore support agro-industrial activity, although production gains also require credit, markets, energy and appropriate institutions. The contribution of engineering is necessary but not sufficient.

Water, soil and land as an integrated engineering system

Water resources, soils and agricultural land are often administered and studied as distinct sectors. On the ground they behave as parts of one system. Land cover influences rainfall interception and overland flow. Soil texture, structure and biological activity affect infiltration and the capacity to store plant-available water. Surface and subsurface drainage determine whether water is retained, routed downstream or held in the root zone. Changes in land use can alter sediment delivery to reservoirs and canals. The engineering response must account for these relationships. A catchment may experience both agricultural water shortages and destructive floods within the same year. This apparent contradiction arises when water is poorly distributed through time and space. The solution may involve combinations of soil infiltration improvement, temporary storage, conveyance rehabilitation, controlled drainage, demand management and better operating information. Simply adding storage or enlarging a drain can fail when upstream land degradation or downstream constraints remain unaddressed.

This integrated perspective also changes the meaning of efficiency. At field scale, reducing seepage or runoff may appear to save water. At basin scale, however, part of the "loss" may previously have contributed to groundwater recharge or recoverable downstream flows. Water-saving claims should distinguish between reduced withdrawals, reduced non-beneficial evaporation and actual reductions in depletion. Likewise, soil conservation should be assessed not only through visible erosion control but also through infiltration, aggregate stability and sustained productivity. The FAO land-and-water assessment and the UNCCD's land-restoration report both support resource management that considers wider system effects (FAO, 2021; UNCCD, 2022).

Engineering sustainable agricultural water resources

Assessment before development

Dependable agricultural water development begins with a credible resource assessment. Engineers need records of rainfall and its seasonal distribution, streamflow duration, groundwater levels, soil characteristics, water quality, competing demand and the condition of existing infrastructure. Where records are short, uncertainty should be represented explicitly. A high-flow year is not a sound basis for sizing dependable dry-season supply. Nor should a single pumping test be treated as proof that an aquifer can sustain abstraction across a large command area. Nigeria's water resources vary between major basins, shallow alluvial aquifers, basement-complex terrains and sedimentary formations. FAO's AQUASTAT Nigeria profile remains useful as a structured national reference, but its 2016 profile and older irrigation datasets should not be treated as current measurements of installed or functioning irrigation capacity (FAO, 2016). Scheme-level inventories should distinguish area originally developed, area presently serviceable, area actually irrigated and area receiving water reliably. These categories are frequently conflated in planning discussions, even though they imply very different rehabilitation needs.

Irrigation performance and the water balance

Irrigation should supply water when the crop needs it and within the limits of the available resource. A defensible design therefore begins with crop calendars, soil water-holding capacity, root depth, expected effective rainfall and atmospheric demand. The FAO-56 methodology of Allen et al. (1998) provides an established framework for estimating reference evapotranspiration and crop water requirements. These estimates require suitable local meteorological inputs; satellite products can help fill spatial gaps but need field-level checks where irrigation decisions are consequential. At its simplest, root-zone water storage changes as irrigation and precipitation enter the soil, while evapotranspiration, drainage and runoff remove water. This balance clarifies why a nominally efficient application device can still perform poorly when irrigation scheduling is wrong. Frequent shallow applications may increase evaporation; excessive irrigation can cause deep drainage, waterlogging or nutrient leaching. In heavier soils, poor drainage may restrict aeration, while sandy soils may require more frequent, carefully managed applications.

Performance assessment should extend beyond pump discharge and canal capacity. Conveyance reliability, equitable distribution, delivery timing, energy requirements and maintenance costs are integral. A scheme that supplies the

upper reaches of a command area while routinely failing tail-end users has an operational problem as well as a physical one. Measurement at representative outlets, transparent rotational schedules and functioning user organizations can be more valuable than installing additional pumps without redesigning distribution arrangements.

Flood management, drainage and conjunctive use

Flood and drainage engineering must be informed by the behavior of the entire floodplain. Embankments may protect one agricultural area but increase water levels elsewhere; undersized culverts can turn a farm road into a barrier to natural drainage. Risk-based designs should examine flood frequency, sediment transport, safe overflow routes and the consequences of exceedance. In the Benue basin, where riverine farming and settlements occupy flood-exposed land, this broader perspective is especially relevant. Site-specific modelling and historical flood mapping are preferable to blanket recommendations for channel enlargement or river training.

Groundwater can provide important flexibility during unreliable rainy seasons, but conjunctive management is essential. Pumping and river withdrawals should be considered together with recharge, baseflow, water quality and the needs of other users. Groundwater monitoring networks, properly designed observation wells and enforceable abstraction arrangements may be less visible than new boreholes, yet they determine whether agricultural groundwater development remains viable. Coastal and low-lying areas also require attention to saline intrusion and drainage-related water-quality problems.

Rehabilitation before unnecessary expansion

Existing public schemes are an important starting point for investment. The World Bank's Transforming Irrigation Management in Nigeria (TRIMING) project illustrates the engineering and institutional complexity of rehabilitating irrigation and dam infrastructure, including the need for sustained remedial works and project oversight (World Bank, 2025). The example should not be reduced to a claim that rehabilitation automatically yields a particular production increase. Its broader lesson is that neglected assets, hydraulic bottlenecks, farmer organization and long-term operation must be addressed together. Decisions on new schemes should compare the full life-cycle costs of alternatives, including energy, desilting, spare parts, drainage and institutional arrangements. Small-scale supplementary irrigation, water harvesting or managed flood-recession agriculture may be suitable in some locations, while others justify larger systems. The most appropriate choice depends on resource reliability, command-area conditions, market access, equity and the ability to maintain the infrastructure after construction teams leave.

Water productivity and the limits of efficiency claims

Agricultural water productivity is commonly expressed as crop output per unit of water consumed or supplied, but the denominator needs careful definition. Production per cubic meter withdrawn is not equivalent to production per cubic meter depleted through evapotranspiration. The first may measure the performance of a delivery organization, whereas the second can better reflect consumptive resource use. An improvement at farm level does not necessarily produce the same saving at catchment level if return flows are reused downstream. Engineers should therefore specify the accounting boundary before reporting efficiency gains. Water Productivity through Open Access of Remotely Sensed Derived Data (WaPOR) and other spatial products can help examine differences across large areas, provided that remote-sensing estimates and production data are checked against local observations (FAO, 2021).

A practical performance audit could select representative locations along a scheme, measure delivered volumes and their timing, record crop calendars and areas actually served, and compare these observations with energy use and maintenance records. This approach would identify whether low performance originates in water availability, network conveyance, scheduling, field application or institutional rules. It would also clarify the relative value of repairing a gate, lining a vulnerable section, improving scheduling or replacing a pump. The least expensive effective intervention is not always the most technologically conspicuous.

Engineering uncertainty into water infrastructure

Climate-informed design should not be understood as simply increasing the size of every dam, channel or drainage structure. More robust practice examines plausible ranges of rainfall intensity, dry-season inflow, sediment yield and demand; tests the sensitivity of a design to uncertain assumptions; and identifies how the asset can be adjusted later. Drainage structures need safe overflow paths when design storms are exceeded. Irrigation networks need operating

rules for periods when supply cannot meet peak demand. Water-storage developments need sediment-management and catchment-protection plans. In each case, the objective is to avoid costly failure without assuming that uncertain future conditions can be predicted precisely. Monitoring is part of design rather than an optional activity after construction. Staff gauges, flow-measuring structures, observation wells, rainfall stations and regular condition surveys allow operators to recognize deterioration before service collapses. Digital transmission can reduce delays where connectivity is dependable, but manual records remain useful if measurements are consistent and archived. An engineering project without a provision for measuring its performance is difficult to manage and almost impossible to evaluate independently.

Sustainable soil engineering and conservation

Soil performs several engineering functions simultaneously: it supports plants and machinery, stores water and nutrients, permits gas exchange and controls the movement of water through the landscape. These functions are affected by texture, bulk density, structure, organic matter and the history of cultivation. A soil-management recommendation that overlooks these properties may solve one operational problem while creating another. Intensive tillage can improve a seedbed temporarily but leave the surface vulnerable to erosion; repeated trafficking on wet soil can create compaction that restricts infiltration and root growth. Montgomery's (2007) synthesis shows why soil loss from conventionally tilled cropland can exceed the pace of natural soil production by substantial margins. The engineering objective is not simply to prevent visible gullies. Sheet and rill erosion can remove productive surface soil before a field appears severely damaged. Conservation measures should therefore be selected through an assessment of slope length, soil erodibility, rainfall erosivity, cover and field operations. Contour-aligned practices, vegetative strips, stable waterways and appropriately designed terraces each have a place, but their suitability differs between gently rolling terrain and steep, highly erodible slopes.

Water management and soil conservation are inseparable. Where infiltration is reduced by crusting or compaction, more rainfall becomes erosive runoff and less remains available for crops. Crop residues, cover crops, organic amendments and reduced soil disturbance can help protect the surface under suitable conditions, although adoption must accommodate competing demands for residues, weed management and local machinery constraints. Conservation agriculture should be treated as a set of site-adapted management choices, not as a universal prescription. Soil engineering also has a traffic-management dimension. Large machinery can improve timeliness, but axle loads, tyre inflation and operation on wet soil determine the risk of compaction. Controlled traffic, suitable tyres and appropriate field access can reduce repeated disturbance. On irrigated land, soil salinity and sodicity must be considered alongside drainage, especially where irrigation water has elevated dissolved salts or where evaporation concentrates salts near the surface. Preventive monitoring is generally preferable to attempting expensive reclamation after serious degradation. Digital soil maps can support reconnaissance and broad-scale planning. Hengl et al. (2017) demonstrated how machine learning could be used to develop global gridded predictions of soil properties, but prediction maps carry uncertainty and should not replace sampling for structure design or detailed land development. The practical route is to combine maps with field pits, laboratory analyses, infiltration tests and farmer knowledge. Engineering designs fail when coarse-scale soil predictions are treated as measurements at a particular field.

Quantifying soil risk before selecting a conservation measure

A sound soil-conservation programme begins by identifying the form, location and likely cause of degradation. Erosion models can support screening, but their coefficients should not be transferred uncritically between contrasting Nigerian landscapes. Measurements of slope geometry, rainfall erosivity, land cover, soil erodibility and current conservation practices provide a starting point; observations following major storms are needed to check whether predicted erosion pathways are credible. Gully control in particular demands attention to contributing drainage area, concentrated flow, head-cut migration and stable outlet conditions. Treating a downstream gully head while leaving the contributing runoff unmanaged invites repeated failure.

The cost of soil degradation is not confined to a reduction in yields. Sediment can shorten reservoir life, obstruct irrigation channels, impair drainage and increase the maintenance burden on rural roads. A conservation proposal can therefore generate benefits beyond the individual field, but these benefits are difficult to capture through a single farmer's investment decision. Catchment-level financing or collective maintenance may be justified where the avoided

costs occur downstream. This is an engineering rationale for linking soil conservation with river-basin planning, rather than treating it solely as an extension recommendation.

Sustainable land engineering and catchment management

Land engineering extends beyond clearing, grading and field layout. It concerns whether a site can sustain a proposed agricultural use without unacceptable soil loss, flood exposure, groundwater damage or conflict with other uses. Land suitability assessments should combine slope, soil depth, drainage, water access, erosion risk and environmental constraints. The highest-yielding land-use option in the short term may not be the most suitable where it increases future rehabilitation costs or removes protective vegetation from sensitive slopes. Digital elevation models and geographic information systems help identify drainage pathways, watershed boundaries, low-lying fields and erosion-prone slopes. These tools are especially useful when investment decisions concern connected areas rather than isolated plots. Their results still depend on the resolution and quality of the underlying elevation information. Small culverts, embankments and artificial drainage channels may not be resolved in satellite-derived elevation models, making field verification essential. Watershed management offers a way to distribute interventions according to where problems originate. Upstream land cover and erosion control influence sediment loads; mid-catchment channels affect routing and storage; downstream floodplains determine where water and sediment are deposited. Vegetative measures can complement structural works, but neither should be introduced without assessing the combined effect. The UNCCD (2022) places land restoration within wider livelihood and governance decisions, an important reminder that agricultural engineering operates in occupied and contested landscapes.

In Nigeria, land-tenure arrangements and changing land use can complicate long-term conservation investments. A farmer may have little incentive to build a durable terrace or maintain a farm pond without sufficient security over the land. Likewise, catchment works involving several communities require agreement about benefits, maintenance and the movement of runoff. Technical feasibility must be considered alongside the institutions needed to sustain performance.

Making smart technologies useful to resource engineering

Remote sensing, sensor networks and digital models can improve resource engineering when their limitations are recognized. NASA's Soil Moisture Active Passive mission, for example, provides observations relevant to soil-moisture monitoring and hydrological analysis, but such products cannot be assumed to represent the moisture status of a particular field at the resolution required for irrigation scheduling (Wernicke et al., 2024). FAO's Water Productivity through Open Access of Remotely Sensed Derived Data (WaPOR) platform for examining agricultural water productivity and spatial differences in performance (Adebayo & Nakalembe, 2026). These datasets are most useful as part of a monitoring strategy that includes measurements on the ground. A responsible digital workflow starts with a management question. If the concern is whether water reaches tail-end farms, the information system must provide outlet flows or reliable proxies at the relevant times. If the concern is declining soil function, repeated measurements of bulk density, infiltration, organic matter or erosion indicators may be needed. Algorithms can combine and interpret observations, but their outputs need calibration, documented uncertainty and an identified decision-maker. An attractive dashboard without reliable inputs or corrective action is not evidence of improved resource management.

Artificial intelligence is potentially useful for rainfall forecasting, identifying anomalies in irrigation operation, classifying land cover and supporting soil-property prediction. Its performance depends on representative training data, field validation and the ability to detect conditions outside the model's experience. Nigeria's varied agroecological environments make this especially important. A model trained on a well-instrumented scheme may not generalize to smallholder plots with different soils, crops and management practices. Investment should therefore be judged against transparent baselines and practical alternatives, including simpler forecasting or measurement methods.

Table 1. Engineering decisions and practical measures of success Making smart technologies useful to resource engineering

Resource/decision	Possible engineering action	Measure requiring verification
Water supply	Rehabilitate conveyance; schedule irrigation; monitor abstraction	Delivery reliability, crop water productivity, energy cost
Drainage and floods	Provide safe outlets; assess floodplain and culvert capacity	Waterlogging duration, damage frequency, downstream effects
Soil condition	Control traffic; conserve cover; stabilize concentrated runoff	Infiltration, compaction, soil loss, operational cost
Land suitability	Use terrain and soil surveys to guide land development	Erosion exposure, drainage adequacy, sustained land function
Digital support	Combine satellite information, sensors and field checks	Decision accuracy, uptake, maintenance and user benefit

Source: (Feeny, 2012)

Nigerian priorities: institutions, financing and professional practice

Nigeria's most immediate difficulty may be less a shortage of engineering concepts than the difficulty of maintaining coherent services across the life of a project. Agencies responsible for river basins, agriculture, environment, roads and local development may operate with different priorities and data systems. One body may build a structure while another is expected to maintain it, sometimes without clear funding or a transfer of technical records. This separation weakens accountability and makes it difficult to learn from failures. A first priority is a serviceable national inventory of agricultural water and land infrastructure, with georeferenced information on condition, function and responsibility. Such an inventory would identify opportunities for rehabilitation and reveal which assets require major redesign. Its usefulness depends on regular updates and transparent definitions. Investment appraisals should state expected operation and maintenance costs, identify responsible institutions and explain how climate uncertainty has been handled. Projects should not be judged solely by hectares nominally developed or the number of structures commissioned. A second priority is applied monitoring and independent evaluation. Universities, research institutes, river basin agencies and professional bodies can jointly develop practical protocols for irrigation performance, soil erosion, field drainage and watershed condition. Data sharing should protect legitimate rights while allowing evidence to inform investment choices. Researchers should report unsuccessful as well as successful interventions, explain the representativeness of field sites and avoid presenting modelled benefits as measured impacts. Training also needs to reflect changed professional demands. Agricultural engineers require a working command of hydraulics, hydrology, soil physics, land surveying and infrastructure design, together with competence in geospatial analysis, instrumentation and data interpretation. These subjects are not competitors. Digital tools increase the importance of sound physical reasoning because plausible-looking outputs can obscure mistaken assumptions. Continuing professional development should therefore connect emerging techniques to field measurement, design standards, safety and maintenance.

A practical framework for integrated action

The proposed approach is to organize climate-resilient agricultural engineering around a recurring sequence: diagnose the catchment and production system; identify the constraint that most seriously limits dependable production; compare feasible engineering and management alternatives; design and implement with local users; and monitor whether the intended service and resource conditions improve. This sequence is intended as a planning framework, not a new empirical model. Its strength lies in assigning responsibility for decisions at the appropriate scale. At catchment scale, the initial diagnosis should examine hydrology, groundwater, sediment sources, flood pathways and competing uses. At scheme scale, engineers should test delivery, storage, drainage and maintenance performance. At field scale, the focus should shift to root-zone water balance, soil condition, machinery traffic and operational feasibility. Information must move in both directions: field observations can reveal why basin-scale predictions fail, while catchment analysis can identify risks that no individual farmer can manage. For an application in the Benue basin, the process would begin with verified rainfall, river-stage and land-use evidence; map the relationship between floodplain farming, drainage outlets and settlements; and identify where seasonal water control is both technically feasible and socially acceptable. Alternative interventions could then be compared on life-cycle cost, distribution of risk, resource sustainability and maintainability. Such a process would offer more defensible decisions than choosing a predetermined technology before the field problem has been established.

Table 2. Suggested implementation sequence and responsibilities

Planning stage	Evidence or decision	Key participants
Baseline diagnosis	Hydrology, soils, land use, infrastructure condition, farmer needs	Engineers, communities, water agencies, universities
Options appraisal	Service standard, cost, climate risk, environmental safeguards	Designers, operators, planners, users
Detailed design	Site surveys, hydraulics, soils tests, construction and maintenance plan	Registered engineers, contractors, authorities
Operation and monitoring	Flows, water tables, soil condition, maintenance records	Operators, water-user groups, extension services
Review and adjustment	Measured performance and corrective action	Asset owners, regulators, researchers, users

Conclusion

Climate-resilient agriculture will not be secured by machinery, artificial intelligence or irrigation expansion considered in isolation. Its reliability rests on how water moves through a catchment, how soils receive and retain it, how land is developed and protected, and whether engineered services remain functional after construction. These relationships are particularly consequential in Nigeria, where seasonal rainfall, floodplain cultivation, heterogeneous soils and uneven maintenance capacity complicate production decisions. Agricultural engineers can make a more durable contribution by connecting catchment-scale assessment with field-scale design and long-term operation. The appropriate test of a "smart" system is not the quantity of digital equipment installed but whether it enables farmers and responsible institutions to make better decisions, reduce avoidable losses and sustain the land and water on which future production depends. Food security and agro-industrial development will benefit most when infrastructure investment is accompanied by credible resource accounting, dependable maintenance and transparent assessment of results.

Recommendations

Public investments in irrigation, drainage and land improvement should begin with an appraisal of existing assets and the hydrological system within which they function. Rehabilitation should be preferred where it can restore reliable service at acceptable life-cycle cost, while expansion should be supported by credible water-balance and environmental assessments. Every major intervention should specify the institution responsible for operation, periodic maintenance and performance reporting. Agricultural water planning should combine surface water and groundwater rather than treating them as unrelated supplies. River-basin authorities and relevant regulators should work towards shared monitoring of abstractions, seasonal storage, groundwater levels and downstream effects. In parallel, universities and engineering practitioners should develop local design datasets for rainfall intensity, soil infiltration, erosion risk and crop-water demand. Such datasets must retain their sources, uncertainties and dates of observation.

Soil conservation and land-development programmes should be based on tested site suitability. Priority measures include safer field drainage, control of concentrated runoff, erosion protection in vulnerable areas, reduced trafficking on wet soils and soil-condition monitoring. Smart technologies should be introduced where they address a defined decision problem and where training, calibration, repairs and data access can be maintained. Procurement specifications should include these recurring requirements, not merely equipment delivery. The Nigerian Institution of Agricultural Engineers can contribute by encouraging common performance indicators, structured technical reviews of major schemes and continuing education that links traditional engineering with digital methods. Joint field demonstrations involving professionals, researchers and farmers would make it possible to assess both technical outcomes and the conditions required for adoption. Such work should publish baseline conditions and limitations, allowing later projects to learn from what actually occurred.

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Lead Paper II: Restoring the Integrated Water Resources and Agricultural Development Mandate of Nigeria's River Basin Development Authorities: A Strategic Pathway to Agricultural Mechanization, Food Security, Climate Resilience and Rural Economic Transformation

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ABSTRACT
Nigeria has about 79 million hectares of agricultural land, of which only 44% is reported to be cultivated, and an estimated 3.14 million hectares of irrigable land, of which less than 7% is reported to be in use [1]. The River Basin Development Authorities (RBDAs), created in the 1970s to harness water for irrigation, domestic and industrial supply and wider socio-economic development, hold a large share of the country's dams, irrigation schemes and agricultural project lands. Over time, however, the link between the water infrastructure they provide and the agricultural production it was meant to support has weakened. This paper advocates restoring that link. It proposes (i) a River Basin Agricultural Mechanization Service Scheme (RBAMSS), delivered by the RBDAs in partnership with contracted Private Sector Agents (PSAs), through which farmers access tractors, implements and trained operators at published, land-area-based tariffs; (ii) a River Basin Agricultural Land Leasing Scheme (RBALLS) that makes suitable, legally available and underused project land accessible to farmers, cooperatives and investors, in compliance with the RBDA Act and the Land Use Act; and (iii) rehabilitation of existing irrigation schemes, organized production clusters, climate-smart technologies, public-private partnerships, agro-industrial development, extension services and a dedicated development fund. A worked machinery-cost example shows that annual utilization, not purchase price alone, determines whether a hire scheme can recover its costs. A four-phase implementation plan with measurable indicators is proposed. The paper concludes that the RBDAs should be repositioned as integrated agricultural development institutions that connect water, land, mechanization, technical support and markets to increase food production, generate employment and stimulate rural economic transformation.

Keywords: River Basin Development Authorities; agricultural mechanization; irrigation; land leasing; public-private partnership; food security; Nigeria.

1.0 INTRODUCTION

Nigeria is richly endowed with surface water and groundwater resources, extensive agricultural land and considerable potential for agricultural production. Yet the country continues to experience food insecurity, rising food prices, unemployment, rural poverty and increasing pressure on its agricultural sector.

The Minister of Agriculture and Rural Development reported in 2022 that Nigeria has about 79 million hectares of agricultural land with only 44% cultivated, and about 3.14 million hectares of irrigable land with less than 7% in use [1]. A 2016 ministerial action plan recorded that the RBDAs had built 148 dams with a combined capacity of about 9.8 billion cubic metres, but that only about 15% of the roughly 3.1 million hectares of irrigable land had facilities for year-round farming [2].
This is one of the paradoxes of our national development: substantial public investment has gone into dams, irrigation facilities, water infrastructure and agricultural project sites, yet many of these facilities and their associated farmlands remain underutilized, and the returns are not commensurate with what government has spent over the years.

The River Basin Development Authorities (RBDAs) were established in the 1970s on an integrated development philosophy: harnessing Nigeria's water resources for irrigation agriculture, domestic and industrial water supply, flood control and broader socio-economic development [3]. Today twelve RBDAs operate under the Federal Ministry of Water Resources and Sanitation (Table 1). Over time, the direct agricultural production activities of the Authorities were wound down, with increasing emphasis on water resources development and other statutory responsibilities (Section 2.2).

This development raises a fundamental policy question:

> *Can Nigeria achieve sustainable food security by developing water resources alone, without ensuring that the agricultural potential of the lands and irrigation facilities associated with these investments is fully realized?*

This paper advocates a deliberate restoration and strengthening of the integrated water resources and agricultural development philosophy of the RBDAs. It is not a call for the Authorities to return to being large-scale food producers. It proposes practical, legally grounded interventions through which the Authorities can directly support farmers, particularly smallholders, by providing mechanization services, facilitating access to agricultural land, expanding irrigation and building sustainable partnerships with farming communities and the private sector.

The central argument is that RBDAs should not merely be institutions for developing water infrastructure; they should become effective platforms for translating water resources and available agricultural land into increased food production, employment and rural economic development. Section 2 reviews the Authorities and the evidence of underutilization; Section 3 sets out the policy and legal basis; Section 4 presents the proposed strategies, including a worked cost model for mechanization services; Section 5 gives an implementation framework with indicators and risks; and Sections 6 and 7 present recommendations and conclusions.

2.0 THE RIVER BASIN DEVELOPMENT AUTHORITIES

2.1 Origin, mandate and coverage

The first river basin authorities were set up in northern Nigeria in the early 1970s [4]. Decree No. 25 of 15 June 1976 extended the arrangement nationwide, and a further authority was added in 1979 [5]. The consolidated River Basins Development Authorities Act (Cap. R9, Laws of the Federation of Nigeria 2004) provides for eleven authorities in its First Schedule [3]. Subsequent administrative adjustments, including the division of the Niger basin into Upper and Lower Niger, mean that twelve RBDAs now operate [6].

Section 4 of the Act charges each Authority with the comprehensive development of surface and underground water resources for multipurpose use; the construction, operation and maintenance of dams, wells, boreholes, and irrigation and drainage systems; the supply of water for a fee approved by the Minister; the provision of access roads and bridges for approved projects; and the preparation of a water resources master plan [3]. Together, the twelve Authorities cover all 36 States and the Federal Capital Territory (Table 1).

Table 1: The twelve RBDAs, their headquarters and States covered

S/N	River Basin Development Authority	Headquarters	States covered
1	Anambra-Imo River Basin Development Authority (AIRBDA)	Owerri	Anambra, Abia, Enugu, Ebonyi, Imo
2	Benin-Owena River Basin Development Authority (BORBDA)	Benin City	Edo, Ondo, Ekiti, Delta (north)
3	Chad Basin Development Authority (CBDA)	Maiduguri	Borno, Yobe, Adamawa
4	Cross River Basin Development Authority (CRBDA)	Calabar	Cross River, Akwa Ibom
5	Hadejia-Jama'are River Basin Development Authority (HJRBDA)	Kano	Kano, Jigawa, Bauchi
6	Lower Benue River Basin Development Authority (LBRBDA)	Makurdi	Benue, Nasarawa, Plateau, Kogi (east)
7	Lower Niger River Basin Development Authority (LNRBDA)	Ilorin	Kwara, Kogi (central and west)
8	Niger Delta Basin Development Authority (NDBDA)	Port Harcourt	Rivers, Bayelsa, Delta

S/N	River Basin Development Authority	Headquarters	States covered
9	Ogun-Oshun River Basin Development Authority (OORBDA)	Abeokuta	Lagos, Oyo, Ogun, Osun
10	Sokoto-Rima River Basin Development Authority (SRRBDA)	Sokoto	Sokoto, Kebbi, Zamfara, Katsina
11	Upper Benue River Basin Development Authority (UBRBDA)	Yola	Adamawa, Taraba, Gombe, Bauchi
12	Upper Niger River Basin Development Authority (UNRBDA)	Minna	Niger, Kaduna, FCT

Note: Basin boundaries follow hydrology, not State boundaries; Adamawa, Bauchi, Delta and Kogi therefore fall partly under more than one Authority. Source: Authority websites, including LBRBDA [6].

2.2 Evolution of the mandate

The institutional history of the RBDAs has been one of repeated change. In the mid-1980s the number of authorities was temporarily expanded to approximately one per State before reverting [5]. A commentary in the *Daily Trust* identifies Decree No. 35 of 1987 as a turning point, requiring the Authorities to relinquish their non-water assets and concentrate on water resource facilities such as dams [4]. By 2016 the then Minister of Water Resources acknowledged that changes in the Authorities' mission, structure and staffing had been made without the necessary legal instruments, and that policy inconsistencies over some forty years had prevented them from reaching their economic potential [2].

Whatever the precise instrument in each case, the practical result was that the direct agricultural production activities of the Authorities were largely wound down, leaving much water infrastructure without the farming enterprise that justified it. It should be noted that the 1979 legislation did not explicitly assign food production to the Authorities, because the Constitution leaves agriculture largely to the States [5]. The proposal in this paper is therefore not that the RBDAs resume large-scale farming, but that they enable production on and around their schemes through mechanization services, leased land, managed irrigation water and support services, working with States and the private sector. More recently the Federal Government has approved the partial commercialization of the twelve Authorities and directed that 500,000 hectares of irrigable land be brought into cultivation [7].

2.3 Evidence of underutilization

Table 2 collects the most useful published indicators. The figures differ in definition and year (potential, equipped, year-round and actually irrigated areas are different things), which is itself a finding: there is no single, current and verified inventory of what the Authorities have built and how much of it works.

Table 2: Selected indicators of agricultural land, irrigation and mechanization

Indicator	Reported value	Source
Agricultural land and share cultivated	About 79 million ha; 44% cultivated (2022)	[1]
Irrigable potential and use	About 3.14 million ha; less than 7% in use (2022)	[1]
Irrigable land with year-round facilities	About 15% of roughly 3.1 million ha (2016)	[2]
Area equipped for irrigation / actually irrigated	293,117 ha / 218,840 ha (FAO data, 2004)	[8]
Public irrigation schemes	65 schemes, 81,103 ha command area	[8]
Dams built by RBDAs	148 dams, about 9.8 billion m³ total capacity	[2]

Indicator	Reported value	Source
Actual irrigated area against 1.5 million ha target for 2020	Less than 100,000 ha (commentary)	[4]
Mechanization power level	About 0.3 hp/ha against 1.5 hp/ha FAO-recommended minimum (as reported)	[9]
Average tractor hire (about 10 hours)	About N80,000 per day (2023) rising to about N205,000 per day (2025)	[9]
Estimated cost of reviving the RBDAs (2016 action plan)	N63.55 billion	[2]

Note: Values are quoted as reported, with their original years; some are commentary or press figures and should be replaced by audited figures (Section 4.3).

2.4 Land pressure and host communities

In some project locations, agricultural facilities remain underutilized while designated farmlands have not reached their intended level of development. Inadequate mechanization, insufficient funding, poor maintenance, limited farmer participation, limited private-sector participation and weak agricultural support systems are the main constraints.

An equally important concern is increasing pressure on project lands. Where land allocated for river basin development remains unused for extended periods, surrounding communities develop competing interests and expectations, resulting in encroachment, competing land claims and disputes between project authorities and indigenous communities. This is prevalent in some project locations and should be documented systematically in the land inventory proposed in Section 5.

Local communities are essential stakeholders. The objective is not to exclude them but to create a system in which they become active beneficiaries of the agricultural development for which the land was designated. The most effective way to protect public agricultural investments is to make them productive, economically beneficial and socially inclusive.

3.0 RESTORING THE POLICY: WATER RESOURCES AND AGRICULTURE MUST WORK TOGETHER

The Federal Government should review the present operational framework of the RBDAs and restore a stronger, practical relationship between water resources development and agricultural production. Water resources development should not end with the construction of dams, canals, dykes, pumping stations and irrigation infrastructure. Such investments should form part of a complete agricultural development programme that includes:

- land preparation and development;
- irrigation and drainage systems;
- agricultural mechanization;
- improved seeds and farm inputs;
- agricultural extension services;
- post-harvest and storage management; and
- agro-processing and market development.

The RBDAs should be adequately empowered and funded to coordinate this integrated approach with State governments, agricultural research institutions, farmers' cooperatives, private investors and relevant federal agencies. The proposal does not require abandoning the water resources mandate; it requires restoring agriculture as a central operational outcome of water infrastructure investments. Every viable irrigation project should have a clearly defined agricultural utilization plan, measurable production targets and an identified arrangement for the farmers who will cultivate the land.

3.1 Legal basis and alignment with national policies

Legal basis. Two provisions of the RBDA Act are central to the proposals that follow. Section 4 sets the water-related functions of the Authorities and also envisages the handing over of cultivable irrigation land to farmers; any leasing scheme must therefore be framed consistently with that function. Section 5 restricts an Authority from acquiring or leasing land without the knowledge and consent of the State Governments in its area of operation, and makes land development for irrigation subject to the Land Use Act [3]. Under the Land Use Act, land within a State is vested in the Governor, so the legal status of each parcel (federal acquisition, State title, customary rights) must be established before it is leased. It is worthy of note, that. Section 5 under the RBDAs applies to lands yet to be acquired. This is because all the existing lands in the RBDAs have already being acquired and compensated for from inception.

Policy alignment. The proposed reforms are consistent with the National Water Resources Policy (2016), the National Irrigation and Drainage Policy and Strategy (2015) and the National Agricultural Technology and Innovation Policy (2022-2027), which together provide foundations for linking water resources, agricultural production and technological innovation [10, 11, 12].

In August 2026 the Federal Government unveiled the National Agricultural Mechanization Policy (NAMP) and the National Agricultural Mechanization Investment Strategy (NAMIS) at a national policy dialogue in Abuja [13, 14]. The strategy aims to move from fragmented public interventions to private-sector-enabled mechanization services, including machinery assembly and leasing, maintenance, spare-parts manufacturing, digital fleet management, operator training, irrigation and post-harvest technology. It also describes a division of roles: the Federal Government provides policy, standards and coordination; States provide land and infrastructure; and the private sector invests and delivers services [13]. It accompanies the Renewed Hope National Agricultural Mechanization Programme, under which 2,000 tractors and over 9,000 implements are being procured and deployed to mechanization service providers on a lease-to-own basis [13, 15]. The headline figure of 4,000 refers to the planned capacity of a tractor assembly plant (2,000 to 4,000 units a year), not to a deployment target [13].

The RBDAs hold land, water, depots, workshops and trained personnel in the rural areas that this strategy targets. They should position themselves as institutional partners in its implementation, particularly through machinery hire services, irrigation development, land utilization and farmer support programmes.

4.0 PROPOSED STRATEGIES FOR THE REVITALIZATION OF RIVER BASIN AGRICULTURAL DEVELOPMENT

4.1 Establishment of a River Basin Agricultural Mechanization Service Scheme (RBAMSS)

4.1.1 The mechanization gap

One of the greatest challenges facing Nigerian farmers, particularly smallholders, is the high cost and limited availability of modern machinery. Mechanization power is reported to be about 0.3 hp/ha against the FAO-recommended minimum of 1.5 hp/ha; average hire charges rose from about N80,000 to about N205,000 per day between 2023 and 2025; and clearing charges on imported tractors can reach 40 to 50% of the purchase price [9]. Many farmers therefore cultivate by hand because they cannot afford tractors, planters, harvesters and threshers, and even where machines exist, hiring costs, transport difficulties and the seasonal concentration of demand limit access.

4.1.2 Lessons from past public tractor-hire schemes

Any new scheme must explain why it will not repeat the failures of earlier public hire services. A survey of tractor hiring services in the Kano River Irrigation Project (an RBDA scheme) found that only about 33% of the tractors were functional, about 28% had been scrapped, only about 20% were serviced monthly, and about 80% of spare parts were sourced in the open market; farmers also paid extra for overtime, fuel and minor repairs not covered by agreements. The same study noted that a 2008 community cooperative tractor services partnership that delivered 1,950 units recorded only about 30% success six months after delivery [16]. The causes (poor maintenance discipline, spare-parts supply, operator skills, unclear charges and weak accountability) are exactly those that the design below is meant to address.

4.1.3 Proposed model

The RBDA should establish mechanization service hubs at strategic locations and deliver services in collaboration with Private Sector Agents (PSAs) selected by competitive tender. The RBDA retains the roles of asset owner or regulator, booking and scheduling, tariff administration and monitoring; the PSA provides machines or operators,

preventive maintenance, spare parts and insurance. Figure 1 shows the flow of applications, work orders, payments and reports. The farmer need only identify the land, specify the service required and pay the approved charge.

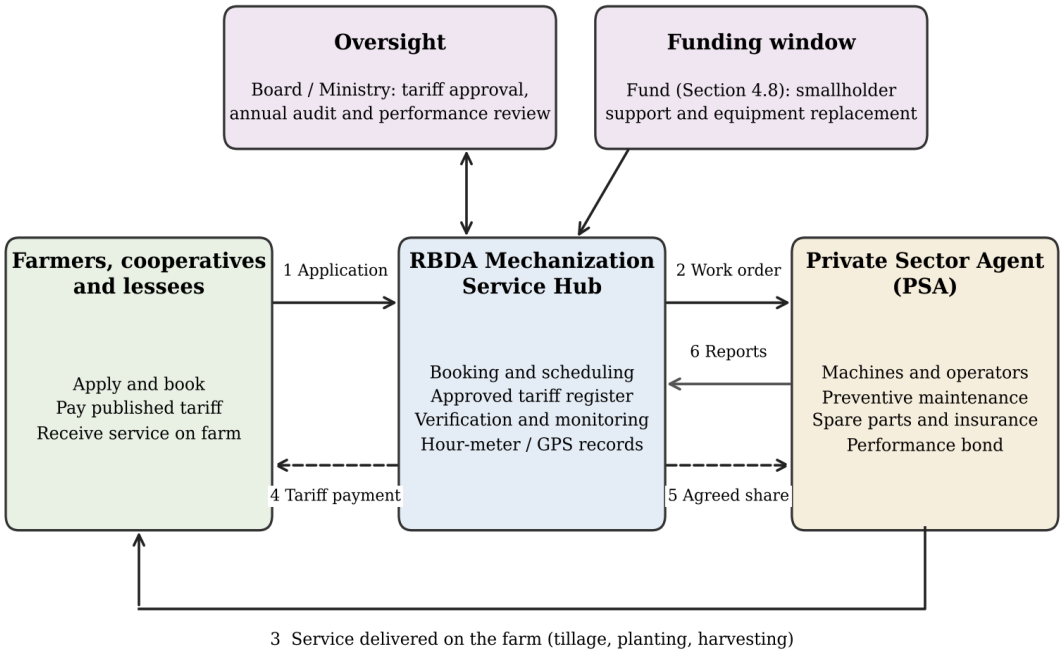

Fig. 1: Proposed institutional flow of the River Basin Agricultural Mechanization Service Scheme (RBAMSS)

Four contractual options are available (Table 3). A hybrid is recommended: options A and B for existing RBDA fleets that need upgrading and commercialization, and options C and D to add capacity quickly and to link the scheme with the lease-to-own programme for service providers already under way [15].

Table 3: Contract options for engaging Private Sector Agents

Option	Machine ownership	Who operates and maintains	Revenue and risk	Best suited to
A. Management contract	RBDA	PSA, for a fee or revenue share	RBDA carries capital and revenue risk; PSA paid for performance	Existing RBDA fleets needing revival
B. Lease or concession	RBDA	PSA, paying a lease or concession fee	PSA carries utilization and operating risk	Hubs with assured demand
C. Service agreement (accreditation)	PSA	PSA	PSA carries all risk; RBDA provides scheme access, booking and tariff regulation	Adding capacity quickly
D. Joint venture or lease-to-own	Shared, then transferred	PSA (youth and women-led providers)	Risk shared through development finance	New service providers

Essential contract terms: competitive selection; performance bond; minimum machine availability (proposed at 85% or more); hour-meter or GPS records; certified operators; a maintenance schedule and spare-parts plan; insurance and liability; a tariff approved by the Board and published; audit rights; and step-in and termination clauses.

4.1.4 Services

The proposed mechanization services should include:

1. tractors and implements for land clearing, ploughing, harrowing and ridging;
2. planters and seed drills for accurate and timely planting;
3. combine and other harvesters, and threshers, for reducing labour requirements and post-harvest losses;
4. shellers for maize and groundnut, and threshers and hullers for rice and other cereals;
5. sprayers and fertilizer application equipment;
6. irrigation pumps and water distribution equipment;
7. land levelling and other specialized machinery; and
8. drying, cleaning and storage equipment, to link field operations with post-harvest handling.

4.1.5 Tariff design and a worked cost model

The scheme should operate on a cost-recovery basis rather than as a free government service. Charges should be affordable enough to encourage use while covering fuel, lubricants, operators' wages, transport, maintenance, repairs and equipment replacement. Charging per hectare is simple for the farmer, but the tariff should differ by operation, and may be adjusted for field size, terrain, soil and distance. The following simple model, based on standard agricultural machinery management practice [17], shows how a tariff can be built up.

Effective field capacity (ha/h) is $EFC = W \times S \times \eta / 10$, where W is the effective working width (m), S the forward speed (km/h) and η the field efficiency. Hourly cost is $C = F/H + v$, where F is annual fixed cost (depreciation, interest, insurance and housing), H is annual hours of use and v is variable cost per hour (fuel, lubricants, repairs and maintenance, labour). The cost per hectare is C divided by EFC, and the break-even annual use at tariff T per hour is $H^* = F / (T - v)$.

Table 4: Illustrative assumptions (to be replaced by current RBDA procurement and operating data)

Item	Assumed value
Delivered cost of 75 kW tractor with plough and harrow	N45,000,000 (assumed)
Economic life; salvage value	10 years; 10% of price
Interest; insurance, housing and tax	15% a year on average investment; 2% of price a year
Fixed cost F	N4,050,000 depreciation + N3,712,500 interest + N900,000 insurance and housing = N8,662,500 a year
Fuel and lubricants	11 L/h at N1,200/L, plus lubricants at 15% of fuel cost = N15,180/h
Repairs and maintenance	60% of price over 10,000 h = N2,700/h
Operator and helper	N1,500/h
Variable cost v	N19,380/h
Disc plough: W = 1.0 m, S = 6 km/h, η = 0.75	EFC = 0.45 ha/h
Offset disc harrow: W = 3.0 m, S = 7 km/h, η = 0.80	EFC = 1.68 ha/h

Table 5: Effect of annual utilization on hourly and per-hectare cost (before PSA margin)

Annual use (h)	Cost per hour (N)	Ploughing (N/ha)	Harrowing (N/ha)	Ploughing (ha/yr)
400	41,036	91,192	24,426	180
600	33,818	75,150	20,129	270
800	30,208	67,129	17,981	360

Annual use (h)	Cost per hour (N)	Ploughing (N/ha)	Harrowing (N/ha)	Ploughing (ha/yr)
1,000	28,042	62,317	16,692	450

Computed from Table 4 and the formulas above. Figures are illustrative; the reported average hire day-rate of N205,000 (about N20,500/h over 10 hours) [9] is not directly comparable because machine size, implement and fuel arrangements are not stated.

Three points follow. First, utilization drives cost: moving from 400 to 1,000 hours a year cuts the cost of ploughing by about one-third. Second, at a tariff of N30,000 per hour the break-even use is H* = 8,662,500 / (30,000 − 19,380) = about 816 hours a year, or 82% of the assumed 1,000 hours, which is thin; a scheme whose tractors work only a few hundred hours a year will not recover its costs. Third, fleet size is set by timeliness, not by annual hours. For example, to plough and harrow 2,000 ha needs 2,000 × (1/0.45 + 1/1.68) = about 5,635 machine-hours; if the suitable planting window is 30 days of 8 hours with 70% workable days (168 hours), the scheme needs about 34 tractor sets, or about 60 ha per tractor. Fleets sized for the peak season sit idle for much of the year unless services are extended to the dry-season irrigated crop, harvesting, haulage and neighbouring farms. The Federal Government's planning figure for its own programme is about 600 ha per tractor per year [15].

Tariffs should be published and reviewed each season. Special consideration for smallholders and organized cooperatives should take the form of explicitly funded support (for example, vouchers financed from the Fund in Section 4.8 or cross-subsidy from commercial users), with clear eligibility criteria, so that subsidy does not undermine cost recovery. Applications could be made at designated offices or through a simple mobile platform, with a transparent booking system to prevent delays and favouritism.

4.1.6 Operators, standards and after-sales support

The 2026 mechanization strategy itself notes that a tractor without an operator is an idle asset [13]. The RBDAs should therefore partner with universities, polytechnics, the National Centre for Agricultural Mechanization and the machinery industry to certify operators and mechanics, set machine standards, and ensure spare-parts supply. Machines should be fitted with hour meters or GPS units so that utilization and maintenance can be audited.

4.1.7 Expected benefits

The scheme would reduce the cost of production; enable farmers to cultivate larger areas; reduce dependence on manual labour; improve the timeliness of planting and harvesting; encourage youth participation; create jobs for operators, mechanics and technical staff; generate internally generated revenue (IGR) for the RBDA; relieve farmers of burdens such as transport and the repair of broken-down machinery; and improve the utilization and maintenance of public equipment. It is also consistent with FAO's work on machinery hire services, which recognizes equipment hiring as an important way of improving smallholders' access to mechanization [18].

4.2 Establishment of a River Basin Agricultural Land Leasing Scheme (RBALLS)

Across several project locations, substantial areas have been designated or acquired for agricultural development, but some remain underutilized. Rather than allowing such lands to remain idle, the Authorities should establish a structured River Basin Agricultural Land Leasing Scheme (RBALLS) under which suitable and legally available land is made accessible to farmers, cooperatives, youth and women agricultural enterprises and credible private investors through transparent lease arrangements, transforming unused land into productive farms while generating revenue and employment.

How the scheme would operate

The Authority should first survey and classify its agricultural lands, assessing each location by soil suitability, water availability, accessibility, drainage, infrastructure and agricultural potential. The land should then be divided into farm units of different sizes for individual farmers, cooperatives, medium-scale commercial farmers and large investors, with a reserved share for youth, women and indigenous farmers. Applicants would indicate their preferred location, farm size, intended crops and capacity to cultivate, and successful applicants would sign formal leases that specify:

- the size and location of the land;
- the duration of the lease;
- the annual or seasonal rental charge;
- permitted agricultural activities;
- responsibilities for land maintenance and conservation;
- water access and irrigation fee arrangements, where applicable;
- conditions for renewal, termination and dispute resolution; and

- requirements for compliance with environmental and land-use regulations.

Lease charges should be reasonable and structured to encourage actual cultivation rather than speculation. Annual, seasonal or multi-year leases may be used, with longer terms for investments requiring substantial infrastructure, subject to applicable law and the Authority's legal powers.

A productive land-use policy

Land made available under the scheme must be used for genuine agricultural production. The Authority should set reasonable cultivation milestones and monitor compliance. Where a lessee repeatedly fails to use the land without acceptable justification, the lease may be reviewed or terminated in accordance with the agreement and applicable law.

Integration with irrigation and mechanization

The real strength of the proposal lies in integrating land leasing with mechanization. A farmer leasing five hectares, for instance, should be able to apply to the RBDA, or to its PSA, for tractor services to prepare the land, obtain irrigation water where available, receive technical advice and organize harvesting and post-harvest operations. This would reduce the difficulties of starting production and create a more attractive environment for young entrepreneurs and investors who lack land and machinery.

Indigenous communities and land ownership

Implementation must be handled carefully where indigenous communities hold customary interests, recognized rights or competing claims over project lands. The objective is not to displace communities or undermine legitimate land rights. The Authority should work with State governments, traditional institutions, host communities and other stakeholders to establish the legal status and boundaries of each proposed leasing area before it is made available. As noted in Section 3.1, Section 5 of the RBDA Act restricts an Authority from acquiring or leasing land without the knowledge and consent of the State Governments concerned, and the Land Use Act must also be observed [3]. Where community participation or consent is legally required it must be obtained, and indigenous farmers should receive priority consideration through cooperative arrangements, leases and other lawful partnerships. This approach will promote peaceful coexistence, protect public investments and ensure that local community's benefit from agricultural development in their areas.

Expected benefits

- brings underutilized agricultural land back into productive use;
- generates sustainable revenue for the RBDA;
- reduces pressure to acquire new land for agricultural projects;
- provides opportunities for smallholder and commercial farmers;
- creates employment and business opportunities for rural communities;
- reduces encroachment and competing land-use pressures through visible, productive land management; and
- attracts private investment into agriculture and agro-processing.

4.3 Rehabilitation and Productive Utilization of Existing Irrigation Projects

The Federal Government should commission a comprehensive, independent audit of existing irrigation projects across all RBDAs. For each scheme the audit should record, in a common format, the design command area, the area actually equipped, the area irrigated in the last three seasons, the condition of dams, canals, pumping stations, drainage systems and access roads, and the water source and reliability. It should also compute performance indicators, including the percentage of design area irrigated, cropping intensity, conveyance and field application efficiency, yield, and water productivity (kg of crop per cubic metre of water).

Priority should be given to rehabilitating existing infrastructure before committing substantial resources to new projects, ranked by cost per hectare restored and expected benefit-cost ratio. Each rehabilitated scheme should have a production plan that identifies the crops to be grown, the farmers to be supported, the hectares to be cultivated and the anticipated output. Operation and maintenance should be put on a sustainable footing through water charges under Section 4 of the Act (approved by the Minister) [3] and, where appropriate, transfer of tertiary-level management to water users' associations. Particular attention should be given to year-round production through dry-season farming where water and environmental conditions permit, as the National Irrigation and Drainage Policy and Strategy encourages [11].

4.4 Establishment of Organized Agricultural Production Clusters

The RBDAs should promote organized production clusters around their major project locations. Farmers should be encouraged to form cooperatives and production groups that can collectively access land, mechanization, irrigation

water, improved seeds, fertilizers and technical support. Clusters make it easier for the Authorities to coordinate agricultural activities, monitor production, provide extension services and insurance coverage, and connect farmers with buyers and investors. They also provide a platform for introducing modern technologies and for encouraging young people to take part in commercial agriculture.

4.5 Introduction of Climate-Smart Agriculture and Emerging Technologies

Climate change is already affecting Nigerian agriculture. The IPCC reports that climate change has reduced agricultural productivity growth in Africa and that rising temperatures, changing rainfall and extreme events pose further risks to crop production [19]. The 2022 floods, reported to have submerged about 70,000 hectares of farmland, showed the exposure of production systems, including those on flood plains and irrigation schemes [20].

In line with the conference theme, the RBDAs should integrate modern agricultural engineering technologies into their operations. Table 6 summarizes where each can be applied. The FAO Climate-Smart Agriculture Sourcebook provides technical guidance for incorporating climate resilience into agricultural planning and investment [21].

Table 6: Climate-smart and emerging technologies for RBDA schemes

Technology	Application in RBDA schemes	Expected benefit
Solar-powered pumping	Dry-season lift irrigation from reservoirs, canals and rivers; reducing diesel use	Lower energy cost; reliable irrigation
Soil-moisture monitoring and scheduling	Sensors and simple scheduling tools to time irrigation by crop stage	Water saving; higher water productivity
Remote sensing and satellite assessment	Mapping cultivated and idle land, monitoring leases and canal condition	Verified data for audit and compliance
Artificial intelligence and forecasting	Decision support for planting dates, water allocation and yield and flood forecasting	Better planning of mechanization and water
Drainage and flood management	Improved drainage, embankments and early warning on flood-prone schemes	Reduced crop loss
Improved machinery and post-harvest technology	Precision planters, solar dryers, threshers and storage	Reduced losses; value addition

4.6 Public-Private Partnerships and Agro-Industrial Development

The RBDAs should encourage credible private-sector participation in production, equipment leasing, processing, storage, transport and marketing. They need not undertake every agricultural activity directly; rather, they should provide the enabling infrastructure and institutional framework within which private investors and farmers operate effectively. The Private Sector Agents (PSAs) introduced in Section 4.1 can be engaged in every aspect of these activities. Such arrangements should follow the Infrastructure Concession Regulatory Commission Act (2005) and the National Policy on Public-Private Partnerships [22, 23], using concession, lease, build-operate-transfer or joint-venture structures as appropriate.

Agro-industrial clusters should be encouraged around strategic project locations. Areas with substantial rice potential could support rice milling and packaging, while maize and soybean areas could attract feed mills and other agro-processing businesses, creating a stronger link between agricultural production and industrial development.

4.7 Strengthening Agricultural Extension and Farmer Support Services

Access to land, water and machinery alone will not guarantee success. The RBDAs should strengthen extension services, providing guidance on improved practices, soil management, crop selection, irrigation scheduling, pest management and post-harvest handling. Demonstration farms should be established at strategic project locations to showcase modern technologies and best practices. Partnerships with universities, research institutes and colleges of agriculture should be encouraged so that persistent challenges in water supply, climate and farming can be addressed through current innovations.

4.8 Establishment of a River Basin Agricultural Development Fund

To sustain these programmes, the Federal Government should consider establishing a dedicated River Basin Water and Agricultural Development Fund. The fund would support rehabilitation of irrigation facilities, acquisition and

replacement of mechanized equipment, land development and farmer support services, and should provide the explicit subsidy window referred to in Section 4.1.5. Its legal basis, sources (appropriation, IGR from mechanization, leases and water charges, proceeds from approved PPPs, and development partners), governance and indicative size should be specified in the implementing instrument. For scale, the Ministry's 2016 action plan estimated the cost of reviving the RBDAs at N63.55 billion [2]; a current costing should be an output of the audit in Section 4.3. A transparent financial management framework, with published annual accounts, is essential to ensure that funds are used for their intended purposes.

5.0 PROPOSED IMPLEMENTATION FRAMEWORK

The reforms should be implemented in phases to ensure practical results and financial sustainability (Table 7). Monitoring runs through all phases rather than only at the end.

Table 7: Phased implementation plan

Phase	Period	Key activities	Lead and partners	Outputs
1. Assessment and planning	Year 1	Inventory of agricultural lands and irrigation infrastructure; independent irrigation audit; identify underutilized and abandoned projects; establish legal status of project lands; machinery needs assessment; select pilot sites; legal opinion on leasing	Ministries of Water Resources and Agriculture; RBDAs; State governments	Verified baseline; pilot list; legal opinion
2. Pilot implementation	Years 2 to 3	Establish service hubs at pilot sites; procure PSAs by tender; deploy machinery; launch leasing; select farmers and cooperatives; publish tariffs and booking system; rehabilitate priority schemes	RBDAs; PSAs; ICRC; development partners	Operating pilots; first tariff schedule
3. Expansion and integration	Years 4 to 5	Extend services and leasing to further communities; strengthen irrigation and extension; attract investors and agro-processors; introduce digital monitoring	RBDAs; State governments; private sector	Scaled schemes; investor pipeline
4. Monitoring and sustainability	Ongoing	Quarterly reporting against indicators in Table 8; annual independent audit; formal reviews at Years 3 and 5; performance-based funding decisions	Federal Government; independent auditors	Annual performance reports

The Federal Government should evaluate the RBDAs under these programmes using measurable indicators (Table 8). Baselines should come from the Phase 1 audit; the targets shown are proposals to be confirmed.

Table 8: Performance indicators

Indicator	Baseline	Proposed target
Hectares of land brought under cultivation (including leased land)	Phase 1 audit	Set per scheme in the production plan
Hectares under irrigation; percentage of design area irrigated	Phase 1 audit	Set per scheme; trend reported each season
Farmers served by mechanization services; hectares covered	Zero for new hubs	Set per hub from demand survey

Indicator	Baseline	Proposed target
Tractors and machines in operation (RBDA and PSA); machine availability	Phase 1 audit	Availability of at least 85%
Annual utilization per tractor (hours)	Phase 1 audit	At or above the break-even level in the tariff model
Revenue from mechanization, leases and water charges; share of operating cost recovered	Current IGR	Operating cost fully recovered by end of pilot
Agricultural output and productivity (t/ha); water productivity	Phase 1 audit	Improvement against baseline
Jobs created; indigenous communities, youth and women participating	Phase 1 audit	Set per scheme
Share of irrigation infrastructure rehabilitated and operational	Phase 1 audit	Set in the rehabilitation plan

This approach ensures that the performance of the RBDAs is measured not only by infrastructure constructed but also by the agricultural and socio-economic benefits delivered. Well-performing RBDAs should be rewarded with additional performance-based funding.

Table 9: Principal risks and mitigation

Risk	Mitigation
Political interference and weak governance	Competitive PSA selection; published tariffs; independent audit; board-level oversight
Machine downtime and poor maintenance	Performance bonds; availability targets; hour-meter or GPS records; spare-parts plan; certified mechanics
Low utilization and unsustainable tariffs	Tariffs built from verified costs (Section 4.1.5); multi-season service; funded smallholder support window
Land disputes and unclear title	Legal status survey; State and community consent; legal opinion; priority for indigenous farmers
PSA default or underperformance	Bonds; step-in and termination clauses; more than one PSA per hub
Climate shocks (drought, flood)	Drainage and flood management; climate-smart practices; crop insurance within clusters

6.0 KEY POLICY RECOMMENDATIONS

Based on the foregoing, the following recommendations are proposed for consideration by the Federal Government, the Federal Ministry of Water Resources and Sanitation, the Federal Ministry of Agriculture and Food Security, the management of the RBDAs and relevant stakeholders:

1. **Policy restoration:** Review and strengthen the operational framework of the RBDAs to restore integrated water resources development and agricultural production as complementary responsibilities, supported by the legal instruments required.
2. **Agricultural mechanization:** Establish River Basin Agricultural Mechanization Service Schemes through which farmers can access tractors and modern equipment, complete with trained operators, at affordable land-area-based rates, delivered directly or through competitively selected PSAs under transparent tariffs and clear accountability arrangements.

3. **Agricultural land leasing:** Introduce structured land leasing programmes to make suitable, legally available and underused River Basin agricultural lands accessible to farmers, cooperatives and private investors, after legal clearance and State consent.
4. **Integrated farmer support:** Link land leasing with mechanization, irrigation, extension services and other agricultural support programmes.
5. **Irrigation audit and rehabilitation:** Commission an independent audit and prioritize rehabilitation and productive use of existing irrigation schemes before developing additional projects.
6. **Community participation:** Involve indigenous communities, traditional institutions and State governments in land administration, planning and implementation.
7. **Private-sector participation:** Promote public-private partnerships in production, equipment management, processing, storage and marketing, in line with the ICRC Act and the National PPP Policy.
8. **Dedicated funding:** Establish sustainable funding arrangements for agricultural development, mechanization and maintenance of irrigation infrastructure.
9. **Performance accountability:** Introduce measurable indicators based on cultivated hectares, output, farmer participation, machine availability, employment and revenue.
10. **Capacity building and standards:** Train and certify operators, mechanics and irrigation technicians; set machinery standards; and secure spare-parts and after-sales support, working with universities and the National Centre for Agricultural Mechanization.
11. **Data and digital monitoring:** Maintain a single, current inventory of lands, schemes and machines, supported by remote sensing and digital booking and fleet-management tools.
12. **National policy harmonization:** Encourage all RBDAs to adopt an integrated agricultural development framework while allowing implementation to reflect the characteristics of their catchments.

7.0 CONCLUSION

The River Basin Development Authorities remain one of Nigeria's important institutional assets for agricultural transformation, food security and rural economic development. The country has invested considerable resources in water infrastructure, dams, irrigation facilities and agricultural project lands. Allowing these investments to remain underutilized is a significant missed opportunity, particularly when food security, employment generation and economic diversification are national priorities.

This paper therefore advocates a return to a stronger relationship between water resources development and agricultural production, supported by mechanization services delivered with private-sector partners, agricultural land leasing, irrigation rehabilitation, climate-smart technologies and private-sector participation. The mechanization scheme would enable farmers to access tractors and modern equipment without the financial burden of purchasing such machinery; the worked cost model shows that it can be sustainable only if tariffs are built from verified costs and the fleet is well utilized. The land leasing scheme would ensure that available land is put to productive use rather than remaining idle or becoming subject to competing land-use pressures.

Together, these initiatives would reposition the RBDAs as facilitators of agricultural production, providers of essential farm services and catalysts for rural economic transformation. The objective is not for government to become the sole producer of food. Rather, government should create the enabling environment by making enduring policies, providing essential infrastructure, making productive land accessible, facilitating mechanization and empowering farmers to produce efficiently.

The RBDAs should not merely provide the water that makes agriculture possible; they should also facilitate the land access, machinery, infrastructure and institutional support that make agriculture profitable. This paper therefore strongly advocates that the Federal Government revisit and strengthen the original policy framework that linked water resources development with agricultural development.

The time has come for the RBDAs to move beyond measuring success primarily by dams constructed and water infrastructure provided. Their success should also be measured by the hectares of farmland cultivated, the number of farmers supported, the volume of food produced, the jobs created and the economic opportunities generated within their operational areas. Nigeria does not merely need more agricultural land or more water infrastructure. It needs an

integrated system that makes its existing water resources, agricultural lands, irrigation facilities and modern machinery work together for national development.

"LET US RESTORE THE RIVER BASINS AS ENGINES OF AGRICULTURAL PRODUCTION, NOT MERELY INSTITUTIONS OF WATER RESOURCES DEVELOPMENT."

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Lead Paper III: Interfacing Climate-Resilient Agricultural Systems with Smart Systems for Sustainable Agricultural Production and Agro-Industrial Growth

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ABSTRACT
Agriculture is central to Nigeria's food security, to employment generation, rural development and industrial growth. However, agricultural production is increasingly threatened by irregular rainfall, drought, flooding, high temperatures, soil degradation, inadequate mechanisation, post-harvest losses and unreliable energy supplies. These challenges require solutions that go beyond conventional farming methods and isolated technological interventions. This paper examines how climate-resilient agricultural systems can be interfaced with SMART System integrated technologies and intelligent management approaches that improve monitoring, decision-making, resource utilisation and operational efficiency. It discusses the complementary roles of agricultural engineering, precision agriculture, digital information, irrigation, mechanisation, renewable energy, post-harvest technologies and agro-processing in developing sustainable agricultural value chains. The paper proposes an integrated framework that connects climate intelligence, resilient infrastructure, smart farm management, efficient post-harvest systems, agro-industrial development and institutional support. It also highlights the roles of government, research institutions, manufacturers, financial institutions, farmers and the Nigerian Institution of Agricultural Engin7eers (NIAE). The paper concludes that Nigeria's sustainable agricultural transformation requires more than increased production or the acquisition of modern equipment. It requires a pleased National implementation roadmap supported by defined coordinated by systems that are climate-responsive, technologically appropriate, economically viable and environmentally sustainable.
Keywords: Climate resilience, SMART systems, agricultural engineering, sustainable production, food security, agro-industrial growth.

1.0 INTRODUCTION AND BACKGROUND

The President and distinguished members of the Nigerian Institution of Agricultural Engineers, invited guests, fellow professionals, ladies and gentlemen.
It is my privilege to present this paper on the important subject:
"Interfacing Climate-Resilient Agricultural Systems with SMART Systems for Sustainable Agricultural Production and Agro-Industrial Growth in Nigeria."
Agriculture remains a major pillar of Nigeria's economy. It provides food, employment, income for rural households and raw materials for industries.
However, Nigerian agriculture is increasingly challenged by:
- Irregular rainfall, drought and flooding.
- High temperatures and changing climatic conditions.
- Soil degradation and declining land productivity.
- Inadequate mechanisation and irrigation facilities.
- Post-harvest losses and inadequate storage.
- High energy costs and unreliable electricity.
- Weak links between agricultural production and agro-processing industries.

These problems affect agricultural productivity, farmers' incomes, food availability and industrial development.
Fortunately, advances in agricultural engineering, digital technology, precision agriculture, artificial intelligence, renewable energy and food-processing technologies provide opportunities to address these challenges.
The central argument of this paper is that climate-resilient agricultural systems must be interfaced with SMART systems to create an integrated, productive, efficient and sustainable agricultural value chain.
The objectives are to explain this relationship, examine Nigeria's agricultural challenges, identify appropriate engineering and smart technologies, and recommend practical strategies for implementation.

The emphasis throughout is on one central message: Climate resilience provides the capacity to withstand agricultural risks, while SMART systems provide the intelligence and technologies to manage those risks efficiently. Their integration is essential for sustainable agricultural production and agro-industrial growth.

2.0 UNDERSTANDING CLIMATE RESILIENCE AND SMART SYSTEMS

2.1 Climate-resilient agricultural systems

Climate resilience is the ability of agricultural systems to anticipate, withstand, recover from and adapt to climate-related disturbances while maintaining productive capacity.
Four principles are important:
1. **Preparedness:** Anticipating risks through weather information and proper planning.
2. Resistance: Designing farms and infrastructure to reduce damage.
3. Recovery: Restoring agricultural production after adverse events.
4. Adaptation: Adjusting farming methods and technologies to changing conditions.
For example, a farmer who combines suitable planting dates, weather forecasts, water harvesting and supplementary irrigation is better prepared for rainfall variability than one who depends entirely on seasonal rainfall.

2.2 SMART agricultural systems

SMART agricultural systems use appropriate technologies, information and intelligent management to improve agricultural productivity and resource efficiency.

Examples include:
- Soil-moisture sensors and weather stations.
- Satellite imagery, GIS and drones.
- GPS-guided machinery and precision farming.
- Automated irrigation systems.
- Digital farm records and mobile advisory services.
- Artificial intelligence for crop monitoring and decision support.
- Smart drying, storage and cold-chain management.

SMART systems do not necessarily mean expensive technologies. A simple moisture meter, mobile-phone weather advisory or locally fabricated efficient dryer can be highly beneficial.
The important considerations are affordability, reliability, maintainability and measurable results.

2.3 Why must these systems be interfaced?

Climate resilience provides the physical and operational capacity to withstand climatic risks, while SMART systems provide information and intelligence for managing those risks.
Consider this example:
- Weather information predicts a dry spell.
- Soil sensors indicate declining moisture.
- The farmer receives an irrigation advisory.
- An appropriately designed irrigation system supplies the required water.
- Farm records help evaluate the resulting improvement in production.

This illustrates the relationship:
SMART information must guide engineering action, and engineering action must produce measurable agricultural results and benefits.

3.0 CLIMATE CHALLENGES FACING NIGERIAN AGRICULTURE

Nigeria's different agroecological zones experience different climatic challenges.
- Northern Nigeria: Drought, irregular rainfall, high temperatures and water scarcity.
- North-Central region, including the Benue Valley: Rainfall variability, flooding, erosion and soil degradation.
- Southern and coastal regions: Intense rainfall, flooding, waterlogging and high humidity.

These conditions are compounded by inadequate irrigation, poor rural infrastructure, limited mechanisation, post-harvest deterioration, unreliable energy and insufficient access to finance and agricultural information.
The challenges are interconnected. Increasing production without adequate storage and processing facilities may simply increase post-harvest losses.

Therefore, our approach must address the entire agricultural value chain, not production alone.

4.0 ENGINEERING INTERVENTIONS FOR CLIMATE-RESILIENT AGRICULTURE

Agricultural engineering provides practical solutions for improving agricultural resilience and productivity.

4.1 Irrigation and water management

Appropriate interventions include:

- Drip and sprinkler irrigation.
- Rainwater harvesting and water storage.
- Solar-powered pumping where economically justified.
- Soil-moisture-based automated irrigation.
- Improved drainage and flood-control structures.

SMART irrigation combines weather information and soil-moisture measurements with irrigation equipment to determine when and how much water should be applied.

The objective is to improve water productivity while avoiding waste and protecting water resources.

4.2 Soil conservation

Soil is the foundation of agricultural production. Its protection is essential for sustainability.

Important interventions include appropriate tillage, erosion control, improved drainage, conservation tillage, contour farming and reduced soil compaction.

Soil mapping and remote sensing can help identify areas requiring attention, while field assessments guide appropriate interventions.

4.3 Appropriate mechanisation

Mechanisation improves the timeliness and efficiency of land preparation, planting, weeding, harvesting, threshing, drying and transportation.

Nigeria requires machinery suited to different farm sizes, including power tillers, tractors, planters, reapers, threshers, shellers and mobile processing equipment.

Three priorities are essential:

1. Machinery-hire services for farmers who cannot afford individual ownership.
2. Local manufacturing and fabrication to improve access to equipment and spare parts.
3. Proper maintenance and operator training to reduce breakdowns and downtime.

SMART systems can also support equipment monitoring, GPS guidance and preventive maintenance.

Mechanisation success should be measured by productivity, reliability, utilisation and operating costs—not simply by the number of machines distributed.

4.4 Climate-resilient infrastructure

Farm roads, culverts, irrigation canals, storage facilities, greenhouses, livestock housing and processing plants must be designed for local rainfall, flooding, temperature, humidity and wind conditions.

The key message is that resilient infrastructure provides the physical foundation upon which smart agricultural operations can function effectively.

5.0 SMART TECHNOLOGIES AND DIGITAL AGRICULTURE

SMART technologies improve agricultural decisions through timely information and intelligent management.

Three areas are particularly important.

First: Precision agriculture.

Soil mapping, moisture sensors, satellite imagery and GPS-guided machinery help farmers apply water, fertiliser and other inputs more efficiently.

Second: Weather intelligence and artificial intelligence.

Weather forecasts help farmers plan planting and harvesting. Artificial intelligence can support crop monitoring, pest detection, yield estimation, weather-risk assessment and machinery maintenance.

These technologies require reliable local data and validation under Nigerian conditions.

Third: Digital inclusion.

Smart agricultural services must be accessible to smallholder farmers, women and young people. Mobile applications should be complemented by SMS, radio, local-language communication and extension services.
Research institutions, universities, the Nigerian Meteorological Agency, extension services and technology providers should collaborate to make agricultural information useful at farm level.
The objective is not technology adoption for its own sake, but better decisions, reduced risks and improved productivity.

6.0 POST-HARVEST ENGINEERING AND AGRO-INDUSTRIAL GROWTH

Agricultural production does not end at harvest. Produce must be preserved, transported, processed and marketed.

6.1 Post-harvest engineering

Important interventions include:
- Improved harvesting and threshing machinery.
- Mechanical and solar-assisted dryers.
- Moisture meters and quality-testing instruments.
- Hermetic storage and properly designed warehouses.
- Cold rooms and refrigerated transportation.
- Hygienic handling and appropriate packaging.
- Temperature and humidity monitoring.

Grains must be dried to appropriate moisture levels before storage, while perishable products such as fruits, vegetables, fish and livestock products may require rapid cooling and reliable cold-chain facilities.
SMART monitoring can help identify moisture and temperature conditions that threaten stored produce.
These interventions reduce losses, improve quality and provide more reliable raw materials for industries.

6.2 Renewable energy

Solar energy can support irrigation, drying and cold storage. Suitable agricultural residues can provide biomass energy or biogas.
Energy systems must be selected according to operational requirements, cost, maintenance and technical feasibility.

6.3 Agro-industrial development

Nigeria has opportunities to add value to cassava, rice, maize, yam, soybeans, oil palm, groundnuts, fruits, vegetables, livestock products and fish.
Agricultural engineers contribute through equipment design, factory layout, processing technology, material handling, energy management, packaging and waste recovery.
Agro-industrial clusters can integrate:
1. Produce aggregation.
2. Cleaning and sorting.
3. Drying and storage.
4. Processing and packaging.
5. Energy and water supply.
6. Transportation and market access.

For example, cassava processing can combine washing, peeling, grating, pressing, drying and milling to produce marketable products.
Agricultural by-products may also be converted into animal feed, compost or biogas where appropriate.
Agro-industrial development creates employment, improves farmers' markets, reduces losses and strengthens domestic production of food and industrial raw materials.
Production, preservation, processing and marketing must therefore be planned as one integrated agricultural value chain.

7.0 INTEGRATED FRAMEWORK FOR IMPLEMENTATION

I propose six interconnected components for interfacing climate resilience with SMART agricultural systems:
1. Climate and resource intelligence: Weather forecasts, soil mapping and risk monitoring.
2. Resilient infrastructure: Irrigation, drainage, soil conservation and appropriate mechanisation.
3. SMART farm management: Sensors, digital records, precision farming and decision-support systems.
4. Post-harvest and energy systems: Drying, storage, cold chains and renewable energy.
5. Agro-industrial integration: Processing, packaging, transportation and market linkages.

6. Institutional and financial support: Research, training, standards, finance and maintenance.
Consider a maize-producing community affected by irregular rainfall and poor storage.
Weather advisories can guide planting; soil-moisture information can guide irrigation; machinery can improve harvesting; efficient dryers can reduce moisture-related losses; and safe storage can preserve grain for markets and processors.
This is what an integrated agricultural system should achieve.
Implementation should be phased:
- Years 1–2: Assess needs, establish baseline data and test technologies.
- Years 3–5: Expand successful systems and strengthen maintenance and market linkages.
- Beyond Year 5: Consolidate successful programmes and incorporate them into long-term agricultural investment planning.
Performance should be measured through yield variability, water productivity, machinery utilisation, post-harvest losses, energy costs, processing output, employment and farmers' incomes.

8.0 FINANCING, COLLABORATION AND THE ROLE OF NIAE

Successful implementation requires financing, research, skilled personnel and institutional collaboration.
Government should support essential infrastructure, research, extension and climate information. Private investors and financial institutions should support viable machinery services, storage, renewable energy and agro-processing.
Possible financing arrangements include equipment leasing, cooperative ownership, pay-per-use services, agricultural credit and public-private partnerships.
Universities, research institutions and manufacturers should collaborate to develop affordable technologies suited to Nigerian conditions.
Recommended actions for NIAE
I respectfully recommend that the Nigerian Institution of Agricultural Engineers:
1. Develop an agricultural engineering agenda integrating climate resilience and SMART systems across Nigeria's agroecological zones.
2. Promote demonstration farms and projects to test technologies under actual field conditions.
3. Strengthen machinery standards, safety and performance evaluation.
4. Encourage local fabrication, manufacturing and agricultural engineering entrepreneurship.
5. Expand professional training in precision agriculture, renewable energy and post-harvest engineering.
6. Strengthen partnerships with government, universities, research institutions, manufacturers and farmer organisations.
7. Establish a follow-up mechanism to monitor the implementation of conference recommendations.
The NIAE must provide professional leadership to ensure that conference resolutions translate into practical results.

9.0 CONCLUSION AND CALL TO ACTION

Distinguished colleagues, the future of Nigerian agriculture depends on our ability to build production systems that are productive, resilient, intelligent and sustainable.
Climate-related risks, inadequate infrastructure, limited mechanisation, post-harvest losses and high energy costs remain major challenges. Agricultural engineering provides opportunities to address these through irrigation, soil conservation, appropriate machinery, SMART technologies, renewable energy, improved storage and agro-processing.
The central lesson of this paper is that climate resilience and SMART systems must not operate independently. They must be interfaced so that information guides engineering decisions, infrastructure supports intelligent operations, and agricultural produce is preserved and converted into economic value.
I conclude with five strategic priorities:
1. Engineer resilience into agricultural infrastructure.
2. Expand affordable and appropriate agricultural mechanisation.
3. Apply SMART technologies to improve agricultural decisions and resource efficiency.
4. Reduce post-harvest losses and strengthen agro-industrial value addition.
5. Build partnerships that convert engineering knowledge into measurable benefits.

Let us commit ourselves to interfacing climate resilience with smart intelligence, engineering innovation with practical application, agricultural production with industrial processing, and professional knowledge with national development.

Let us build agricultural systems that can withstand climate shocks, use resources wisely, produce sustainably, minimise losses, create industries and secure food for present and future generations.

The task before the Nigerian Institution of Agricultural Engineers is to ensure that engineering knowledge is translated into practical solutions for sustainable agricultural production and inclusive agro-industrial growth in Nigeria.

"Let us move from conference deliberations to practical collaboration and measurable action. Together, we can interface climate resilience with SMART systems to build productive and sustainable agricultural systems for Nigeria."

Thank you for your kind attention.

God bless the Nigerian Institution of Agricultural Engineers, and God bless the Federal Republic of Nigeria.

Lead Paper IV: Beyond Automation: Harnessing Artificial Intelligence and Robotics for Intelligent, Precision-Driven and Climate-Smart Agricultural Transformation in Africa

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ABSTRACT
Agriculture contributed 26.15% of Nigeria's real GDP in the second quarter of 2026 and grew by 4.39% [1], yet climate change has already reduced agricultural productivity growth in Africa by an estimated 34% since 1961, more than in any other region [2]. Mechanization has long been the engineering answer to low productivity. This paper argues that the next step is to go beyond automation: from machines that replace labour to systems that sense, decide, act and learn, and that are designed, built and governed locally. The paper reviews eight areas: AI-powered decision support; computer vision; IoT and edge AI; autonomous robots and unmanned machinery; robotics for planting, harvesting and postharvest handling; AI-driven climate-smart resource optimisation; indigenous innovation and commercialisation; and agricultural engineering education and practice. It relies on recent, online-verifiable evidence. Three findings recur. First, results obtained on laboratory datasets overstate field performance: a widely cited plant-disease model scored 99.35% on held-out laboratory images but only about 31% on images from other conditions [3], and fewer than 30% of the studies in a 2025 review of AI and robotics in agriculture validated their results in real agricultural conditions [4]. Second, the commercial robot market is concentrated elsewhere: a 2025 technical review of 145 commercial and prototype robots found that about 63% originated in Europe and 8% in Asia [5]. Third, low-cost edge hardware, locally assembled machines and generative-AI advisory services are already working in Nigeria and neighbouring countries, usually at pilot scale and often with developer-reported results. The paper proposes a layered "agricultural intelligence stack", worked examples for drone coverage, edge-model memory and screening accuracy, a regulatory map (NDPA 2023, NigCARs Part 21, the AU and Nigerian AI strategies), a curriculum framework for agricultural engineering education, a five-year phased implementation plan with measurable indicators, and twelve recommendations. The central message is that intelligence in agriculture is not delivered by buying robots; it is built by combining local data, field-validated models, robust and repairable hardware, enabling policy and trained people.

Keywords: artificial intelligence; agricultural robotics; precision agriculture; edge AI; computer vision; climate-smart agriculture; local manufacturing; agricultural engineering education; Nigeria; Africa.

1.0 INTRODUCTION

African agriculture faces a convergence of pressures: a growing population, volatile weather, degraded soils, ageing farmers, scarce rural labour and high post-harvest losses. Nigeria illustrates the stakes. Agriculture accounted for 26.15% of real GDP in Q2 2026, with year-on-year growth of 4.39%, up from 2.82% a year earlier [1]. The sector is therefore too important to be left running on hand tools, rain-fed guesswork and paper records.

The IPCC reports that climate change has reduced agricultural productivity growth in Africa by 34% since 1961, "more than any other region", and that warming above 2 °C will reduce staple crop yields across most of Africa [2]. In May 2025 floods at Mokwa, Niger State, killed at least 150 people according to officials [6], and a month earlier more than 10,000 hectares of rice farmland in the same local government area were reported destroyed, with the flooding believed to follow a water release from the Jebba dam [7]. Events of this kind show that farm decisions about planting, water, harvest and storage now depend on information that arrives too late or not at all.

Agricultural engineers have traditionally answered with mechanization: tractors, implements, pumps, threshers. Mechanization remains essential, and Nigeria unveiled a new National Agricultural Mechanization Policy in August 2026 [8]. But a tractor that cannot be scheduled, tracked, repaired or matched to the right field at the right time is only half a solution. The question for this conference is therefore:

> *Can Nigeria and Africa move beyond simply automating farm operations, towards agricultural systems that are intelligent (they learn from data), precise (they act on the right place, time and quantity) and climate-smart (they protect resources and resilience), while building the technology, the industry and the skills at home?*

This paper answers "yes, conditionally". It does not claim that robots will soon replace smallholder labour, nor that artificial intelligence is a substitute for roads, seed, credit and extension. It shows where the evidence is strong, where it is thin, and what agricultural engineers must do. Section 2 sets out a conceptual framework; Sections 3 to 9 address the eight themes of the paper; Section 10 reviews governance; Section 11 considers education, research and professional practice; Section 12 proposes an implementation framework; and Sections 13 and 14 give recommendations and conclusions. Where a result is reported by a company or the press rather than in a peer-reviewed source, the text says so.

2.0 FROM MECHANIZATION TO INTELLIGENCE: A CONCEPTUAL FRAMEWORK

2.1 Three levels of technology

It helps to distinguish three levels. **Mechanization** replaces human or animal power with machine power (a tractor ploughs). **Automation** replaces routine control with programmed control (a timer-driven pump, a GPS-guided tractor). **Intelligence** adds sensing, inference and learning, so that the system chooses what to do from data and improves with experience (a system that reads soil moisture and the forecast, decides whether to irrigate, and corrects itself when it is wrong). "Beyond automation" means building the third level on top of the first two, not skipping them.

2.2 The agricultural intelligence stack

Figure 1 organises the technologies discussed in this paper as a stack of five layers. Each layer depends on the one below it, and the quality of the whole is limited by the weakest layer. Many failed digital-agriculture projects have impressive upper layers (a model, an app) on a weak lower layer (no reliable sensor data, no power, no connectivity, no one to repair the device). The right-hand column shows the enabling conditions, which are largely institutional rather than technical, and the left-hand strip shows the feedback loop that distinguishes intelligence from automation.

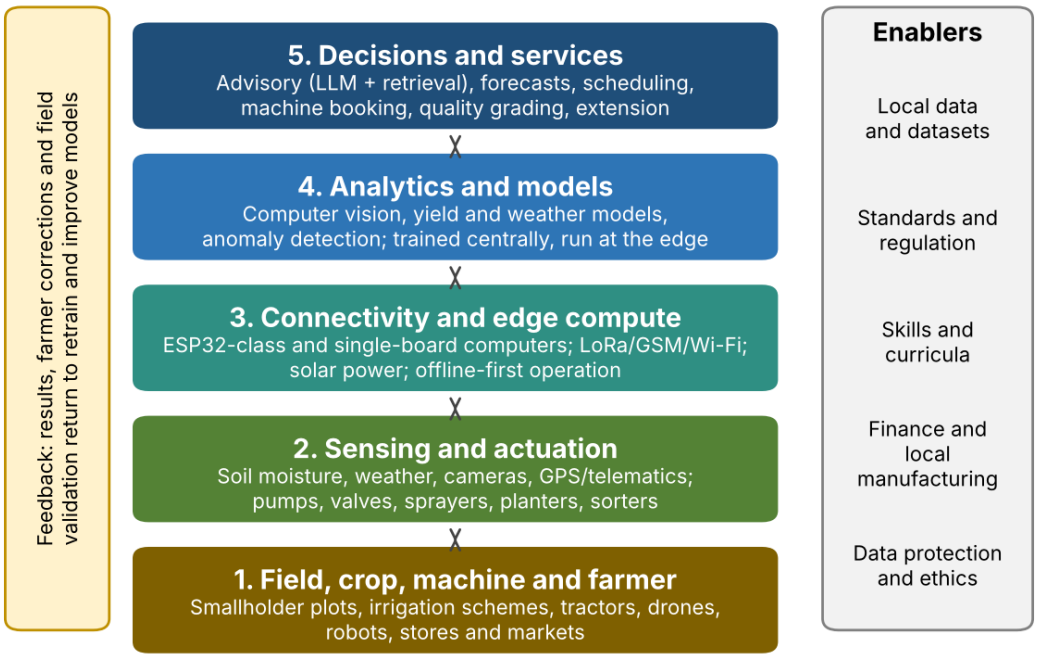

Fig. 1: A layered agricultural intelligence stack (conceptual framework proposed in this paper)

2.3 Policy context

The policy environment is increasingly supportive. The African Union's Continental Artificial Intelligence Strategy, endorsed by African ICT ministers in June 2024, calls for an "Africa-owned, people-centered, development-oriented, and inclusive" approach, with priorities in infrastructure, talent, datasets, innovation and partnerships [9]. Nigeria unveiled its National Artificial Intelligence Strategy in Lagos in April 2025, with 12 goals and 34 initiatives, and invited industry to volunteer as sector champions in areas that include agriculture [10]. The new National Agricultural Mechanization Policy (NAMP) and Investment Strategy aim to move from fragmented public interventions to private-sector-enabled mechanization services, including machinery assembly and leasing, spare-parts manufacturing, digital fleet management and operator training [8]. These three instruments meet in the field: AI needs machines, machines need data and service systems, and both need skilled people. The headline "4,000 tractors" in press coverage of the NAMP refers to the planned capacity of an assembly plant, not to a deployment target [8].

3.0 AI-POWERED PRECISION AGRICULTURE AND INTELLIGENT DECISION-SUPPORT SYSTEMS

3.1 What decision support means for the smallholder

Precision agriculture means applying the right input at the right place, time and rate. For most African farmers the first precision problem is not variable-rate fertilizer; it is simply knowing when to plant, what is wrong with a crop, and what to do about it. Decision-support systems (DSS) turn data into a recommendation that a farmer or extension agent can act on. The most promising current example is generative-AI advisory delivered through messaging and voice.

Farmer.Chat, developed by Digital Green and partners, is a retrieval-augmented system: it retrieves content from a curated agricultural knowledge base and uses a large language model to compose an answer, with translation and speech support. The developers report that it had engaged over 15,000 farmers and answered over 300,000 queries across Kenya, India, Ethiopia and Nigeria; in Kenya, 8,805 users sent more than 225,500 queries, about 29 per user. Roughly 75% of questions were answered, and 66% of the unanswered ones were due to gaps in the content base rather than model failure [11]. Two lessons follow. The quality of local, curated content is the binding constraint, not

the language model. And the figures are developer-reported with no controlled comparison against conventional extension, so they show feasibility and uptake, not proven yield or income impact [11].

3.2 AI forecasts as decision support

Weather and climate information is the other major decision input. In 2025 the University of Chicago, Google Research and India's Ministry of Agriculture and Farmers' Welfare sent AI-based monsoon forecasts by SMS to 38 million farmers. The forecasts blended Google's NeuralGCM model with ECMWF's AI forecasting system and historical data, and are reported to have predicted monsoon onset up to a month ahead and an unusual dry spell [12]. The source is a developer blog and gives no accuracy metrics or measured farmer outcomes, so it should be read as evidence of delivery at scale, not of verified benefit [12]. For Nigeria, the transferable elements are the partnership with the national agriculture ministry, the use of the farmer's existing phone, and the last-mile message design.

3.3 Design principles for Nigerian decision-support systems

1. **Content before models.** Build and maintain verified, localised content (crop calendars, varieties, pest and disease guides in Hausa, Tiv, Igbo, Yoruba and Pidgin) before scaling the chatbot.
2. **Retrieval and citation.** Answers should be grounded in retrieved sources and should say "I do not know" when the content base has a gap, as the Farmer.Chat gap analysis shows that content gaps are the main failure mode [11].
3. **Channels farmers already use.** SMS, voice and WhatsApp-type messaging; no app that requires continuous data.
4. **Human in the loop.** Extension agents should review flagged answers and feed corrections back into the content base.
5. **Measure outcomes, not usage.** Track yield, input use and income against comparison groups, not just queries answered.

Table 1: AI decision-support evidence reviewed in this paper and its limits

System	Reported result	Limit of the evidence
Farmer.Chat (generative advisory)	15,000+ farmers; 300,000+ queries; about 75% of questions answered [11]	Developer-reported; no controlled comparison; content gaps limit answers
AI monsoon forecasts, India (2025)	Forecasts sent to 38 million farmers; onset predicted up to a month ahead [12]	Developer blog; no accuracy metrics or measured farmer outcomes
Nuru offline cassava diagnosis	Six-leaf accuracy 74-88%, against 40-60% for extension agents and 20-32% for farmers [13]	Preprint; one crop; tested in coastal Tanzania; training effects not significant

4.0 COMPUTER VISION FOR CROP MONITORING, DISEASE DETECTION AND QUALITY ASSESSMENT

4.1 The lab-to-field gap

Computer vision is the most visible AI technology in agriculture, and the one most prone to over-claiming. Mohanty, Hughes and Salathe trained a deep convolutional network on 54,306 images of 14 crop species and 26 diseases (38 classes) and reported 99.35% accuracy on a held-out test set from the same collection. When the same model was tested on images taken under different conditions, accuracy fell "substantially, to just above 31%" (31.40% and 31.69% on two online image sets) [3]. The result remains instructive a decade later: models learn the background, lighting and capture conditions of the training set as well as the disease. A 2025 review of more than 10,000 AI and robotics publications found that fewer than 30% validated their results in real agricultural conditions, and that Sub-Saharan Africa is under-represented in the research landscape [4].

4.2 Evidence from African field testing

The PlantVillage Nuru app, developed with Penn State University for cassava, works offline once downloaded, which matters where connectivity is poor [14]. It detects cassava mosaic disease, cassava brown streak disease and green mite damage. In a symptom-recognition assessment of 170 images, a preprint reports that Nuru on a single leaf scored 54%, similar to trained extension agents; using six leaves (three upper, three lower) raised accuracy to 74-88%, compared with 40-60% for trained extension agents, 20-32% for trained farmers and 80-90% for trained researchers [13]. This is encouraging: a phone can give a farmer something close to a researcher's diagnosis. It is also a reminder

that accuracy depends on protocol (six leaves, not one) and that human training alone produced no significant improvement in extension agents' scores in the same study [13].

4.3 Why accuracy alone is not enough: a worked example

Consider a scouting model applied to 1,000 plants of which 10% (100 plants) are diseased. Suppose it detects 80% of diseased plants (sensitivity 80%) and correctly clears 90% of healthy plants (specificity 90%). It will find 80 true cases and wrongly flag 10% of the 900 healthy plants, which is 90 false alarms. Its precision is 80 / (80 + 90) = 47%: more than half of the "disease" alerts are false. Overall accuracy is (80 + 810) / 1,000 = 89%, which sounds excellent. A farmer who sprays on every alert would waste inputs; one who learns to ignore alerts would miss disease. Models should therefore be reported with sensitivity, specificity, precision and confusion matrices on **independent field images**, by crop, variety, season and device, and thresholds should be set for the cost of a false alarm versus a missed case.

4.4 Quality assessment and grading

Vision for quality assessment (colour, size, ripeness and defects of grain, tubers and fruit) is a more controlled problem than field diagnosis because the camera, lighting and background can be fixed in an enclosure. This is where local engineering can deliver early value: sorting stations for tomato, mango, citrus, yam and grain at aggregation points, with a defined price premium for graded produce. Section 7 returns to this theme.

4.5 Recommendations for computer-vision work in Nigeria

- build open, labelled **Nigerian field datasets** (crop, variety, growth stage, camera, light, location) rather than relying on imported laboratory sets;
- separate training and test data by **site and season**, not just by random split;
- report field validation results, and publish failures as well as successes;
- use explainability checks (heat maps, occlusion tests) to show that the model looks at the plant, not the background; fewer than 3% of the reviewed publications mention saliency maps, SHAP or LIME [4];
- run inference **on the device** where connectivity is poor (Section 5).

5.0 IoT, EDGE AI AND SENSOR-DRIVEN AGRICULTURAL INTELLIGENCE

5.1 Why the edge matters in Africa

Most precision-agriculture systems are designed to run in the cloud and presume reliable connectivity. A March 2026 review of low-cost edge AI and TinyML for agriculture notes that this limits their use on smallholder farms, and finds a "clear architectural shift toward localized inference with centralized training" [15]. Microcontroller-class platforms (ESP32, STM32, ATMega) dominate the surveyed inference hardware, and around half of the reviewed works quantise their models; however, flash, RAM, latency and energy measurements are often not reported, which hampers comparison and reproducibility [15]. For engineers, the lesson is to profile every deployed model against its hardware budget and publish the numbers.

5.2 A tiered architecture

Table 2 proposes a three-tier architecture matched to what is available at each point in a Nigerian agricultural value chain. Sensing and simple decisions run at Tier 1, vision and local analytics at Tier 2, and training, forecasting and fleet analytics at Tier 3. The Espressif ESP32-S3, for example, offers a dual-core processor running up to 240 MHz, 512 KB of internal SRAM, support for external PSRAM, 2.4 GHz Wi-Fi, Bluetooth 5 (LE) and vector instructions intended to accelerate neural-network workloads [16]. This is enough for soil-moisture control, simple keyword or image classification and telemetry, but not for large vision models.

Table 2: Three-tier edge-to-cloud architecture for Nigerian farms and value chains

Tier	Typical hardware	Typical tasks	Connectivity and power
1. Field node	ESP32-class microcontroller; soil-moisture, temperature and flow sensors; relay or valve driver	Sensing, threshold or small-model decisions (irrigation on/off), local logging	Solar plus battery; Wi-Fi, LoRa or GSM burst upload; works offline

Tier	Typical hardware	Typical tasks	Connectivity and power
2. Local gateway	Single-board computer or edge GPU at a cooperative, store or sorting station; camera	Image classification and grading; aggregation of Tier 1 data; farmer alerts	Mains or solar; GSM or fixed link when available; local cache
3. Cloud and platform	Cloud or university server	Model training and updates; forecasts; fleet and market analytics; dashboards	Broadband; receives summaries, not raw video

5.3 A worked example: will the model fit?

Model memory is set by the number of parameters and the number format. A 32-bit floating-point weight takes 4 bytes; an 8-bit integer (INT8) weight takes 1 byte, so INT8 quantisation cuts weight storage to one quarter, before activation memory and runtime overhead are added. Table 3 compares model sizes with the 512 KB internal SRAM of an ESP32-S3 [16].

Table 3: Weight storage of illustrative models (weights only) against 512 KB of internal SRAM

Parameters	Float32	INT8	Fit in 512 KB internal SRAM?
100,000	400 KB	100 KB	INT8 fits with room for activations; float32 does not
500,000	2.0 MB	500 KB	Marginal; no room for activations, so not practical
1,000,000	4.0 MB	1.0 MB	No; needs PSRAM or flash and slower access
3,000,000	12 MB	3.0 MB	No; suited to a Tier 2 single-board computer

Note: Arithmetic only (parameters multiplied by bytes per weight, 1 KB = 1,000 bytes). Actual deployments also need memory for activations, input buffers and firmware, so the usable margin is smaller. Hardware limits from the manufacturer's product page [16].

5.4 Telematics and sensor data on machines

Sensors are not only for crops; they make machines manageable. Hello Tractor's platform, described in 2018 by its co-founder, attaches a tracking device to tractors so that owners can monitor use, receive service alerts and detect unauthorised use or fuel theft, while trained agents book services for farmers, record GPS-located plots and group nearby bookings into profitable jobs [17]. The same source reports that a Nigerian operator with about 250 tractors reportedly doubled its fleet after adopting the platform; these are company-reported figures [17]. A later partnership with John Deere was reported to target 10,000 tractors over five years on a pay-as-you-go model with telematics supplied through Hello Tractor, with projected outcomes (9 million hectares, 37 million tonnes of additional food, over 2 million jobs) that are projections from a press release rather than measured results [18]. The engineering principle for any public mechanization scheme is the same: hour meters or GPS on every machine so that utilization and maintenance can be audited.

6.0 AUTONOMOUS AGRICULTURAL ROBOTS AND UNMANNED FARM MACHINERY

6.1 What the global market looks like

A technical review published in 2025 catalogued 145 commercial and prototype agricultural robots from 123 companies. About 63% were from Europe, 28% from America, 8% from Asia and 1% from Oceania; the review does not report Africa separately. By function, weed control accounted for about 26%, tool carriers 19%, crop or soil monitoring 14%, plant protection 8%, transport 6% and seeding 5%. About 43% were battery-electric and 12% solar-photovoltaic powered; 75% ran on tyres; the average reported weight was about 1,405 kg [5]. The same review concludes qualitatively that harvesting robots have not yet matched human pickers in success rate [5].

A parallel bibliometric review shows where the research effort sits: aerial robots (mostly UAVs) make up 40.33% of Scopus publications on the topic and monitoring robots are the most common functional role; India (1,412), China (750) and the United States (707) lead Scopus publication counts [4]. Taken together the reviews suggest that the technology most mature for tropical smallholders is the aerial platform for monitoring and spraying, followed by small ground robots for specific tasks, while fully autonomous tractors and general-purpose harvesters are not near-term options for small, irregular fields.

6.2 Matching platforms to Nigerian conditions

Table 4: Robot and unmanned-machine platform classes and their fit to Nigerian smallholder conditions

Platform	Best-fit tasks	Advantages here	Constraints
Multirotor drone (UAV)	Crop scouting, mapping, spot or low-volume spraying	Mature; fast coverage; no field access needed on wet or fragmented land	Battery and payload limits; NCAA registration and operator rules; operator training; weather
Small ground robot (tracked or wheeled, solar or battery)	Seeding, weeding, row scouting in high-value or nursery crops	Light soil impact; can be built locally on ESP32 or similar controllers	Rough terrain; weed and crop discrimination in mixed plots; navigation without RTK
Robotic implement on a conventional tractor	Precision planting, section control, auto-steer	Uses existing tractor fleet; incremental	Needs GNSS corrections, calibration and trained operators; high cost
Autonomous tractor or large harvester	Large, regular fields	Labour saving on large estates	Cost; field size; safety; limited local support; not a priority for smallholders
Fixed-station robot (sorting, packing)	Grading and sorting at aggregation or processing points	Controlled environment; high accuracy achievable; immediate price premium	Needs steady power, maintenance and a buyer who pays for grades

6.3 A worked example: drone coverage

Effective field capacity follows the standard machinery-management relation EFC (ha/h) = W x S x eta / 10, where W is the effective swath (m), S the forward speed (km/h) and eta the field efficiency (which here absorbs turning, battery swaps and refilling). Assume a spraying multirotor with an effective swath of 4 m, a speed of 5 m/s (18 km/h) and an efficiency of 0.70. Then EFC = 4 x 18 x 0.70 / 10 = 5.04 ha/h. To treat a 200 ha scheme in one pass takes 200 / 5.04 = about 40 flight-hours, or about five 8-hour drone-days; two drones would finish in about two and a half days. These are illustrative assumptions, not measurements of any particular machine. The practical point is that a drone service is a logistics business: batteries, charging (often from solar), water supply, operator scheduling and spray-drift management determine real capacity far more than the nominal swath.

6.4 Locally built robots: early evidence

Local engineers are already building small robots. A self-assembled seed-sowing robot built around an ESP32 microcontroller, reported in the FUDMA Journal of Agriculture and Agricultural Technology, achieved an average planting accuracy (relative to the ideal inter-seed spacing) of 98.5% and was faster than manual sowing [19]. This is a proof of concept on a small scale and its field durability, cost and economics still need to be demonstrated, but it shows that low-cost microcontrollers make local robotics feasible. In Akwa Ibom, Project TAT AI (Transforming Agriculture Through Artificial Intelligence) was unveiled in Uyo on 6 May 2026 under a memorandum of understanding among six organisations, including the University of Uyo and Akwa Ibom State University, to test university innovations in autonomous harvesting and smart storage on real farms through a "Lab-to-Land" model, with first innovations to be showcased in November 2026 [20]. The article reports no performance figures [20].

6.5 Unmanned aircraft: regulation matters

Nigeria regulates drones under the Nigeria Civil Aviation Regulations 2023, Part 21 (Remotely Piloted Aircraft Systems). All remotely piloted aircraft must be registered; commercial operators need an RPAS Operator Certificate (valid for five years), a security clearance and end-user certificate, and insurance matched to the risk of the operation; operations are classed as open, specific or certified [21]. In February 2026 the Minister of Aviation and Aerospace Development directed the regulator to develop a comprehensive national framework for unmanned aerial systems, noting that drones are increasingly used for agricultural spraying [22]. Agricultural drone programmes should therefore be designed with the regulator from the outset, including operator training and certification and spray-safety rules.

7.0 ROBOTICS FOR PLANTING, HARVESTING, PROCESSING AND POSTHARVEST MANAGEMENT

7.1 Where the losses are

Postharvest loss is a larger and more tractable target for engineering than in-field autonomy. A 2025 literature review of fruit and vegetable value chains found a median whole-chain loss of 25% in sub-Saharan Africa, based on 66 openly accessible articles. Across the reviewed literature, tomato losses along the whole chain had a median of 31% (range 10.5% to 76%) [23]. The review reports no Nigeria-specific loss percentages, so Nigerian figures should come from local measurement [23]. Table 5 shows the stage-wise medians and the highest values reported, with a matching engineering opportunity for each.

Table 5: Reported fruit and vegetable losses by stage and corresponding robotics or AI opportunities

Stage	Median loss	Highest reported	Engineering opportunity
Harvest	6%	23%	Maturity detection by vision; harvest-aid devices and, for high-value crops, selective picking
On-farm postharvest handling	15%	54%	Low-cost grading and sorting stations; improved crates; precooling
On-farm storage	5%	38%	Sensor-controlled solar cold rooms and dryers; humidity and temperature alerts
Transport and distribution	5%	63%	Telematics, route planning and load matching; vehicle cargo monitoring
Market	15%	60%	Vision-based quality grading to set price and shelf life; shelf-life prediction
Processing	5%	32%	Machine-vision sorting before processing; automated feeding; yield-loss tracking

Note: Medians and highest values are those reported for fruit and vegetables across the reviewed studies [23]; the opportunities column is the author's proposal.

7.2 Harvesting, planting and processing

Selective harvesting robots for fruit remain a research frontier and have not yet matched human pickers [5]. For Nigerian conditions the near-term priorities are different: planting accuracy (as in the seed-sowing robot above [19]), mechanised harvest aids for tree crops, and processing automation. Where an operation is repetitive, takes place in a controlled space and the product has a clear price premium for quality, fixed-station robotics pays first: sorting yams by condition, tomatoes by ripeness, mango by size and defects, and grain by contamination.

7.3 Design rules for postharvest intelligence

- design for **dust, heat, humidity and power cuts**: sealed enclosures, wide-range supplies, solar-battery backup;
- use **fixed lighting and backgrounds** in sorting stations to remove the domain-shift problem that harms field vision (Section 4);
- measure **throughput, grading accuracy, damage rate, energy use and cost per tonne**, and compare with manual sorting;

- make machines **repairable locally** with commodity parts and documented firmware;
- link graded output to **buyers and prices** from the start; without a price premium there is no business case.

The author's own research programme works in this space: an AI-based quality-detection device for tropical fruit and vegetables (mango, orange and tomato) built on Raspberry Pi and ESP32-S3 platforms with INT8-quantised convolutional networks, a robotic yam-sorting system using audio and machine vision, and a smart solar drip-irrigation system built around the ESP32. These projects are at different stages of design, testing and review, so no performance figures are reported here; they are cited only as examples of locally led work, and results will be published through the normal peer-review route.

8.0 AI-DRIVEN CLIMATE-SMART AGRICULTURE AND RESOURCE OPTIMISATION

8.1 Why climate information is now an engineering input

The IPCC's Africa fact sheet states that agricultural productivity growth has been reduced by 34% since 1961 due to climate change, "more than any other region"; that warming above 2 °C will reduce yields of staple crops across most of Africa; that early-warning systems based on targeted climate services "can be effective for disaster risk reduction"; and that index-based insurance can help transfer risk and aid recovery in food systems [2]. These are design requirements for agricultural engineers: irrigation scheduling, planting-date advice, drainage, storage and insurance should draw on forecast and observation data, not only on the calendar.

8.2 Three optimisation loops

1. **Water.** Soil-moisture sensors with ESP32-class controllers and solar pumps can schedule drip or furrow irrigation by crop stage and forecast rainfall, so that water is applied when the crop needs it and not when diesel is available. The efficiency gain should be measured against the farmer's current practice on the same site.
2. **Energy.** Solar pumping, solar drying and solar cold rooms reduce diesel use; sizing should be based on measured site solar data and load.
3. **Inputs.** Satellite and drone imagery, soil tests and yield maps allow spot application of fertilizer and pesticides; for smallholders the realistic first step is zoning of fields and timing advice rather than variable-rate machinery.

8.3 Early warning and shared data: the flood lesson

At Mokwa, farmers said water was released from the Jebba dam "without proper communication with the communities" [7], and about five weeks later a flash flood killed at least 150 people [6]. Whatever the final causes, the case shows the value of linking dam and river-level data, rainfall forecasts and community alerts, and of publishing release schedules in advance. AI forecasting can help, but only if basin authorities, the national meteorological and hydrological agencies and local governments share data and have agreed alert protocols. This is an engineering and institutional task together.

8.4 Guarding against false precision

Optimisation models fitted to one climate and soil can fail in another. Climate-smart systems should therefore (i) report forecast uncertainty to farmers, (ii) keep a human-readable fallback (the calendar and the extension agent), and (iii) record outcomes to recalibrate. The India monsoon example is promising, but its published description gives no accuracy metrics [12]; Nigerian pilots should publish theirs.

9.0 INDIGENOUS INNOVATION, LOCAL MANUFACTURING AND COMMERCIALISATION OF AGRICULTURAL TECHNOLOGIES

9.1 The case for local design and manufacture

Imported robots and sensors are designed for other soils, crops, field sizes and service networks, and the supply of spare parts and skilled technicians is the usual point of failure. Local design and assembly lower the cost of ownership, create skilled jobs, and allow machines to be adapted to Nigerian crops such as yam, cassava, sorghum, rice and tree crops. The 2026 mechanization strategy itself envisages machinery assembly, spare-parts manufacturing and operator training as part of the service system [8].

9.2 What is already happening

- **Tractor assembly.** In April 2024 NASENI announced plans, with the Nasarawa State Government and Bobtrack Tractors, to use the Agricultural Machinery and Equipment Development Institute (AMEDI) in

Lafia for tractor manufacturing and assembly in the north-central zone; no capacity or investment figure was stated, and an MoU had yet to be confirmed in the report [24].

- **Digital service platforms.** Hello Tractor, a tracking and booking platform operating in Nigeria, has partnered with John Deere in a reported programme for 10,000 tractors over five years [17, 18].
- **University and incubator projects.** Project TAT AI in Akwa Ibom [20] and the ESP32 seed-sowing robot [19] illustrate a pipeline from the laboratory to the field.
- **National policy.** The NAMP and the National AI Strategy provide an opening for local content and sector champions [8, 10].

9.3 A commercialisation pathway

Most agricultural prototypes in Nigerian universities stall between a working prototype and a product that a farmer will buy. Table 6 sets out stages, the typical gap at each stage, and the support needed. The reasoning is that a product reaches the market only when it has demonstrated performance in the field, can be manufactured repeatably at a known cost, is serviceable, and has a business model that someone will pay for.

Table 6: A commercialisation pathway for locally developed agricultural AI and robotics (author's proposal)

Stage	Evidence required	Typical gap	Support needed
1. Prototype	Works on the bench; documented design and code	Single unit; no field data	University labs; TETFund and similar research grants
2. Field validation	Tested on farms across seasons and sites; accuracy, throughput, energy and failure data reported	No independent test; no comparison with current practice	Testing at research institutes and farms; Lab-to-Land partnerships
3. Pilot product	Ten or more units; costed bill of materials; local parts	Quality varies; no service model	Incubators; local workshops; standards bodies
4. Market launch	Price, warranty, training and spare parts; service agents	Working capital; farmer credit; after-sales	Development finance; lease-to-own; service agents (hire models)
5. Scale	Repeatable production; dealer network; data to improve product	Competition from imports; cost of capital	Local-content policy; procurement; export

9.4 Intellectual property, open hardware and standards

Universities should decide early what to patent, what to publish and what to release as open hardware. For low-cost agricultural devices, open designs and documented firmware speed up adoption and local repair, while revenue comes from manufacturing, service and data products rather than from licence fees. National standards for agricultural robots, drones and sensors, including safety, electromagnetic compatibility, spray-drift and performance testing, should be developed with the Standards Organisation of Nigeria and the National Centre for Agricultural Mechanization so that local products can be compared with imports on a like-for-like basis.

10.0 GOVERNANCE, DATA, SAFETY AND ETHICS

Intelligent systems create new duties. Table 7 maps the main instruments and what they mean for agricultural engineers.

Table 7: Regulatory and policy map for agricultural AI and robotics in Nigeria

Instrument	Relevance	Implication for designers
Nigeria Data Protection Act 2023 (NDPA)	Section 37 restricts exclusive reliance on automated decision-making where it has legal or similarly significant effects, subject to exceptions, and the data subject can seek human intervention and contest the decision [25]	Credit, insurance or subsidy eligibility scored by AI needs human review and a route of appeal; carry out impact assessments for high-risk processing
NigCARs 2023, Part 21 (RPAS)	Registration; operator certificate; security clearance; open, specific and certified risk categories; camera and privacy limits; capturing images or video can itself be data processing under the NDPA [21]	Register drones, certify operators, and restrict imaging of persons and private property; plan data retention
National framework for unmanned aerial systems (directed Feb 2026)	Regulator tasked with a comprehensive policy for unmanned aircraft; agricultural spraying is a recognised use [22]	Engage in consultation; provide agricultural spray and safety input
AU Continental AI Strategy (2024)	Africa-owned, people-centred approach; priorities in infrastructure, talent, datasets, innovation and partnerships [9]	Align datasets and capacity-building with continental priorities
Nigeria National AI Strategy (2025)	12 goals and 34 initiatives; five pillars; agriculture a sector for champions [10]	Volunteer as sector champions; propose agricultural AI initiatives
National Agricultural Mechanization Policy (2026)	Private-sector-enabled mechanization, assembly, spare parts, digital fleet management and operator training [8]	Include telematics, data standards and operator certification in schemes

10.1 Principles

1. **Data ownership and consent.** Farm data belong to the farmer or cooperative; consent should be informed, in local languages, and revocable. Sensitive and location data need extra care under the NDPA.
2. **Transparency.** Farmers should be told when advice is machine-generated and how confident it is. Explainability tools are rarely used in the literature (fewer than 3% of publications mention them [4]), which should change.
3. **Safety.** Robots and drones near people require stop functions, geo-fencing, spray-drift control, training and insurance.
4. **Inclusion.** Women, youth and older farmers should be part of design and testing; do not assume smartphone ownership or literacy.
5. **Accountability.** Define who is responsible when advice is wrong: the developer, the extension provider or the farmer.

11.0 THE FUTURE OF AGRICULTURAL ENGINEERING EDUCATION, RESEARCH AND PROFESSIONAL PRACTICE

11.1 Education

The National Universities Commission (NUC) approved 13 new undergraduate programmes in October 2025, including a B.Sc. Artificial Intelligence, as an outcome of the CCMAS addendum process, with universities permitted to offer them only after a Resource Assessment Visit [26]. This signals that AI is becoming a mainstream discipline in Nigerian universities. Agricultural engineering programmes should respond not by becoming computer-science departments but by embedding data, sensing and control in the agricultural engineering curriculum so that graduates can build, deploy and maintain intelligent farm systems. Table 8 proposes a module framework that can be fitted into the existing minimum standards through electives, project work and laboratory upgrades. It is a proposal for discussion by the profession, not an NUC requirement.

Table 8: Proposed intelligent-agriculture modules for agricultural and biosystems engineering programmes (author's proposal)

Level	Module content	Practical work	Assessment
Years 1-2	Programming (Python, C/C++); electronics and sensors; data handling and statistics	Sensor node on a microcontroller; data logging	Lab reports; code review
Year 3	Control systems and instrumentation; machine vision and machine learning basics; IoT networks and power systems; solar energy	Camera-based grading; solar irrigation controller	Field tests; mini-project
Year 4	Robotics and mechatronics for agriculture; edge AI and model optimisation; precision agriculture and remote sensing; ethics and regulation	Capstone: field-tested device or system with cost model	Public demonstration; independent field validation
Postgraduate	Advanced machine learning for agriculture; UAV systems; climate and hydrological modelling; commercialisation	Thesis with open dataset and code	Peer-reviewed output; prototype testing report

Laboratories need a minimum shared kit: microcontroller boards, sensors, a small drone, a camera station, a solar test bench and a workshop for mechanical fabrication. Industrial attachment should place students in farms, service providers and manufacturers, and external examiners should include practitioners. Staff training is as important as curriculum change.

11.2 Research agenda

- **Field-validated models** for Nigerian crops and conditions, with open datasets, and reporting of failure cases;
- **Edge AI** benchmarks for agricultural tasks on commodity microcontrollers, with full resource reporting (flash, RAM, latency, energy) which the literature still lacks [15];
- **Low-cost robotics** for seeding, weeding, scouting and sorting; durability and economics under local conditions;
- **Impact evaluation** of AI advisory against conventional extension; the available evidence is self-reported [11];
- **Climate-smart system design** that integrates forecasts, soil moisture, energy and farm economics;
- **Governance research** on data ownership, liability and inclusion.

11.3 Professional practice

Professional bodies, including the Nigerian Institution of Agricultural Engineers, should (i) update competence frameworks to include data, control and AI, (ii) run certification for drone pilots, machine operators and technicians, (iii) publish guidelines for field validation and reporting of intelligent systems, and (iv) provide a forum where university researchers, manufacturers, regulators and farmers test products together. The conference platform can host an annual field-validation challenge in which entrants' systems are tested on the same plots and published against common metrics.

12.0 PROPOSED IMPLEMENTATION FRAMEWORK

The proposals should be implemented in phases over five years, starting with pilots that can fail cheaply and learn (Table 9). Monitoring runs through all phases.

Table 9: Phased implementation plan

Phase	Period	Key activities	Lead and partners	Outputs
1. Foundations	Year 1	Establish national field-image and sensor data repositories with data-protection rules; baseline audit of postharvest losses; faculty and technician training; draft module framework; engage NCAA, NITDA and standards bodies	Universities; NIAE; NCAM; NITDA; State agencies	Datasets; baseline; curriculum draft; MoUs
2. Pilots	Years 2-3	Pilot AI advisory in two local languages; edge irrigation and sorting stations at cooperatives; drone spraying service under NCAA rules; field validation challenge; Lab-to-Land trials	Universities; extension services; cooperatives; private firms	Operating pilots; field-validated results
3. Scale-up	Years 4-5	Expand successful pilots; local pilot production; service agents and training centres; lease-to-own financing; integrate with mechanization policy schemes	Manufacturers; NASENI; development finance; State governments	Scaled schemes; local products on market
4. Monitoring	Ongoing	Annual independent evaluation against Table 10; public reporting; review at Years 3 and 5	NIAE; independent evaluators	Annual performance report

Table 10: Performance indicators (targets to be set from the Phase 1 baseline)

Indicator	Baseline	Proposed target
Farmers receiving digital advisory; share reporting a changed practice	Phase 1 survey	Set per pilot; independently verified
Models field-validated (independent sites and seasons) against all models deployed	Phase 1 audit	All deployed models validated before scale-up
Open Nigerian datasets (images, sensor data) published	Phase 1 audit	Set per crop priority
Water, energy and input savings against farmer practice (paired comparison)	Pilot baseline	Positive and statistically tested
Postharvest loss in pilot chains (before and after)	Baseline audit	Reduction targeted per chain
Devices in operation; uptime; mean time to repair	Zero	Uptime set per device class
Local content: units assembled or manufactured locally; jobs created	Phase 1 audit	Increasing annual share
Graduates and technicians trained and certified	Phase 1 audit	Set per institution

Table 11: Principal risks and mitigation

Risk	Mitigation
Over-claiming from laboratory results	Mandatory independent field validation; publish confusion matrices and failures
Weak lower layers (power, sensors, connectivity, repair)	Design for offline operation; solar backup; local service agents; spare-parts plan
Content and data gaps in advisory systems	Invest in curated local content and update cycles; flag unanswered queries for review
Regulatory or safety incidents (drones, robots)	Early engagement with NCAA; certified operators; insurance; geo-fencing
Data misuse or loss of trust	NDPA-compliant consent; data governance board; local data storage where practicable
Prototype-to-market gap	Commercialisation pathway (Table 6); lease-to-own; procurement preference for tested local products
Digital exclusion of women, older and low-income farmers	Voice and SMS; group-based access; inclusive testing

13.0 KEY RECOMMENDATIONS

The following recommendations are proposed for the Federal Government, State governments, the Nigerian Institution of Agricultural Engineers, universities, research institutes, the private sector and development partners:

1. **Adopt the "beyond automation" framework:** plan mechanization, sensing, data and skills together using the intelligence stack, not as separate projects.
2. **Build national agricultural datasets:** create open, labelled, field-collected image and sensor datasets for priority Nigerian crops, with data-protection safeguards.
3. **Require field validation:** make independent field testing across sites and seasons a condition for public funding or procurement of AI and robotic systems, and require reporting of sensitivity, specificity and precision.
4. **Invest in curated local content for advisory systems:** support extension agencies and universities to maintain verified content in major Nigerian languages and run generative-AI advisory with human review.
5. **Prioritise edge and offline designs:** fund low-cost, solar-powered, repairable devices with published resource profiles.
6. **Target postharvest first:** pilot sorting, grading and cold-storage intelligence in tomato, yam, mango, grain and other high-loss chains, with measured losses before and after.
7. **Regulate drones and robots enabling, not blocking:** work with the NCAA to certify agricultural drone operators and publish spray-safety guidance as the national framework is developed.
8. **Strengthen climate services and data sharing:** link river-basin, dam and meteorological data with community alerts and index insurance, learning from the 2025 flood events.
9. **Support indigenous innovation and local manufacturing:** use the commercialisation pathway, local-content procurement and lease-to-own finance to move tested prototypes into production through NASENI, incubators and private manufacturers.
10. **Reform curricula and laboratories:** embed data, sensing, control, robotics and AI ethics in agricultural engineering programmes through electives, projects and laboratories, aligned with the new NUC programmes.
11. **Upgrade professional practice:** create competence frameworks, certification for drone pilots and technicians, and an annual national field-validation challenge hosted by the Institution.
12. **Measure and publish results:** adopt the indicators in Table 10, evaluate independently and publish failures as well as successes.

14.0 CONCLUSION

Nigeria's agriculture is large, climate-exposed and still largely manual. Mechanization is necessary but not sufficient. The evidence reviewed here shows both promise and caution. Generative-AI advisory has reached tens of thousands of African farmers, offline phone-based diagnosis can approach researcher-level accuracy on one major crop, low-cost microcontrollers can run useful models and local robots, and AI weather forecasts can reach tens of millions of farmers by SMS. But laboratory accuracy routinely overstates field accuracy, most research is not validated in real fields, the global robot industry is built elsewhere, and much of the available evidence is developer-reported.

The way forward is therefore not to import automation wholesale, nor to wait for perfect technology. It is to build the full stack: field-validated models on local data; robust, repairable hardware designed and made in Nigeria; data, safety and ethical rules that farmers can trust; policies that join mechanization, climate services and AI; and a generation of agricultural engineers trained to design, test and maintain intelligent systems. Agricultural engineers are well placed to lead because the problem sits at the boundary of machines, biology, water, energy and data.

The measure of success is not the number of robots in a showroom, but the hectares farmed with better decisions, the tonnes saved after harvest, the water and energy conserved, the farmers who trust the advice they receive, and the jobs and companies created at home.

"LET US MOVE BEYOND AUTOMATION: BUILD AN AFRICAN AGRICULTURE THAT SENSES, DECIDES, ADAPTS AND LEARNS, DESIGNED, MANUFACTURED AND GOVERNED BY AFRICANS."

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Paper ID 10:

Postharvest Changes in Total Soluble Solids of Onions as Affected by Temperature and Relative Humidity

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ABSTRACT

Total soluble solids (TSS) indicate compositional change in stored onion (Allium cepa L.), but the joint effects of storage temperature and relative humidity (RH) on Nigerian cultivars remain poorly documented. Dadin-Kowa Red onions were stored for eight weeks under nine temperature–RH combinations: 25, 30, and 35 °C combined with 60, 65, and 70% RH. The combinations were tested simultaneously in nine independently controlled sections formed by subdividing three main storage compartments. At weekly intervals, one fresh onion bulb was sampled from each section and its juice was measured twice with a handheld refractometer. Because each treatment combination occupied one section and duplicate readings were technical measurements of the same juice sample, results are presented descriptively rather than as independent-replicate tests of treatment effects. Mean TSS rose from 9.99 °Bx at day 7 to 13.06–13.07 °Bx at days 42–49, then fell to 12.43 °Bx at day 56. Across the tested conditions, mean TSS was 11.04, 12.27, and 11.93 °Bx at 25, 30, and 35 °C, respectively, and 11.81, 11.78, and 11.66 °Bx at 60, 65, and 70% RH. Higher TSS did not necessarily indicate better bulbs because warmer conditions were also associated with greater weight loss and rottenness in the companion analysis. The combination of 25 °C and 65% RH is identified as a promising condition within the tested range based on the combined descriptive evidence, although confirmation requires an experiment with independent replication.

KEYWORDS: Onion, Total soluble solids, Storage temperature, Relative humidity, Postharvest quality

1. INTRODUCTION

Onion (*Allium cepa* L.) is among the most widely produced and consumed vegetables worldwide, with global output exceeding 90 million tonnes per year (Food and Agriculture Organization of the United Nations [FAO], 2021). Because the crop is harvested seasonally but eaten year-round, supply depends on storage, and postharvest losses of roughly 20–40% are commonly reported (Suravi et al., 2024). After harvest, bulbs are cured so that the neck seals and the outer scales dry into a protective skin that limits water loss and the entry of pathogens (Galsurker et al., 2018). Thereafter, storage conditions govern bulb quality for most of the marketing season.

Temperature and relative humidity (RH) are the two storage variables to which bulbs are most sensitive. Onion is classified as non-climacteric (Downes et al., 2010), so quality change in storage is driven mainly by water loss, respiration, sprouting, and disease rather than by a ripening cascade. Warmer storage increases weight loss (Sohany et al., 2016), whereas excessive humidity and condensation promote decay and low humidity increases desiccation. The conditions recommended for long-term storage of dry onions are 0 °C and 65–70% RH, and storage between 5 and 25 °C favors sprouting (Postharvest Research and Extension Center, n.d.). Smallholders in tropical Nigeria, however, generally lack refrigeration, and ambient temperatures in Gombe State range from 24 to 48 °C (Audu et al., 2013). Identifying the best attainable temperature–humidity combination above the cold-chain range is therefore a practical question.

Total soluble solids (TSS), measured in degrees Brix (°Bx), is a rapid index of the soluble sugar and solute concentration of the bulb. During storage it is expected to reflect two opposing processes: water loss, which concentrates solutes, and the consumption or conversion of carbohydrates through respiration and senescence, which lowers them. TSS therefore does not move in one direction. In red onion bulbs held at several temperatures, for

example, TSS increased until about day 40 and then declined by day 60 (Sohany et al., 2016). Whether a given TSS value signals a better or a worse bulb depends on which process dominates and cannot be judged from TSS alone.

Evidence for Sub-Saharan African cultivars is scarce, and no consensus exists on the temperature–humidity range that best balances TSS, weight loss, and rottenness. Dadin-Kowa Red onion (locally known as Zobo), widely grown in Gombe State, has received little attention in controlled-storage research. This paper reports the TSS component of a larger study that also measured weight loss and rottenness (Yunusa, 2025). TSS is treated separately because its interpretation is ambiguous, as noted above, and because the full three-way layout needs detailed reporting; the companion variables are used to interpret the TSS patterns. The objectives were to (a) describe the complete weekly TSS trajectory under nine temperature–RH combinations over eight weeks, (b) summarize how temperature, RH, and storage time, singly and in combination, relate to the observed TSS values, and (c) assess what the TSS patterns imply for choosing storage conditions.

2. MATERIALS AND METHODS

2.1 Study site and period

The study was conducted in the Department of Agricultural Technology Laboratory, Federal College of Horticultural Technology, Dadin-Kowa, Gombe State, Nigeria, from July to October 2023. The area is tropical (643 m above sea level), with annual temperatures of 24–48 °C and annual rainfall of 760–1,110 mm (Audu et al., 2013).

2.2 Storage structure

Onions were stored in a purpose-built structure consisting of three main compartments, each subdivided into three sections to accommodate the nine temperature–RH combinations simultaneously. Each of the nine sections had its own temperature and RH sensors and independent control arrangements, including heating/cooling elements and extractor fans connected to the control system. The system compared sensor readings with assigned set points and operated the control components to maintain the target conditions. Temperature and RH were recorded from the display three times daily. The nine sections, rather than the three main compartments, were the locations to which treatment combinations were assigned with each section having 10kg onions.

2.3 Plant material and curing

Dadin-Kowa Red onion, grown with normal cultural practices, was used. Under ambient conditions its shelf life is approximately 2–3 weeks. Bulbs were inspected for damage and for intact outer scales, and bulb diameter was measured with a vernier caliper (range 3.2–9.27 cm). Immediately after harvest, bulbs were cured for 24 h at 25–35 °C and 70% RH to reduce neck rot and moisture loss during storage and to promote scale color. Bulbs were spread evenly within the assigned storage sections.

2.4 Experimental design and treatments

A 3 × 3 treatment arrangement was used, comprising temperatures of 25, 30, and 35 °C and RH levels of 60, 65, and 70%. The temperature levels were selected to represent conditions that could realistically be achieved without refrigeration under local ambient temperatures (24–48 °C); (Sohany et al., 2016), while the RH levels bracketed the 65–70% range recommended for dry onions (Postharvest Research and Extension Center, n.d.). The nine temperature–RH combinations were established simultaneously, with one combination assigned to each of nine independently controlled sections formed by subdividing the three main compartments. One fresh bulb was sampled from each section at each of eight weekly sampling times (days 7, 14, 21, 28, 35, 42, 49, and 56). Each treatment combination was represented by one storage section. Thus, the sampled bulbs and duplicate refractometer readings do not constitute independent replication of the storage treatment.

2.5 Total soluble solids measurement

At each 7-day sampling, one fresh onion bulb was sampled from each of the nine temperature–RH sections. Two to three drops of clear juice from each bulb were placed on the prism of a handheld refractometer, and TSS was read in °Bx. Sampling was destructive, so a new bulb was used at each sampling time. Two readings were taken from the same juice sample for each section and sampling time. These duplicate readings were technical measurements and were averaged to provide one descriptive TSS value for each sampled bulb; they were not treated as independent experimental replicates.

2.6 Statistical analysis

TSS values were summarized descriptively by temperature, RH, storage time, and their combinations, and are reported as means. The duplicate refractometer readings from each juice sample were technical readings and were not treated as independent replicates. Because each temperature–RH combination was assigned to a single independently controlled section, the design did not provide independent replication of treatment combinations, and inferential tests (analysis of variance and mean-separation tests) were therefore not applied. Means and weekly patterns are reported descriptively. Confirmation of treatment effects requires a follow-up experiment with multiple independently controlled storage units per treatment combination.

3. RESULTS AND DISCUSSION

3.1 Descriptive overview

The descriptive summaries show variation in TSS across temperature, RH, and storage time. Because the duplicate refractometer readings were not independent experimental replicates and each treatment combination occupied only one storage section, no inferential tests are reported. The observed means are used to describe patterns within this experiment and not to establish statistically significant treatment effects.

3.2 Main effects of temperature and relative humidity

Descriptively, mean TSS was lowest at 25 °C (11.04 °Bx), highest at 30 °C (12.27 °Bx), and intermediate at 35 °C (11.93 °Bx) (Table 1). The RH means were close to one another: 11.81 °Bx at 60% RH, 11.78 °Bx at 65% RH, and 11.66 °Bx at 70% RH. The 0.15 °Bx spread between the 60% and 70% RH means is small. Because treatment combinations were not independently replicated, these differences are descriptive and should not be interpreted as statistically significant differences.

Table 1. Main effects of temperature and relative humidity on total soluble solids

Factor	Level	Mean TSS (°Bx)
Temperature	25 °C	11.04
	30 °C	12.27
	35 °C	11.93
Relative humidity	60%	11.81
	65%	11.78
	70%	11.66

Note. Means are descriptive summaries of the observations available for each factor level. No inferential groupings are shown.

The observed temperature pattern should not be taken as a formal ranking of treatment effects, and higher TSS did not necessarily indicate better bulbs. In the companion data from the same experiment, mean weight loss (averaged over the eight samplings) increased with temperature (21.86%, 26.94%, and 46.74% at 25, 30, and 35 °C), and rottenness was lowest at 25 °C (7.90%, against 8.32% and 8.40%; Table 6). Both warmer treatments therefore combined higher mean TSS than 25 °C with greater weight loss and rottenness. TSS accumulation tracked storage-induced change, and the lower TSS at 25 °C may reflect slower change. This is not a general claim that low TSS is desirable, because TSS also contributes to flavor; it means that TSS cannot be used alone to rank the conditions.

The observed RH range was small. The 0.15 °Bx difference between 60% and 70% RH is about 1.3% of the mean and may be comparable to the resolution of some handheld refractometers. The direction of the RH pattern also varied with temperature (Section 3.3), so TSS alone is not sufficient to select an RH level.

3.3 Effect of storage time

Averaged descriptively over temperature and RH, TSS rose from 9.99 °Bx at day 7 to 13.06 °Bx at day 42 and 13.07 °Bx at day 49, before falling to 12.43 °Bx at day 56 (Table 2). The peak in the observed means therefore occurred at

days 42–49 rather than at the end of storage. This rise-then-fall pattern resembles that reported for red onion bulbs held at other temperatures (Sohany et al., 2016), although the present design does not support inferential claims about differences between sampling times.

Table 2. Mean total soluble solids by storage time

Storage time (days)	Mean TSS (°Bx)
7	9.99
14	10.66
21	11.09
28	11.56
35	12.12
42	13.06
49	13.07
56	12.43

Note. Means are descriptive summaries across the temperature–RH combinations at each sampling time. No inferential groupings are shown.

Water loss probably contributed to the early rise: in the same experiment, mean weight loss increased from 7.08% at day 7 to 47.99% at day 49 (Yunusa, 2025), which would concentrate solutes. Between days 49 and 56, however, weight loss continued to climb (to 51.88%) while TSS fell, which suggests that consumption of soluble carbohydrate in respiration or senescence outweighed concentration at that stage. These mechanisms are inferences from the pattern; sugar composition, dry matter, respiration, and sprouting were not measured.

3.4 Temperature and relative humidity patterns

The descriptive temperature-by-RH means show that the pattern across RH levels varied by temperature (Table 3). At 35 °C, TSS fell as RH rose (12.21, 11.93, and 11.66 °Bx at 60, 65, and 70% RH), a descriptive spread of 0.55 °Bx. At 30 °C, TSS was similar at 60% and 65% RH (12.34 and 12.35 °Bx) and somewhat lower at 70% RH (12.12 °Bx). At 25 °C, TSS rose slightly with RH (10.87, 11.07, and 11.19 °Bx). Because the direction of the observed RH pattern differed between 25 and 35 °C, the overall RH means alone do not capture all descriptive variation.

Table 3. Mean total soluble solids (°Bx) by temperature and relative humidity

Temperature	60% RH	65% RH	70% RH
25 °C	10.87	11.07	11.19
30 °C	12.34	12.35	12.12
35 °C	12.21	11.93	11.66

Note. Values are descriptive means for the corresponding temperature–RH combination. No inferential groupings are shown.

In the companion data, rottenness values at 35 °C were similar across RH levels (8.32%, 8.34%, and 8.30%), while weight loss rose slightly with RH. These descriptive patterns do not explain the fall in TSS with RH at 35 °C, and the mechanism remains unresolved.

3.5 Temperature and storage-time patterns

The descriptive TSS trajectory differed across the three temperature settings (Table 4). TSS at 25 °C was the lowest of the three temperatures at every sampling. It peaked at day 42 (12.55 °Bx) and then declined to 11.33 °Bx at day 56.

At 30 °C, TSS was highest of the three through day 42 (10.52 °Bx at day 7 against 9.52 °Bx at 25 °C), peaked at 13.53 °Bx at day 42, and fell to 11.83 °Bx by day 56. At 35 °C, TSS started between the other two, overtook 30 °C from day 49 (13.73 against 13.47 °Bx), and continued rising to 14.13 °Bx at day 56, the highest weekly mean observed. At day 56 the three temperature means were therefore 2.80 °Bx apart. The lower overall mean at 35 °C than at 30 °C (Table 1) reflects its slower start and the earlier decline at 30 °C, not a lower TSS late in storage.

Table 4. Mean total soluble solids (°Bx) by storage time and temperature

Storage time (days)	25 °C	30 °C	35 °C
7	9.52	10.52	9.95
14	10.23	11.33	10.42
21	10.60	11.97	10.70
28	11.00	12.38	11.30
35	11.10	13.13	12.13
42	12.55	13.53	13.08
49	12.00	13.47	13.73
56	11.33	11.83	14.13

Note. Values are descriptive means for the corresponding temperature-by-time combination. No inferential groupings are shown.

3.6 Relative humidity and storage-time patterns

The descriptive differences among RH levels varied over the storage period (Table 5). Differences among RH levels were 0.3 °Bx or less through day 42 and showed no consistent order early in storage. They widened to 0.45 °Bx at day 49 and 0.78 °Bx at day 56, when TSS was 12.78 °Bx at 60% RH, 12.52 °Bx at 65% RH, and 12.00 °Bx at 70% RH. TSS peaked at day 49 at 60% RH (13.35 °Bx) and at day 42 at 70% RH (12.97 °Bx). These are descriptive differences, not significance-tested comparisons.

Table 5. Mean total soluble solids (°Bx) by storage time and relative humidity

Storage time (days)	60% RH	65% RH	70% RH
7	10.02	10.08	9.88
14	10.67	10.68	10.63
21	11.07	11.12	11.08
28	11.40	11.70	11.58
35	12.02	12.15	12.20
42	13.15	13.05	12.97
49	13.35	12.95	12.90
56	12.78	12.52	12.00

Note. Values are descriptive means for the corresponding RH-by-time combination. No inferential groupings are shown.

3.7 Combined temperature, RH, and storage-time patterns

The weekly means for all nine temperature–RH combinations are given in Appendix A (Table A1). These values illustrate how the observed pattern varied across combinations, but they do not establish a statistically significant three-way interaction because independent treatment replication was absent. The lowest cell mean was 9.45 °Bx (25 °C, 60% RH, day 7) and the highest was 14.45 °Bx (35 °C, 60% RH, day 56). The largest late-storage decline occurred at 30 °C and 70% RH, where TSS fell from 13.50 °Bx at day 42 to 10.95 °Bx at day 56. The highest TSS at day 56 coincided with the greatest weight loss at 35 °C, so a high TSS value alone did not signify better overall quality.

3.8 TSS compared with weight loss and rottenness, and recommended conditions

Because TSS cannot rank the conditions alone, it is compared in Table 6 with weight loss and rottenness from the companion analysis of the same experiment (Yunusa, 2025). Rottenness was lowest at 65% RH (7.92%, against 8.58% at 60% and 8.12% at 70%), and weight loss was equal at 60% and 65% RH (31.49%) and higher at 70% (32.58%). The combination of 25 °C and 65% RH had the lowest weight loss (20.98%) and the lowest rottenness (7.65%) of all nine combinations, with an intermediate TSS of 11.07 °Bx.

Table 6. Total soluble solids compared with weight loss and rottenness

Condition	TSS (°Bx)	Weight loss (%)	Rottenness (%)
25 °C	11.04	21.86	7.90
30 °C	12.27	26.94	8.32
35 °C	11.93	46.74	8.40
60% RH	11.81	31.49	8.58
65% RH	11.78	31.49	7.92
70% RH	11.66	32.58	8.12
25 °C, 65% RH	11.07	20.98	7.65

Note. TSS values are descriptive summaries from this manuscript. Weight loss and rottenness are means from the companion analysis (Yunusa, 2025) and are included for context only; they are not analyzed here.

Among the conditions tested, 25 °C with 65% RH appears promising based on the combined descriptive TSS, weight-loss, and rottenness evidence, not on TSS alone. In the companion data, this combination had the lowest weight loss and rottenness. This should be treated as a provisional recommendation because each temperature–RH combination was represented by one storage section and treatment effects were not independently replicated. The 60% RH level had the highest rottenness in the companion data, but treatment comparisons require confirmation in a replicated study. The recommendation is relative to the tested range: even at 25 °C, mean weight loss across the eight samplings was about 22% (Yunusa, 2025), and temperatures of 5–25 °C favor sprouting in stored onions (Postharvest Research and Extension Center, n.d.), which was not assessed here.

3.9 Limitations

Only one cultivar was tested during one study period, so responses may differ for other Nigerian landraces or harvest years. TSS was measured destructively with a handheld refractometer, and the small differences among some RH means may be close to the instrument's resolution. Each temperature–RH combination was assigned to one independently controlled section, so there was no independent replication of the storage treatment. The weekly bulbs were sampled from the same section and therefore do not provide independent replication of the assigned storage environment. The duplicate readings were technical measurements of the same juice sample. For these reasons, the results are presented as descriptive patterns and no inferential claims are made. A follow-up study should include multiple independent storage units per treatment combination and report the number of independent replicates clearly. Sugar composition, dry matter, respiration, pungency, and sprouting were not measured, so explanations for the TSS trajectory remain hypotheses. The eight-week window is shorter than commercial storage periods, and the weight-loss and rottenness values come from a companion analysis and are not tested in this paper.

4. CONCLUSION

TSS in Dadin-Kowa Red onion showed clear descriptive variation across storage time and the tested temperature–RH combinations. Mean TSS rose from 9.99 °Bx at day 7 to 13.06–13.07 °Bx at days 42–49 and then fell to 12.43 °Bx at day 56; at 35 °C, the observed mean continued to rise to 14.13 °Bx at day 56. The RH means differed by only 0.15 °Bx between 60% and 70%, and the direction of the RH pattern varied with temperature. Because each treatment combination was represented by one storage section, these patterns should be regarded as descriptive rather than statistically confirmed treatment effects. Higher TSS did not necessarily indicate improved quality, as the companion data showed greater weight loss and rottenness under warmer conditions. Among the tested conditions, 25 °C and 65% RH appears promising based on the combined descriptive evidence, but this recommendation requires confirmation in a replicated experiment. Further work should include multiple independent storage units per treatment combination, sugar composition, dry matter, and sprouting, and should extend across seasons and cultivars.

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APPENDIX A

Table A1. Weekly mean total soluble solids (°Bx) for all temperature–relative humidity combinations

Day	25 °C, 60%	25 °C, 65%	25 °C, 70%	30 °C, 60%	30 °C, 65%	30 °C, 70%	35 °C, 60%	35 °C, 65%	35 °C, 70%
7	9.45	9.55	9.55	10.55	10.65	10.35	10.05	10.05	9.75
14	10.00	10.25	10.40	11.50	11.30	11.15	10.50	10.40	10.30
21	10.50	10.65	10.60	11.70	12.00	12.20	11.00	10.70	10.40
28	10.50	11.00	11.50	12.00	12.65	12.50	11.70	11.45	10.75
35	10.60	11.10	11.60	13.00	13.10	13.30	12.40	12.25	11.70
42	12.45	12.55	12.60	13.50	13.60	13.50	13.50	13.00	12.75
49	12.00	11.95	12.05	14.00	13.35	13.00	14.05	13.55	13.60
56	11.45	11.50	11.05	12.45	12.10	10.95	14.45	13.95	14.00

Note. Column headings give temperature and relative humidity. Each value is the mean of two technical refractometer readings from the juice sample of one bulb.

Paper ID 11:

Artificial Intelligence and Machine Vision for Precision Agricultural Mechanization in Southern Nigeria: Evidence Gaps, Barriers, and Frameworks.

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ABSTRACT

Nigeria's mechanization level, measured in horsepower per hectare, falls far short of the Food and Agriculture Organisation (FAO) recommendation of 1.5 hp/ha. In African countries, this value is much lower, at only 0.027 hp/ha, and even lower in the country's southern part, where most farms are characterized by acidic, fragmented land in a humid climate. This study sought to determine the factors influencing the adoption of artificial intelligence/machine vision for precision mechanization in speciality crops (e.g., rice, cassava, oil palm, yam, maize) in Nigeria. Published and unpublished works (Scopus, Web of Science, Google Scholar, PubMed, IEEE Xplore, African Journal Online, and grey literature resources) were reviewed according to the levels-of-evidence hierarchy. Works published between 2010 and 2026 were considered. The evidence level of algorithm-crop associations was then evaluated on the evidence hierarchy. Random Forest/Gradient Boosting for rice yield prediction was the only method with local (Cross River and other Nigerian) validation evidence; others—Convolutional Neural Networks (CNNs)/Support Vector Machine (SVM) for cassava disease detection, unsupervised learning-based soil zoning for oil palm, and Reinforcement Learning for irrigation scheduling—were either applied locally using non-local evidence or based on theoretical considerations. The strongest local evidence for using machine vision for post-harvest quality control came from real-time fruit grading and sorting with convolutional neural networks (CNNs). The key barriers to entry were an unreliable electricity and broadband network, high tax, and the cost of vision equipment, a highly fragmented land distribution, and the lack of data governance and privacy rules, resulting in a data desert. Another issue was observed in gender, as female farmers, who accounted for 72% of cassava processors, were less inclined to adopt automated post-harvest mechanization (18%) than their male counterparts. The article proposes Edge-Cloud collaborative intelligence; Smart-Mechanization-Hub-assisted local data governance and sandboxes; NATIP's gradual take-off in Nigeria using Cortex-M4/TinyML-Jetson/Coral; and the prioritization of local data repository/sandbox and the collection of primary data.

KEYWORDS: *Artificial Intelligence; Machine Vision; Precision Agriculture; Agricultural Mechanization; Machine Learning; Smallholder Farmers*

INTRODUCTION

Agriculture plays a vital role in Nigeria's economy, accounting for 22-25% of the country's Gross Domestic Product (GDP) and 34-38% of Nigeria's population (FAO, 2023; World Bank, 2024). Unfortunately, environmental factors including forested lands and highly weathered, acidic soils hinder mechanization in the South-South region of Nigeria, and curtail crop production (e.g., studies on the quality and weathering of soils in South-South Nigeria) (Echem et al., 2026). Despite these environmental shortcomings, the South-South region of Nigeria remains a prolific producer of oil palm, cocoa, cassava, yam and other commodities. Therefore, according to a report by NATIP (2022, as cited in NCAM, 2024), Nigeria has achieved only a level of mechanization of 0.027 horsepower per hectare against a recommended 1.5 horsepower per hectare for developing countries as recommended by the Food and Agriculture Organisation (FAO). This information situates Nigeria's mechanisation level and provides background for considering mechanisation options, including artificial intelligence. Mechanization in Nigeria has traditionally relied on draft animals and tractors to replace manual and animal power. Nevertheless, tractor-based mechanization cannot meet Nigeria's current need for precision farming. In recent years, agriculture 4.0 has been promoted worldwide as a new

approach that uses cyber-physical systems based on Internet of Things technologies to ensure food security while adapting to climate change (Anderl, 2015; Benos et al., 2021).

Therefore, Artificial Intelligence (AI) could be a great advantage in automating crop production while being sustainable despite the challenges of climate change. This study reviews the potential of using AI and machine vision techniques in mechanizing and revolutionizing agriculture in southern Nigeria.The review seeks to answer two questions: first, what do scholarly and professional information resources say about mechanizing agriculture in general and southern Nigeria in particular? Specifically, what AI and machine vision innovations have been proposed or implemented to mechanize agriculture? In addition, which infrastructural, economic, and sociocultural factors would enable or challenge the adoption of AI by smallholder farming systems? Evidence is compiled to identify gaps, barriers, and approaches, and to set priorities for future research directions. While previous reviews have examined AI in agriculture globally or in sub-Saharan Africa, this review is novel in its specific focus on Southern Nigeria, its use of a levels-of-evidence hierarchy to classify crop-algorithm pairings as 'validated locally' (tested using Nigerian data), 'validated elsewhere' (tested on the same crop or task but using non-Nigerian data) or 'theoretical extrapolation' (not tested on the particular crop or task but inferred by analogy). This approach calls attention to a gap in evidence, specifically, that most applications of AI and machine vision to the region's prioritized crops have not been locally validated and that Nigeria lacks an agricultural data governance framework.

METHODOLOGY

The literature on the use of artificial intelligence, machine vision, and precision agriculture technology to mechanize agriculture in southern Nigeria was reviewed using keywords in Scopus, Web of Science, Google Scholar, PubMed, IEEE Xplore, and African Journals Online (AJOL). Relevant articles published between 2010 and 2026 for inclusion were considered in the search run on 15th July 2026.

Search strategy: Search terms that yielded relevant research works included machine learning, artificial intelligence, machine vision, computer vision, precision agriculture, agricultural mechanization, smallholder farmers, Nigeria, Southern Nigeria, cassava, rice, oil palm, post-harvest, edge computing, and Agriculture 4.0. In addition to database searches, we also conducted a grey literature searchconducted a grey literature search by exploring the websites of related organizations such as the Food and Agriculture Organisation (FAO), the National Centre for Agricultural Mechanisation (NCAM), and government agencies for reports, policy briefs, media releases, and other relevant publications.

Inclusion and screening criteria: The literature review focuses on the use of AI, machine vision, and precision agriculture to mechanize agriculture and agricultural production, with sub-Saharan Africa and Nigeria as the focal point. In addition to screening titles and abstracts, full texts of the short-listed articles were read and reviewed. Based on search strategy, a total of 250 records were identified, 130 screened based on search terms, 53 records excluded for reasons ranging from title and abstract against the eligibility criteria, records clearly out of scope, pre-2010 records, and non-English records, and 67 were included after full-text review, journals (36), conference proceedings (2), grey literature searches including news and industry reports (29) because they often contain information on economic and other statistics and highlight challenges and issues not captured in peer-reviewed journals. The data extracted from news and industry reports were used as supplemental literature to support findings from peer-reviewed journals, as these reports are considered secondary literature. Data reported in commercial and media outlets were compared to those published in government agencies. Since the current research did not produce any primary data, such as surveying or interviews, the only option was to review the literature publishing research findings in northern Nigeria, which declined to include southern Nigeria. One limitation of this research is the use of secondary data. The data used in this research was published by news and industry outlets, which means that it was not peer-reviewed. Therefore, future research on the same topic should utilize primary data to obtain more credible and reliable results and findings.

RESULTS AND DISCUSSION

3.1 Current State of AI and Machine Vision Applications in Precision Agriculture and Mechanization

Precision agriculture uses machine vision and machine learning to support data-driven decision-making, predictive analytics, and mechanization (Benos *et al.*, 2021). In Southern Nigeria, AI-adapted agricultural machinery remains in

its infancy, indicating low levels of precision farming in the region. Additionally, precision agriculture initiatives in the region appear to be led mainly by private AgTech organizations, with few government-led initiatives identified in the sources reviewed. While precision agriculture has seen remarkable software applications for estimating evapotranspiration, growing-degree-days, and irrigation scheduling (Benos *et al.*, 2021), little is known about these technologies' on-the-ground applications and impact in Southern Nigeria.

Known precision agriculture initiatives in Nigeria fall under two broad categories of ML-integrated mechanization (Figure 1). However, these statistics are reported at the continental level, not specifically for Southern Nigeria. For example, Hello Tractor is a precision agriculture start-up platform that uses connected IoT devices, telematics, and machine learning to enable small-scale farmers to rent agricultural machinery on demand (Blended Finance Taskforce, 2020). Hello Tractor reports that its platform connects over 2.5 million smallholder farmers in Africa, with nearly 8,000 tractors and harvesters and 6.8 million acres engaged. On the other hand, Growth Gateway (2025) reports about a network of 5,000 tractors in Nigeria, Kenya, and Uganda, which serve over 2 million farmers and cultivate more than 3 million acres, which indicates discrepancies, as multiple sources provide statistics within their scope. Hello Tractor's website states it operates in 18 African countries, having over 5,000 tractors and serves more than 2 million farmers on 6.8 million acres. Hello Tractor reports that farmers who use its technology record an average increase of 227% in their income as they benefit from increased planting timelines and productivity. However, the rise could be an indication that the technology recommends the right planting time and the use of machinery to increase yields. However, Hello Tractor has no information on the technology's efficacy in the Southern region (Empower Africa, 2026).

In Nigeria, the Federal Government has begun rolling out more than 2,000 John Deere tractors and heavy-duty equipment under the Renewed Hope National Agricultural Mechanisation Programme (RH-NAMP), with the Bank of Agriculture leading implementation and Heifer International providing support. The program has trained 4,000 operators to operate and maintain these tractors and their accessories. Every tractor is designed to clear about 600 hectares in a year. The tractors are bought by approved mechanization service providers on a leasehold basis and not for personal use (The Sun Nigeria, 2026; Ministerial Leadership Program, 2023). The program targets to create a mechanization as a service economy in which farmers acquire services on a competitive payment scheme (Federal Ministry of Information and National Orientation, 2026). The plan also targets to produce a mega tractor manufacturing plant that can rollout 2,000 to 4,000 units of tractors annually (Bank of Agriculture BOA, 2026; Federal Ministry of Agriculture and Food Security, 2026). Besides, the statistics mentioned above are not specific to the Southern Provinces, and this study did not find any segregated statistics for the Southern Provinces.

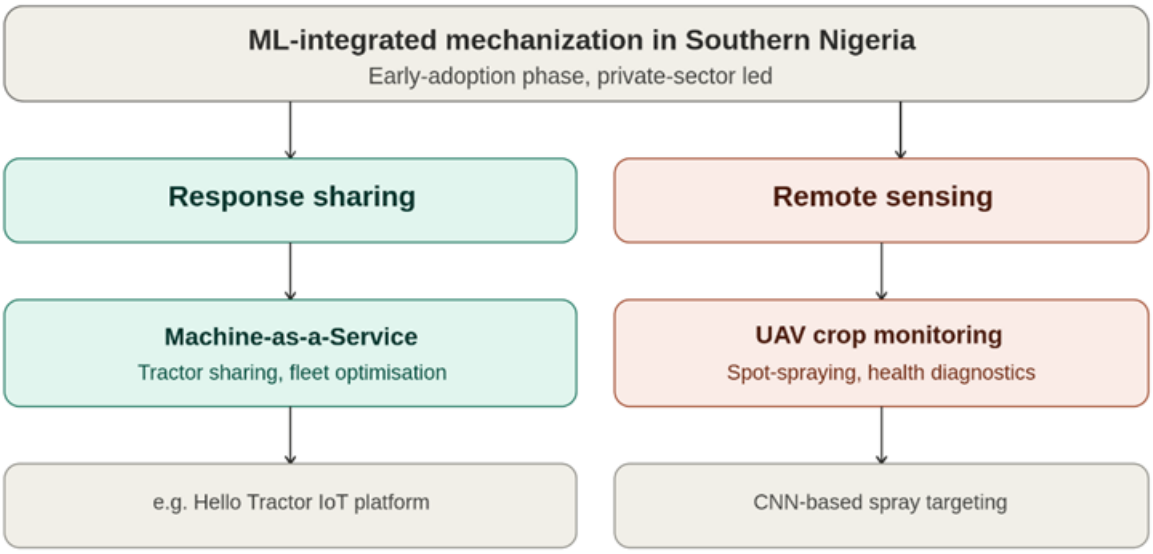

Figure 1. Machine learning (ML)-integrated mechanization domains in Southern Nigeria: (1) machine-as-a-service sharing platforms for tractor sharing and fleet optimization, and (2) machine-vision-based remote sensing for UAV crop monitoring and precision spraying.

Although it is undeniable that there are signs of the adoption of remote sensing methods based on machine vision in the Nigerian South, their use is still limited (Figure 2). Within the framework of the TAT AI Project, agricultural robots that will assist in harvesting and storing are presented as a promising technology to be adopted in Akwa Ibom (Premium Times, 2026). However, it should be noted that this is a purely projected activity, and no information has been received about the results of their implementation. Studies of the application of remote sensing in Nigeria show that both the Random Forest algorithm and Long Short-Term Memory networks are able to delineate croplands and estimate yield. However, research conducted in the country's northern regions, as well as analysis of nationwide data sets, does not cover their use in the southern regions (Gajardo et al., 2025; Ibrahim & Balzter, 2024; Jiya et al., 2025). A recent study that compared the accuracy of deep learning models used in cropland mapping in Nigeria concluded that the F1-scores were different in various agro-ecological zones, with the highest value (0.903) being reported in the Southern Guinea Savanna, while the lowest F1-score (0.667) was detected in the Rainforest areas (Ajoniloju et al., 2026). As such, the Nigerian South ought to prioritize adoption of remote sensing technologies, since most of the reviewed studies relied on data or algorithms tested either in the north or at the national level.

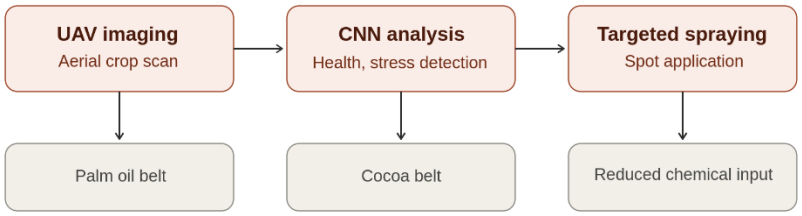

Figure 2. Machine vision pipeline for precision spraying: UAV image capturing, image classification (using CNNs) for health and stress detection and targeted spraying as an intervention, applied to palm oil and cocoa belts, resulting in reduced chemical usage.

3.2 AI and Machine Vision Model Suitability for Primary Crops in Southern Nigeria

Choosing the right AI approaches for crops such as rice, cassava, and oil palm in Nigeria relies on distinguishing between locally tested models, those validated in other regions of the country, and those based on theoretical assumptions (Figure 3). The figure below schematically shows the distribution of AI paradigms proposed or implemented in precision agriculture for rice, cassava, and oil palm. For instance, supervised machine vision (CNN, SVM) is mainly applied in cassava, particularly for disease prediction. Unsupervised learning (K-means, PCA) is proposed for oil palm soil and nutrient zoning. In contrast, reinforcement learning (Q-learning, Deep Q-Networks) has been proposed for rice irrigation and harvesting schedules.

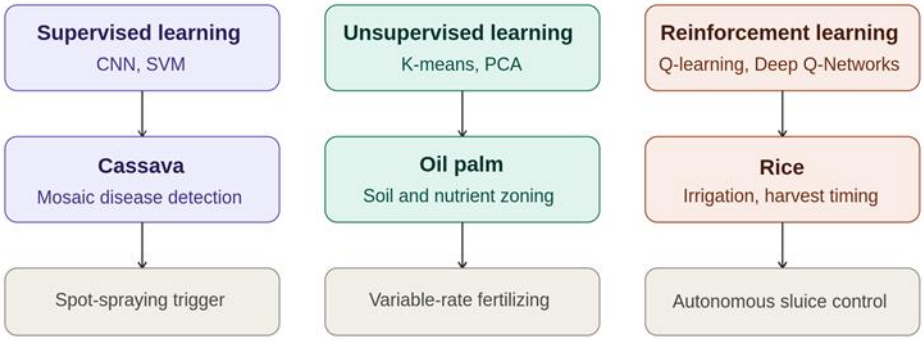

Figure 3. Mapping of AI paradigms to crop-specific precision agriculture applications

In Nigeria, the technique most cited for cassava (Manihot esculenta) is supervised machine vision, primarily for the prediction of diseases. Cassava Mosaic Disease (CMD) is a major viral disease which affects the production of cassava. The percentage of incidence recorded in 2015 and 2017 was 43.80% and 12.25% respectively in South West and North Central Nigeria (Eni et al., 2021). Convolutional Neural Networks (CNNs) have been applied to classify CMD, as well as other cassava leaf diseases, with reported accuracies between 93 % and 98%, depending on the disease. Specifically, Ramcharan et al. (2017) report 98% accuracy for brown leaf spot, 96% for red mite damage, 95% for green mite damage, 98% for cassava brown streak, and 96% for cassava mosaic disease, with an overall accuracy of 93%, on held-out data. This high accuracy was achieved using a benchmark dataset of cassava leaf images, from East Africa, and not Nigeria, and it is yet to be tested, the application performance on Nigerian cassava varieties on the field, under the local conditions. In particular, the review of ML and DL methods for crop disease diagnosis recently emphasized that the imbalance of the data sets and their specificity may be significant challenges for model's generalizability. For instance, the PlantVillage database, the most popular one, has a bias toward healthy and some particular disease states, thus limiting the scope of models to others (Ngugi et al., 2024). The authors underline the need for extensive and properly annotated image sets covering a large variety of crops to achieve the wide application of algorithms.

Researchers have applied Random Forest and Gradient Boosting to rice yield prediction in Nigeria using sensor and remote-sensing data, with evidence from Cross River State (South) and Adamawa State and the Hadejia and Auyo areas (North). Indeed, the Random Forest algorithm performed comparably well in Cross River State (Ingio *et al.*, 2024). Meanwhile, other combinations of rice and supervised learning algorithms in northern Nigeria (Hadejia and Auyo) have recorded an R2 as high as 0.9529, with Random Forest among the methods explored (Abdurrahman & Muhammad, 2025). Accurate yield prediction lets farmers time mechanical harvesting to minimize losses, which account for almost 30% of regional production (Haruna *et al.*, 2023).

For South-South mangrove and South-Eastern rainforest areas, I suggest conducting a study that will involve using unsupervised learning algorithms such as K-Means and PCA to classify the soil type. In relation to the oil palm plantations, clustering algorithms can be used to analyze the data collected from the soil acidity, moisture, and NDVI sensors and create an informed strategy of differential fertilizer application to counter the threat of overly acidified soils in the South. There is evidence of similar research conducted in Nigeria; the work done by Aliyu et al. (2020) used PCA and K-Means clustering to define zones of variation in properties of the soil in maize production belt of Nigeria. However, the article mentioned above used Inception-V3 and Random Forests supervised learning models trained on image data, not sensor data, and the body of the research does not mention either oil palm, clustering, or Nigeria. Hence, I am suggesting extrapolation at the conceptual level, and therefore, while not impossible, such a study would be an interesting endeavor for the further exploration of the topic.

Finally, Reinforcement Learning could be a viable avenue for autonomous weeding and irrigation in intercropped cassava and yam fields. Indeed, the complexity of such fields presents a significant computer vision challenge due to obstructed views and occluded targets. This challenge could be addressed by training an RL agent to navigate the intercropped field and determine the optimal weeding path (Benos *et al.*, 2021). Regarding irrigation, although research on maize used Q-learning to find the best time to open and close the sluice gates (Alkaff *et al.*, 2025), the same approach could be tested in southern Nigeria rice cultivation. Indeed, that region is highly dependent on rain-fed agriculture, making the ability to time irrigation to crop needs even more valuable. However, a key caveat is that none of the aforementioned Reinforcement Learning applications has been tested in the context of Nigerian agriculture.

3.3 Evidence Status of Crop-Algorithm Pairings

Based on the evidence described in Table 1, the current status of each pairing can be categorized as either "Validated locally" (the combination was tested on either Southern or Nigerian crops), "Validated elsewhere" (the pairing was tested on the indicated crop/task but outside of Nigeria/South), and "Theoretical extrapolation" (the combination was not tested on the specified pairing but is theoretically plausible). Outside of rice yield prediction, UAV-based yam biomass estimation, and prototype post-harvest sorting systems, none of the combinations have been validated in the Nigerian context. Given the evidence, it is logical to rely first on the pairings validated in Nigeria (rice yield prediction and yam biomass estimation), noting that the yam work was conducted at a research station. Treat all other

combinations as research opportunities, with the greatest need for local validation for the two pairings based on theoretical extrapolation (oil palm soil zoning and rice reinforcement learning).

Table 1. Crop-algorithm pairing summary

Crop	AI Paradigm / Task	Evidence Status	Basis
Cassava	Supervised CV (CNN/SVM) for CMD and foliar disease detection	Validated elsewhere. 90-98% accuracy from a non-Nigerian benchmark dataset; Nigerian UAV work validates detection/counting only.	Ramcharan *et al.*, 2017; Nnadozie *et al.*, 2023
Cassava	YOLO foundation models and K-means clustering for post-harvest physiological deterioration (PPD) detection and quantification	Validated elsewhere. Non-Nigerian benchmark dataset; not tested under Nigerian post-harvest conditions.	Ayalde *et al.*, 2024
Rice	Random Forest / Gradient Boosting for yield forecasting	Validated locally. Tested with Cross River and other Nigerian rice-region data.	Ingio *et al.*, 2024; Abdurrahman & Muhammad, 2025
Rice	Reinforcement Learning (Q-learning/DQN) for irrigation and harvester navigation	Theoretical extrapolation. Cited RL study addresses maize irrigation, not rice, and not in Nigeria.	Alkaff *et al.*, 2025; Benos *et al.*, 2021
Oil palm	Unsupervised learning (K-means, PCA) for soil/nutrient zoning	Theoretical extrapolation. K-means/PCA validated for soil nutrient zoning in Nigerian maize belt, not oil palm.	Aliyu et al, 2020
Yam	UAV imagery for biomass prediction and shoot growth characterization of single-staked yam plants	Validated locally (research station). UAV RGB imagery with support vector regression gave $R^2 = 0.79$ for shoot biomass of white Guinea yam at IITA, Ibadan; not tested on farmers' fields and does not predict tuber yield or maturity.	Iseki *et al.*, 2026
Tomato / fruit	CNN and SVM image classification for sorting, grading, and ripeness detection	Validated locally (prototype stage). Nigerian-developed systems; no field validation or commercialization reported.	Ogukah, 2025; Mommoh et al., 2024; Oyefeso et al., 2025

3.4 Machine Vision Applications in Post-Harvest Quality Control and Logistics

Local production evidences for post-harvest technologies are more than the production-phase technologies described previously, although most are at the prototype level. Food waste takes place at all stages of the supply chain: roughly 35% on the farm, 30% in post-harvest processes, and 20% during transportation (Olawale et al., 2025). According to the authors, a pilot program for ML-based cold storage regulation reduced post-harvest losses of perishable goods by 60%. ML-enabled transportation also reduced food waste during transit by 20%. The authors demonstrated that the proposed solution was effective; however, it is unclear whether it would apply in southern Nigeria. Adejumo et al. (2025) report a 35 percent increase in the starch yield and a 28 percent increase in net returns due to the application of automated technologies as opposed to the manual ones. The numbers refer to the overall mechanization of production process and do not specifically refer to the application of machine vision technologies, thus emphasizing the economic rather than optical performance benefits. Even so, only 18% of the 570 processors surveyed had adopted automated technologies, and maintenance and variable costs were among the key factors driving adoption. These are

mechanically processed systems rather than machine vision systems, so they provide information about adoption economics but not vision performance. Therefore, they are not machine vision systems but rather mechanically processed systems.

Meanwhile, local academic research offers more promising prototype evidence for using machine vision in agriculture. Ogukah (2025) developed a convolutional neural network (CNN) that enables real-time sorting of tomatoes by colour using a Raspberry Pi computer; cooperatives could test a similar approach for sorting vegetable crops. Several other more recent studies have also used convolutional neural networks to assess fruit ripeness and identify defects (Mommoh et al., 2024). Oyefeso et al. (2025), on the other hand, analyze the use of regular image processing plus the use of support vector machines in assessing fruit shape, which might need fewer resources and thus be more practical for local adoption, though this has yet to be proven. In the same manner, none of the researchers mentioned have managed to bring their findings into the marketplace or implement the proposed solutions in a large scale.

Based on the information provided by Haruna et al. (2023) and Anozie & Owoeye (2025), it can be suggested that food losses and waste in Nigeria comprise 30-50% of all perishables, which makes the use of machine vision at the post-harvest level very promising for adoption in the country; however, its cost-effectiveness is not yet evident. Thus, based on the data presented, machine vision technologies at the post-harvest stage should be prioritized (see Table 1).

When transitioning to Agriculture 4.0 in Southern Nigeria, attention should be paid to adapting the AI-based methods described in Table 1 to specific crops and the realities of local farmers. Supervised CNNs, including the MobileNet architecture, are a candidate approach for cassava. Implemented on a compact computer such as a Raspberry Pi, this technology could be tested on drones to monitor cassava crop health and optimize pesticide use; reducing pesticide use is especially relevant for farmers in wetter areas (Nnadozie *et al.*, 2023). Nevertheless, the study cited above shows only that drones can count cassava plants (Nnadozie et al., 2023); using such technology to control disease remains hypothetical (Table 1). Meanwhile, rice production systems in Ebonyi State are inefficient in water use and harvesting because of unpredictable rainfall patterns. According to Benos *et al.* (2021) and Alkaff *et al.* (2025), reinforcement learning methods such as Deep Q-Networks have been proposed for irrigation scheduling, and a maize study applied Q-learning to it so that it could be tested for rice water management in southern Nigeria; no such test has been reported (Table 1).

3.5 Barriers to AI and Machine Vision-Driven Precision Agriculture Adoption in Southern Nigeria

The shift from traditional mechanization to AI-enabled precision farming entails various challenges, ranging from infrastructural to socio-economic ones (Figure 4). Southern Nigeria lacks reliable electricity and internet coverage; hence, the area cannot embrace big data and cloud computing. Although Adeyemi et al. (2024) report these issues occurring in Gwagwalada Area Council, Abuja (North Central Nigeria), similar problems can also resonate in the south. However, the sources do not elaborate on whether such circumstances also exist in the South. The high cost of imported equipment, fragmentation of ownership of the land by many owners, and reluctance of farmers to adopt capital- and technology-intensive methods slow down the development of precision farming in the area (Ayoola et al., 2025; Omeje et al., 2025). Local researchers also reveal a dearth of data, namely, the absence of local data about agriculture that can be used to train and validate AI models in precision farming. According to Ngugi et al. (2024), most of the publicly available data are specific to a crop, country, or region, and, therefore, unsuitable for use in another geographical location with dissimilar agricultural practices. This implies that models that have been trained on non-local data may not be applicable in local settings such as Nigeria because they were not tested on local data.

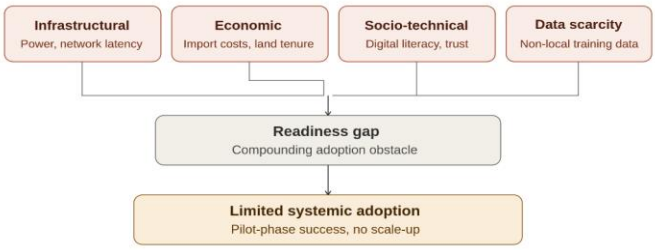

Figure 4. Barriers to AI and machine vision adoption: infrastructural (power, connectivity), economic (capital costs, land tenure), socio-technical (digital literacy, trust), and data-scarcity (non-local training data) factors compound into a readiness gap that limits systemic adoption.

3.5.1 Infrastructural and Technical Constraints

One major problem with adopting artificial intelligence for smart mechanization is the condition of the infrastructure that is currently in place. Sophisticated technology relies on dependable internet and electricity, which many parts of southern Nigeria are unable to provide. Adeyemi et al., (2024 and Ngugi et al., (2024) reported that unreliable 4G and 5G network coverage limits the extent to which autonomous machines can operate in real-time . Expanding electrical coverage to rural areas or opting for a solar option would reduce operational costs and minimize the dependence on the unreliable national grid. In Nigerian minigrid projects, for instance, agribusinesses cut energy costs by as much as 82% by swapping fossil fuel-powered equipment for electric alternatives. At the same time, the cost of minigrid electricity dropped by 25% (Energising Agriculture Programme [EAP], 2024). The availability of broadband internet in Nigeria was 50.58% as at November 2025 and increased to 51.97% in December 2025. However, it varies in different parts of the country between urban(65%) and rural(20-30%) areas and between the country's south (Lagos) and the north (Tekedia, 2025; Guardian Nigeria, 2026). Grid access reveals a similar disparity: over 80% of the urban population has access to electricity (World Bank, 2023b), whereas only about one third of the rural population does (World Bank, 2023a), and rural electrification is still an active government priority (Voice of Nigeria, 2026). With this level of availability, cloud-based autonomous machines that need to operate in real-time are unlikely to be suitable for much of rural Nigeria.

3.5.2 Economic Implications and Land Tenure Policies

Nigeria's mechanization level is 0.027 hp/ha, far below the Food and Agriculture Organisation's recommended 1.5 hp/ha (NATIP, 2022). Therefore, if Nigeria wants to adopt AI technologies for mechanization, it must reduce its capital asset base, as most AI-assisted machinery, such as drones with visual sensors or automated tractors, would be imported and thus inaccessible to small-scale farmers because of exchange rates and tariffs unless collectivization occurs.Land tenure policy is another factor that influences precision agriculture adoption by Nigerian farmers due to the fact that Nigeria has communal and customary freehold tenure policies which lead to fragmentation and great variation in farmland sizes hence mechanization is not appropriate (Iheke, 2015; Sekumade, 2017). Farmers also practice intercropping and non-sequential planting which the currently available agricultural intelligence technologies cannot handle hence they will need modification (Eze et al., 2011; Adekunle, 2013).

3.5.3 Sociotechnical Fit and Digital Literacy

A key barrier to adopting AI-assisted mechanisation is that local technicians often cannot maintain computer vision equipment, so users may have to rely on manufacturers for repairs, which is both time- and capital-intensive (Adeyemi *et al.*, 2024). Additionally, many farmers are reluctant to adopt AI-assisted technologies and prefer conventional methods that have been proven effective to technologies that conflict with established local practices. While Ayoola *et al.* (2025) document this in Abuja (North Central Nigeria), farmers in Southeast Nigeria show similar attitudes (Omeje *et al.*, 2025).

3.5.4 Gender Considerations

Excluding women smallholder farmers from mechanization creates additional problems beyond those listed in the previous section for farm mechanization in general. Studies (Takeshima, 2024; Adejumo et al., 2025) in different countries show that mechanization tends to accelerate the shift away from farming toward other work, which is higher for women than for men. Consequently, while promoting the technology, gender issues related to the application and use of mechanization need to be considered. For example, women constituted 72% of the 570 cassava processors surveyed, but only 18% of all processors had adopted fully automated processes and the maintenance and variable costs significantly influenced adoption (Adejumo et al., 2025; Takeshima, 2024). However, sex-disaggregated adoption rates for AI and machine vision technologies specifically were not established in the sources reviewed, representing a critical gap for future research and policy. For example, a North Central Nigeria study on agricultural mechanization had 670 respondents, 95% male and 5% female (Dauda *et al.*, 2012). Studies in Nigeria indicate that

women farmers are often excluded from technology demonstrations and from adopting innovations (Okoronkwo *et al.*, 2025; Ayoola *et al.*, 2025). With this knowledge, policymakers can develop gender-responsive mechanization promotion policies that recognize the different roles, needs, and opportunities of women and men and promote their equal participation in agricultural production. It is important to recognize gender differences if Nigeria has to achieve mechanization. Women face many socio-economic and structural barriers such as land ownership, access to credit and extension services.

3.5.5 Data Governance and Cybersecurity

With the rise of connected machinery and computer vision models comes the need for data governance and cybersecurity, as farmers upload and store data, including images, in the cloud. Who owns this data? What are the implications of these ownership rights? What happens to this data during a cyberattack on the servers? Nigeria enacted the Nigeria Data Protection Act in 2023, which covers personal data and is overseen by the Nigeria Data Protection Commission (Federal Republic of Nigeria, 2023). Nevertheless, the sources reviewed did not find a data governance framework specific to agriculture covering farm images, machine telemetry, and farm management data, which leaves farmers vulnerable to exploitation by large organizations and companies seeking commercial profit. It contains sensitive details regarding farmers' finances, practices, and exposure to climate-change risks, and can be used to influence credit allocation, insurance policies, and land acquisition by buyers. A model data governance policy ought to stress farmers' ownership of the data, informed consent, and the principles of data minimisation (UNCTAD/FAO, 2026). It should also stress and mandate data encryption both in rest and transit, and explicit breach notification and accountability mechanisms. The data governance policy should also permit independent audits and the publication of impact assessments by stakeholders in the agricultural sector. These considerations are part of the responsible innovation principles that is increasingly embedded in precision agriculture governance internationally, and should be institutionalized in Nigeria to build trust and guarantee long-term adoption of AI-assisted agriculture technologies.

3.5.6 Climate Change Projections and Model Limitations

A further limitation on AI-assisted mechanization is its dependence on historical climatic data to train prediction models, such as those that are used to predict pest surges, which constrains its ability to adapt mechanization models to changing trends, especially in southern states, where rainfall is more erratic. For instance, the hybrid CNN-LSTM with attention model developed to predict rainfall in the Niger Delta and Anambra States using data from 1981-2024 cannot accurately predict below-average rainfall in the wet season. It records Nash-Sutcliffe Efficiency values of −1.16 and −3.47 in July and August, respectively (Nwazelibe *et al.*, 2026). The model performs well in the dry season, predicting rainfall with more than 80% accuracy, but performs worse in the wet season, with accuracy below 21% for monthly rainfall amounts during the same period. A key risk is that operators may use mechanised equipment, such as irrigation systems, inappropriately, and erroneous yield estimates may affect harvest planning and food security.

3.6 Frameworks for Contextualising AI-Assisted Mechanisation in Southern Nigeria

This review identifies frameworks for contextualizing AI-assisted mechanization in Southern Nigeria that do not represent existing frameworks. As such, the following are proposed:

3.6.1 Edge–Cloud Collaborative Intelligence

Given the unreliable electricity supply and limited broadband penetration in rural Nigeria, it is recommended that AI-assisted mechanization leverage Edge AI (AI processing performed locally on devices at the edge of the network, rather than in the cloud) to make critical irrigation and weed control decisions at the edge while only uploading less critical data, such as yield prediction data, to be stored on a central cloud server. The framework would let robotic weeders and harvesters make real-time farm decisions without relying on a stable broadband connection, which is unavailable in most parts of Southern Nigeria. The proposal suggests the application of low-power edge-computer hardware like NVIDIA Jetson and Google Coral Edge TPUs for real-time decision-making on irrigation and weeding, as well as the monthly uploading of yield data to the cloud through cellular networks when broadband connectivity is available (Reddy et al., 2024).

3.6.2 The Smart Mechanisation Hub (SMH) Service-Delivery Model

To reduce the high cost of mechanization equipment and address fragmented readiness for mechanization, it is recommended that Smart Mechanisation Hubs (SMHs) be established to offer smart mechanization as a service to host farms across Southern Nigeria. s.In return, farmers would provide the equipment with data to optimize scheduling for other farmers and reduce idle time. While IoT-assisted mechanization has been suggested, the recommendation goes further by suggesting that AI analyze the data to optimize usage. The recommendation draws on existing mechanization-as-a-service models such as Hello Tractor (Section 3.1), whose effectiveness in southern Nigeria remains undocumented, and proposes mainstreaming them through appropriate policies. This approach aligns with UK FCDO-funded mechanization initiatives in Nigeria under the RISA-KECC project, which has supported the creation of CONESAM as a national coalition for agricultural mechanization and the co-creation of appropriate machinery, benefiting over 800 agribusinesses (RISA Fund, 2026). As such, the review recommends developing a pilot Smart Mechanization Hub (SMH) in Southern Nigeria that can rent out AI-assisted tractors, test out various models, and eventually scale up the most productive ones.

3.6.3 Localized Data Governance

Local data governance policies should guide the collection, use, and ownership of farm data generated by various AI-assisted mechanization equipment, prioritize farmers' ownership and control of their data, emphasize informed consent, and minimize the risks of sharing information. This approach would go a long way toward promoting ethical AI while also enabling mechanization. Many of the computer vision models reviewed here were trained on non-Nigerian data (Section 3.2). As such, local research institutions such as the Agricultural Research Council of Nigeria should develop open-source image sets for local crops such as cassava, yam, oil palm, and others to support the development of image recognition devices such as TinyML (Ngugi *et al.*, 2024). It is also recommended that extension agents be rebranded as Digital Intermediaries and trained to use various AI-assisted mobile apps to help farmers understand the technology (Okafor & Akanwa, 2025; Ayoola *et al.*, 2025).

3.6.4 Cost Feasibility of Various Edge Machine Vision Hardware

Various works recommend using edge computers such as NVIDIA Jetson and Google Coral Edge TPUs to develop machine vision equipment. However, this review highlights the costs of adopting Edge computers and other vision-based sensors, such as cameras and depth sensors, to provide a realistic perspective on these technologies. Based on the given review, the Coral Dev Board is priced at approximately $150, and the Coral USB Accelerator costs about $60 (Coral, n.d.). On the other hand, the currently recommended edge AI platform, the NVIDIA Jetson Orin Nano Super, has a cost of $249 (NVIDIA, n.d.).

The review also notes maintenance costs and the technical expertise required to maintain the equipment, which is not available in the local Nigerian context to program microcomputers, Linux systems, and optimize AI models. Recurrent costs such as repairs and maintenance are difficult to estimate without primary data; this gap remains and should be addressed through the primary data collection recommendation. As such, the review recommends exploring more affordable alternatives, such as ARM Cortex-M4 microcontroller cores that power TinyML, which draw far less power than GPU- or TPU-based boards and may be better suited to off-grid deployment in the South.

3.6.5 Recommended Primary Data Collection Protocol

Most of the review's findings came from secondary data, including extrapolating Northern Nigerian findings to infer the whole country (see Table 1), commercial equipment cost data, and projected costs. Therefore, primary data collection is needed, including surveys assessing farmers' perceptions of mechanization, its costs, and barriers to adoption; exploring gender differences; and collecting actual costing data to verify some of the review's assumptions. As such, it is recommended that primary data be gathered using the following protocols: (1) surveys on farmers' perceptions of mechanization, its costs, and challenges, including gender differences; (2) key informant interviews to understand the problems and opportunities better; (3) costing data to verify some of the projected costs of mechanization equipment; and (4) data collection on the effectiveness of various visual-based AI models in the Southern Nigerian context to verify the "data desert hypothesis" that Ngugi *et al.* (2024) report. Much of the literature on computer vision in agricultural mechanization uses non-local data to train algorithms. For instance, Ramcharan *et*

al. (2017) developed convolutional neural networks (CNNs) for cassava disease and pest detection using non-Nigerian field images.

CONCLUSION AND RECOMMENDATION

4.1 Conclusion

In Southern Nigeria, the adoption of AI and machine vision for mechanized farming appears led by private organizations, with little enthusiasm from public authorities. The potential value of AgTechs in the area was shown for rice production with Random Forest and Gradient Boosting algorithms already in use in Cross River and other states growing this culture, and for yam biomass estimation with UAVs tested in a research farm in Ibadan, and computer vision prototypes developed at universities for post-harvest processing. The potential of vision-based disease detection in cassava, soil area segmentation for oil palm cultivation, and reinforcement learning for irrigation have only been demonstrated on foreign data and are not available yet to Nigerian farmers.

The main barriers to the adoption of AI-driven mechanized farming by local farmers are poor digital infrastructure, such as the lack of broadband access, the high cost of mechanization equipment, the complexity of land ownership relations, low literacy rates, risk perception, and the absence of training data for local crops. Another potential barrier to wider adoption is gender, as women dominate in certain areas, such as cassava processing, and may be more vulnerable to such risks as the complexity of adoption and have less access to mechanization resources. At the same time, women may be more exposed to other factors, such as the opportunity cost of mechanization and the lack of mechanization training.

AI models currently available in Nigeria and promoted for use in farming have been trained on climate data that is becoming unreliable due to changes in rainfall patterns. For mechanized farming, the adaptation of AI models is therefore decreasing in value for farmers as an informational advantage over local competitors who do not use such models. Thus, if irrigation is used as a tool to regulate the timing of mechanized field work, rainfall data will need to be explicitly included in the algorithm in order to build a competitive advantage. Nigeria's data protection regulation practices, like the Nigeria Data Protection Act 2023, do not contain specific provisions for data processing from connected devices and computer vision scanning images of agriculture. Nigerian legislators should resolve this issue, for the country is nearing a pilot phase's end and the beginning of real-world implementation of AI-assisted mechanized farming.

4.2 Recommendations

1. The following recommendations are phased based on the urgency of addressing the identified barriers and the time required for institutional and infrastructural development.

2. In the short term (within 2 years), the Ministry of Agriculture and NCAM should prioritize the developments already undertaken for inclusion in the NATIP and budget accordingly for shared infrastructure. Cooperatives can build Smart Mechanization Hubs (SMHs) with increased capabilities (Cortex-M4/TinyML→Jetson→Coral) in stages and conduct a cost-benefit analysis based on vendors' suggested prices (rather than entry-level equipment).

3. In the medium term (2–5 years), ARCN and the universities should prioritize generating reference data for computer vision-based cassava disease detection, oil palm soil zoning, and reinforcement learning for irrigation (Table 1). Regulatory sandboxes must be created so that data privacy legislation for agricultural data (and the personal information contained therein) can be developed, including standard data-sharing practices and breach notification, before data-sharing platforms take off. Agricultural extension agents should be reskilled as digital literacy facilitators, with a mandate to adopt AI-assisted advisory services alongside their traditional advisory functions. Where possible, prioritize digital literacy as a supplement to traditional farm advisory services.

4. It is recommended that equity considerations be addressed by prioritizing gender-disaggregated data collection and financial inclusion strategies at all stages, as factors beyond infrastructure and price disproportionately impact female farmers, who may face lower literacy levels and lower participation in mechanization (to be verified

through the primary data collection in Section 3.6.5). This is despite women making up 72% of the cassava processors surveyed and therefore serving as critical nodes in the cassava value chain.

5. Universities should prioritize expanding their computer vision research for post-harvest processing (see the tomato and fruit grading use cases), as it appears to offer strong short-term adoption potential at relatively low equipment cost. The climate research stations should reprioritize efforts to retrain irrigation and harvest-scheduling AI models for mechanized farming to reflect changing climate patterns, rather than relying on historical data.

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Paper ID 12:

Hate Speech Detection Using Machine Learning Techniques

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ABSTRACT
Hate speech is any form of speech that causes individual or group of people to feel annoyed. It causes a lot of violent and misunderstanding among the people. It is very important to provide a system that will detect whether a speech is hate or not. This research focuses on training and evaluating machine learning algorithms for hate speech detection. The dataset used in this research was obtained from kaggle dataset repository, it contains about 31,962 real-world twitter posts. The dataset has been preprocessed using python library to convert the twitter post to lower case, remove all the punctuations and special characters, stop word removal and stemming. Count vectorizer was used for feature extraction, 80 % of the dataset was used for training the algorithms and 20% for testing. Four machine learning algorithms namely; Logistic regression, Multi-Layer Perceptron (MLP), Support Vector Machine (SVM) and Naïve Bayes were trained and evaluated. Result show that Logistic regression outperformed the other algorithms with accuracy 95.81%

KEYWORDS: Accuracy, Hate speech, Machine learning.

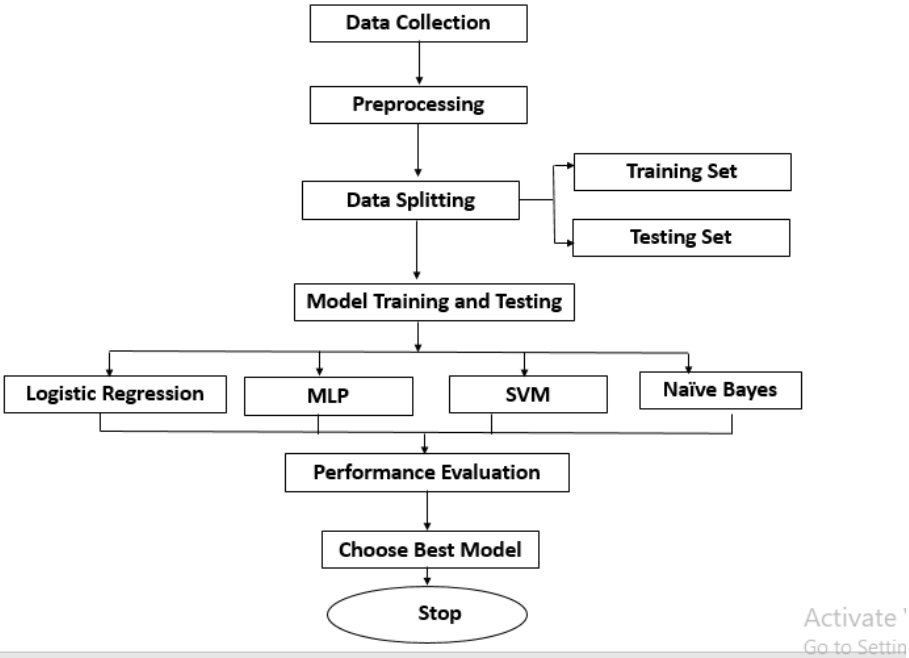
1. INTRODUCTION

Nowadays, many people communicate through social platforms like facebook, twitter, Instagram and others. Some people hurts others with hate speech. Hate speech can define as an abusive or hatred expression against individual or group of people (Alaoui et al., 2022). Hate speech is any form of speech that causes individual or group of people to feel annoyed. It causes a lot of violent and misunderstanding among the people. It is very important to provide a system that will detect whether a speech is hate or not. There is need to develop a machine learning model that can detect whether a speech is hate or not. This research focuses detecting hate speech using machine learning models with high accuracy for better hate speech detection.

(Alaoui et al., 2022) In their paper trained and evaluated Naïve bayes algorithm using two different twitter dataset (tweet_Num1 and tweet_num2), the model is able to achieved the highest accuracy of 93.06% with tweet_num2. In another research, traditional shallow learning models were compared with deep learning models using the dataset collected from kaggle repository. Deep learning models proven to be the accurate techniques with BiLSTM yield a highest accuracy of 90.2% (Toktarova et al., 2023). A research in (et al., 2021) shows that six machine learning algorithms namely; Support Vector classifier, Multinomial NB, Linear Support vector, Logistic regression, decision tree and random forest were trained and evaluated using the dataset collected from social media like facebook, twitter. Linear Support Vector Classifier outperformed other algorithms with f1-score 64%. Four deep learning models; LSTM, BiLSTM, GRU, BIGRU were trained and evaluated, result shows that BiLSTM outperformed the other deep learning models with 88.15% accuracy (Debele & Woldeyohannis, 2022). Twitter dataset was used to evaluate deep learning models, result show that pre-trained BERT achieved high accuracy of 92% (Irfan et al., 2024).

2. MATERIALS AND METHODS

Figure 1: Flowchart of the proposed methodology



2.1 Data Collection

The dataset used in this research was obtained from kaggle (online dataset repository). The dataset consists of 31,962 tweet post record. It also contains two columns namely label; which indicate whether the twitter post is hate speech or not, "1" indicate hate speech and "0" indicate non Hate speech, and the other column is tweet; which contains the post content. Tweet column is used as Independent variable (X), where Label column is used as Dependent variable (Y).

2.2 Preprocessing:

After the dataset had been collected, the next step was preprocessing, in which the raw data was prepared for feeding into a machine learning model. It is the first and most important step in developing a machine learning model; this step was necessary to convert raw data into a clean dataset. The dataset was preprocessed as explained below:

2.2.1 Punctuation and Special Characters Removal

Natural Language ToolKit (NLTK) library were used to remove all characters that are not alphabet by substituting all the characters that do not belong to A-Z or a-z with an empty string, this means all special characters and punctuations were removed.

2.2.2 Conversion to Lower Case

After removing the punctuations and special characters from the tweet posts, the post was also converted to lower case to make it easy for the machine to interpret the words; this is because the lower case and upper-case words are treated differently by the machine.

2.2.3 Stop Words Removal

Stop words are words that are meaningless and add nothing to the content; however, they occur more frequently in every text document. Stop words removal has many advantages, such as increasing the amount of memory space, since a large amount of text is removed, and it also reduces the noise from the dataset since the research considered only meaningful contents. Some of the Stop words are: about, a, an, as, are at, by, be, from, for, in, is, on, how, or, the, that, this, these, was, when, where, who, what, will, too, e. t. c (Yau & Husain, 2026)

2.2.4 Stemming

Stemming is a technique of reducing the word to its root stem, e.g., washing, washed, all are reduced to wash. Generally, what stemming does is remove the suffix and prefix from words like “ing”, “es”, “s”, etc. In this research, we used the NLTK library called Porter Stemmer to stem the words of the news text.

2.3 Feature Extraction

After preprocessing, the next step is feature extraction. The performance of machine learning classifiers greatly depends on the feature extraction technique (Yau & Husain, 2026). Hate speech detection falls under the domain of Natural Language processing (NLP, which is the branch of artificial intelligence that analyses processes and efficiently retrieves text data). Therefore, the dataset is in the form of text, and before feeding text data into a machine learning model, it must be converted into numeric values. Count Vectorizer (CV) was used as feature method which transform text data into numerical vectors so that machine learning models can understand.

2.4 Train Test Split

The dataset was split into 80:20 ratios, that is, 80% for training and 20% for testing. This is because of the size of the dataset, which is large enough (31,962 twitter post), and if the dataset is large, an 80:20 ratio is more preferable

2.5 Performance Evaluation

The performance of the classifiers in this work was evaluated using Accuracy.

Accuracy: it is the evaluation metric calculated by dividing the number of correct predictions by the total number of predictions. The formula is given by:

$$Acccuracy = \frac{(TP + TN)}{(TP + TN + FP + FN)}$$

3. RESULTS AND DISCUSSION

The result obtained from the research was presented in Table 1 below:

Table 1: Performance Metrics for Machine Learning Algorithms

Model	Logistic Regression	MLP	SVM	Naïve Bayes
Accuracy (%)	**95.81**	**95.23**	**95.17**	**94.12**

3.1 Result Evaluation

Logistic regression appeared to be the best performing classifier with Accuracy of 95.81%. It is well known that Logistic Regression has the capability of solving binary classification problems and so produced such wonderful

results. MLP happens to be the second best algorithms with Accuracy of 95.23%; this was due to the ability of MLP to model non-linearly separable dataset and have the ability to also learn quickly. SVM achieved the accuracy of 95.17%; for the simple reason that SVM performs well with even unstructured and semi structured data such as text, images and trees. Naïve Bayes appeared to have low performance of 94.12% accuracy.

4. CONCLUSION

The research focuses on hate speech detection using Machine Learning algorithms where; four algorithms were trained and evaluated and result shows that Logistic regression outperformed the other three algorithms with 95.81% accuracy. In this research, twitter post was used to train and evaluate the models. For future work, it is recommended that the proposed machine learning model should be train on more than one dataset to evaluate its performance.

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Paper ID 13:

Smart AI Invoice Generator: An AI-Driven Web-Based System for Invoice Automation and Business Record Management in Small Enterprises

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ABSTRACT
This project presents the design and development of a Smart AI Invoice Generator aimed at improving invoice generation and business record management for small and local businesses. Many small businesses still rely on manual invoicing methods, which are often associated with calculation errors, poor record keeping, delays in invoice preparation, and difficulties in managing customer and sales information. To address these challenges, this study developed a web-based invoice management system that integrates Artificial Intelligence through the Google Gemini API to automate invoice generation from natural language prompts. The system also provides features such as user authentication, customer management, product management, invoice creation and management, dashboard analytics, sales tracking, PDF invoice generation, and business profile management. The Waterfall Software Development Life Cycle (SDLC) model was adopted to guide the development process, while modern web technologies including React.js, Node.js, Express.js, MongoDB, and Tailwind CSS were used for implementation. The developed system was tested to ensure functionality, usability, and reliability, and the results showed that it generates invoices accurately, improves record management, reduces manual effort, and enhances operational efficiency. The study concludes that the Smart AI Invoice Generator provides an effective, user-friendly, and affordable solution for small businesses and recommends future enhancements such as customer account registration, integrated messaging and PDF invoice sharing, and graphical business analytics using bar charts and pie charts for improved decision making.

KEYWORDS: Artificial Intelligence, Invoice Automation, Small Business, Web Application, Google Gemini API, Business Record Management.

1 INTRODUCTION

According to (Williams, 2017), the internet, without doubt, has played an important role in digitalizing business processes across companies and organizations of all sizes (Williams, 2017). It has introduced multiple new channels through which businesses can interact with their customers. A report by (Ield, 2024), an Information Technology (IT) research institution, reveals that 70% of all customer interactions will move towards digital, more interactive settings and would be experienced on demand through mediums such as web, mobile and social media platforms (Williams, 2017). The generation of today understands technology more than ever and require services delivered as quickly as possible, whenever and wherever they desire.

Nowadays, invoices, which are one of the most important documents exchanged between business partners, should be produced with the intention of disseminating them to a broader range of devices through multiple channels which include web and SMS. Handling invoices, product inventory, customer relations and other business transactions via the internet have been found to be a cost-effective way of accomplishing such tasks. Industry experts predict that communication via internet invoices will enable issuers influence customer behaviour in a positive way (Williams, 2017). According to (Li et al., 2023), in today's rapidly evolving business landscape, organizations are increasingly turning to artificial intelligence (AI) to streamline their financial operations (Arslan, 2022). According to (Ield, 2024) Market Guide for Account Payable Invoice Automation (APIA), the market has experienced unprecedented growth, with 32% of enterprises now processing more than 100,000 invoices annually (Arslan, 2022). This surge in volume has driven organizations to seek intelligent automation solutions that can handle complex invoice processing requirements while maintaining accuracy and compliance (Samborska-goik et al., 2026).

The increasing adoption of internet technologies and digital business platforms has significantly contributed to the growth of digital invoicing systems. According to (Xiong, 2024), digital invoicing systems have become essential tools for modern businesses because they support automation, reduce paperwork, and improve transaction transparency (Rajani et al., 2025). The researchers explained that organizations adopting digital invoice systems experience faster invoice processing, improved customer satisfaction, and better financial management (Mugo et al., 2017). Furthermore, recent technological advancements such as cloud computing, mobile applications, and artificial intelligence have accelerated the development and implementation of digital invoice systems across various industries. Research conducted by (Kumar et al., 2023) revealed that digital invoice systems enhance operational efficiency by enabling real-time invoice tracking, secure data storage, and easy retrieval of financial records (Dragomirescu et al., 2025).

The study also noted that digital invoicing contributes to environmental sustainability by reducing the use of paper documents in business operations (Yarlagadda, 2025). Despite these advances, manual invoicing remains prevalent. According to (Devadarshini et al., 2025), in contemporary business environments, invoice processing remains one of the most important financial operations within organizations (Gajera, 2026). Businesses generate and process large numbers of invoices daily in different formats and layouts as part of their routine transactions. Despite the rapid advancement of digital technologies, many organizations still depend on manual invoice processing methods, which require significant human effort and time (Gajera, 2026). Such methods are often associated with operational inefficiencies, increased labor costs, delays in processing, and a higher likelihood of errors during data entry. Studies have shown that manual invoice processing is considerably more expensive than automated alternatives, making it difficult for organizations to achieve optimal efficiency and productivity. As a result, businesses are increasingly adopting digital invoice management systems to automate invoice processing, improve accuracy, reduce operational costs, and enhance overall financial management (Deshpande, 2024).

In Nigeria, the growth of digital technologies and electronic business operations accelerated significantly after the COVID-19 pandemic, as many businesses sought automated solutions to support remote transactions and improve operational efficiency. According to (Gajera, 2026), businesses are increasingly depending on electronic transactions, digital payment systems, and automated invoicing solutions as part of the growing digital economy (Santos, 2024). Furthermore, Nigerian small and medium enterprises (SMEs) have increasingly adopted digital technologies to remain competitive and improve business performance. (Kshirsagar et al., 2025) stated that the use of information technology among SMEs in Abuja has contributed significantly to operational efficiency, competitive advantage, and improved business management (Adefarati et al., 2026).

Despite the rapid advancement in digital technologies and the increasing adoption of computerized financial systems, many local businesses in Nigeria still rely heavily on traditional manual invoicing methods for managing business transactions and customer records. These manual invoicing methods often involve the use of paper documents, notebooks, and basic record-keeping techniques, which are associated with several operational challenges such as calculation errors, duplication of records, delays in invoice processing, poor financial tracking, and difficulties in retrieving stored information (Abdullah & Gassar, 2025). Studies have shown that traditional invoice processing consumes significant time and financial resources within organizations. Manual invoice handling also increases the risk of human error, poor workflow management, and loss of important business records. As business transactions continue to increase in volume and complexity, local businesses face difficulties in managing invoices efficiently using traditional approaches. Furthermore, many local businesses and small-scale enterprises in Nigeria have not fully adopted effective invoice management systems due to limited access to technology, lack of awareness, poor technical knowledge, and financial constraints. In addition, poor invoice management practices can negatively affect customer satisfaction, financial account ability, and business productivity. Delays in invoice generation, inaccurate transaction records, and inefficient management of customer information may reduce the effectiveness of business operations and decision-making processes. Therefore, there is a need for the development of an efficient Invoice Management System that will help local business owners automate invoice processing, improve record management, reduce operational errors, enhance transaction efficiency, and support better business operations.

This study is significant because it focuses on improving how local businesses manage their invoices and business transactions through the use of technology. The development of an AI Invoice Generator will help local businesses

generate invoices quickly and accurately, thereby improving the speed and efficiency of business operations. The system will also enable business owners to properly record and track customer information, product details, and sales transactions in an organized manner. Furthermore, the study will help reduce the challenges associated with manual invoice processing such as calculation errors, duplication of records, and poor record management. By automating these processes, local businesses will be able to save time, reduce operational costs, and improve overall productivity. In addition, this study will serve as a useful reference for students, researchers, and developers who are interested in developing similar systems for business management.

2. RELATED WORKS

According to (Freitas, 2025; Saravanan & Narmatha, 2026), an invoice is a commercial document that includes an itemized list of goods or services furnished by a seller to a buyer relating to a sale transaction, that usually specifies the price and terms of sale, quantities, and agreed-upon prices (Reuters, 2019; Williams, 2017). Invoice processing is a business function that involves managing incoming invoices from initial receipt through to payment. It is carried out by the accounts payable department and is a critical component of the procure-to-pay process as the final step of any procurement activity. Traditionally, each of these steps would be carried out manually by a member of the accounts payable team, but accounts payable automation software is increasingly being used to create efficiencies (Pandey & Singh, 2025). According to (Li et al., 2023), invoice management has been significantly improved in terms of speed, accuracy, and efficiency with the advent of AI technology (Samborska-goik et al., 2026). An AI invoice processing system is a technology driven system that utilizes Artificial Intelligence (AI), Machine Learning (ML), and Optical Character Recognition (OCR) to automatically capture, extract, validate, and process invoice data while minimizing manual intervention and improving operational efficiency (Mugo et al., 2017; Xiong, 2024).

Several researchers have studied techniques for processing and extracting information from invoice documents. (Kumar et al., 2023) proposed a new invoice parsing method based on a two-phase optimization structure that eliminates the need for predefined invoice classes (Studies, 2025). In the first phase, individual invoice components are detected using machine learning techniques such as Support Vector Machine (SVM), Maximum Entropy, and Histogram of Oriented Gradients (HOG) to generate possible candidates. In the second phase, the system divides the invoice into several parts and organizes them to reconstruct the full structure. While the method performed well, it focuses on invoice parsing using machine learning techniques and does not address the development of a simple generation system for small businesses. (Dragomirescu et al., 2025) developed a cognitive application aimed at transforming invoice processing in the Procure-to-Pay (P2P) process using cognitive technologies to automate data extraction (Yarlagadda, 2025). (Devadarshini et al., 2025) showed that morphological image processing techniques such as dilation, erosion, and opening operations can be applied using the OpenCV library to remove noise and skewness from invoice images before performing OCR, which improves the accuracy of text recognition (Santos, 2024). (Kshirsagar et al., 2025) proposed structured invoice recognition method based on deep learning techniques using artificial intelligence models to identify invoice fields and extract structured information (Freitas, 2025). (Reuters, 2019) highlighted that automation reduces errors commonly associated with manual invoicing processes and enhances the accuracy and quality of financial documents. (Saravanan & Narmatha, 2026) examined the role of electronic invoicing in improving financial transparency and accountability, finding that e-invoicing systems provide detailed electronic records of transactions and document every stage of the invoicing process, creating a reliable audit trail. (Samborska-goik et al., 2026) examined the impact of digital invoicing systems on financial transparency and accessibility of financial information, finding that digital invoices provide authorized stakeholders with immediate access to financial data.

3. METHODOLOGY

The development of the Smart AI Invoice Generator followed the Waterfall Software Development Life Cycle (SDLC) model, which operates in a systematic, sequential manner across six phases:

1. Requirements Analysis: Observation and informal interviews were conducted with small business owners in selected business locations within Kano and Jigawa States to identify operational challenges and determine requirements (e.g., user authentication, AI-powered generation, sales tracking, secure storage).
2. System Design: Creating the overall architecture, frontend user interface wireframes, database schemas, and visual UML models.

3. System Implementation: Writing actual program code using modern web development technologies including React.js, Node.js, Express.js, MongoDB, and Tailwind CSS.
4. System Testing: Running functional, integration, usability, and security tests to identify and resolve defects.
5. System Deployment: Configuring database connections, environments, and integrating the Google Gemini API.
6. System Maintenance: Bug tracking, updating security features, and maintaining library dependencies.

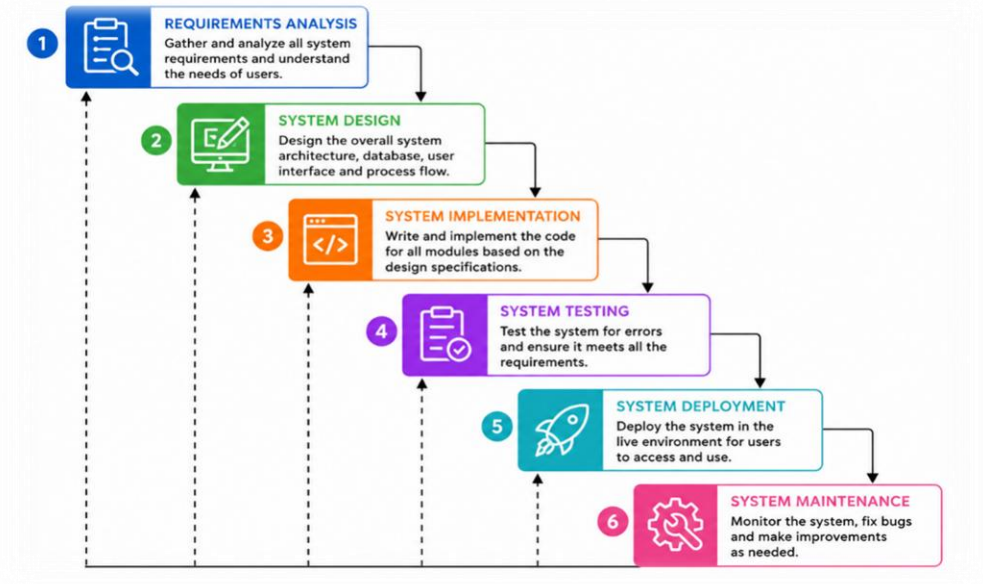

Figure 1: Waterfall Software Development Life Cycle Model used in the study.

Investigation of local pharmacies and provision stores in Kano and Jigawa States revealed that the majority of businesses still rely on manual methods (notebooks, paper slips, and receipt books) to record sales. Under this system: A customer requests products or services. The business owner manually writes details, unit prices, and quantities in paper records. The business owner performs calculation of totals manually. An invoice is prepared and issued, while a physical copy is kept. This manual process has major flaws: high risk of arithmetic calculation errors, significant time consumption, loss or damage to physical files, poor customer management, lack of security, and the complete absence of centralized storage, real-time tracking, or business analytics.

The proposed Smart AI Invoice Generator is designed as a web-based full-stack application. It provides a centralized database repository for secure business record-keeping, eliminating the risk of lost or damaged paper documents. The core innovation is the integration of the Google Gemini API, which allows business owners to type a plain natural language sentence and instantly generate a fully structured, multi-item invoice.

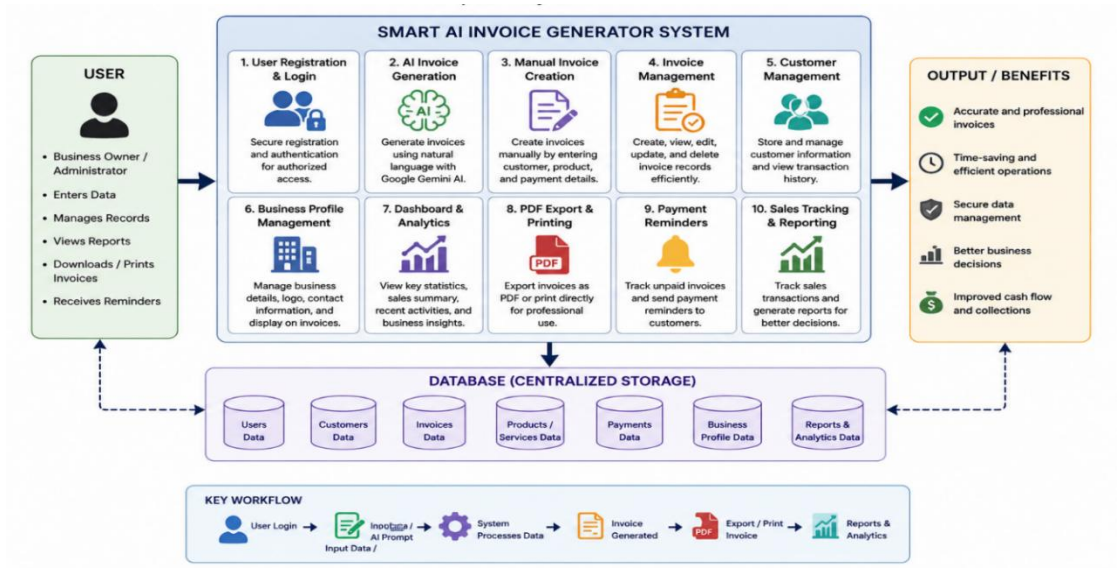

Figure 2: Web-Based Multi-Layer System Architecture Diagram.

The major modules of the proposed system are:

1. User Registration and Authentication: Securing accounts using credentials, utilizing JWT and bcryptjs.
2. AI-Powered Invoice Generation: Automated natural language parsing into structured invoices.
3. Manual Invoice Creation: A form-based backup input for traditional manual entries.
4. Invoice Management: Complete CRUD operations on generated invoices.
5. Customer Information Management: Storing details, transaction history, and communication logs.
6. Business Profile Management: Customizing business logo, address, and name for PDF branding.
7. Dashboard and Analytics: High-level sales overview, paid/unpaid trackers, and AI-driven business insights.
8. PDF Export and Printing: Converting invoice objects into downloadable/printable PDFs.
9. Payment Reminder Management: Automatic and manual payment tracking for outstanding balances.
10. Sales Tracking and Reporting: Historical sales log to analyze operational trends.

4. SYSTEM IMPLEMENTATION, TESTING, AND RESULTS

The full-stack application utilizes the modern MERN Stack architecture:

Frontend Implementation: Developed as a Single-Page Application (SPA) using React.js (version 18+) and compiled with Vite for fast build processing. Navigation is managed without complete page reloads via React Router. Styled responsively with Tailwind CSS utility classes. API integration is handled using the Axios HTTP client. Interactive user feedback is rendered using React Hot Toast, while dates are normalized via Moment.js.

Graphical elements utilize Lucide React icons.

Backend Implementation: Implemented using Node.js runtime and Express.js framework to build modular, RESTful endpoints. Security is managed through password hashing using bcryptjs and session tokens via JSON Web Token (JWT). File uploads (such as business logos) are handled by the Multer middleware. Secure cross-domain request handling is established through CORS configuration.

Database Implementation: Implemented using MongoDB, a document-oriented NoSQL database. Object modeling, schema constraint enforcement, and query handling are implemented through Mongoose ODM. Schemas defined include: User Schema (full name, email, encrypted password), and Invoice Schema (customer references, date, item arrays with quantities/unit prices, payment status, total amount, due date).

The primary innovation of the system is the implementation of an AI-driven invoice generation engine using the Google Gemini API via the official Google Generative AI backend SDK. The pipeline functions as follows:

1. The user inputs a natural language description (e.g.,"Create an invoice for John Doe containing 5 bags of rice at NGN 25,000 each and 2 cartons of milk at NGN 12,000 each").
AI Invoice Generation Pipeline Natural Language Prompt →Backend Server →Gemini API (Structured JSON Extraction) →Backend Validation → Frontend Render

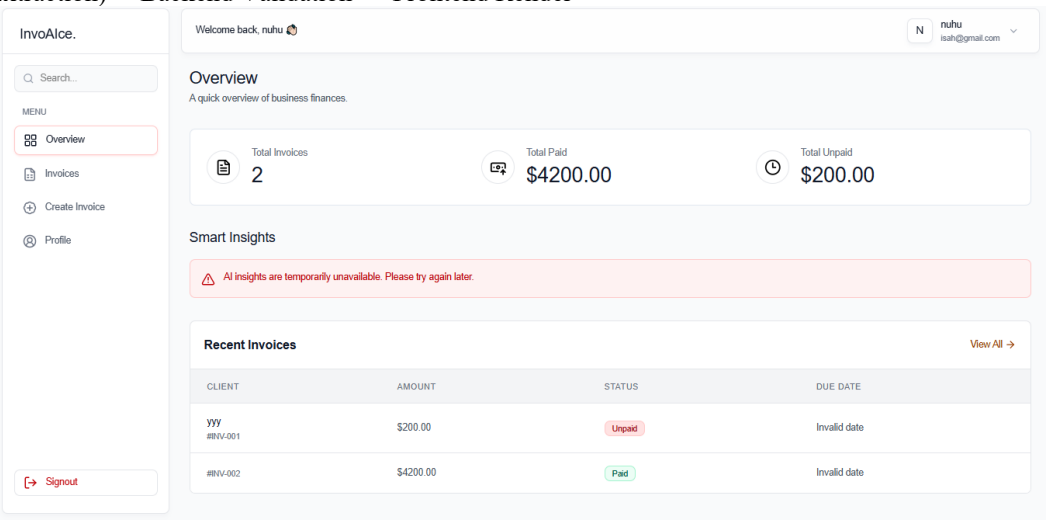

Figure 3: Dashboard.

2. The frontend sends the plain text to the backend API.
3. The backend constructs a structured prompt instructing the Google Gemini API to parse the text and return a strict, structured JSON payload.
4. The Gemini API performs Named Entity Recognition (NER) to extract customer details, product name, quantities, and unit prices, and calculates sub-totals.
5. The backend validates the JSON against schema rules to ensure data integrity.
6. The structured, calculated invoice is returned to the frontend where the user verifies and edits it before saving to MongoDB.
Robust testing was performed across multiple categories:
1. Functional Testing: Verified user on boarding, credentials hashing, dashboard tracking, CRUD operations, PDF rendering, and AI generation. All core modules operated successfully.
2. Performance Testing: Monitored database read/write speeds. Operations executed with low latency, and AI extraction successfully returned structured payloads within acceptable response times.
3. Security Testing: Attempted access to protected API endpoints without token verification. The back-end blocked unauthorized attempts, verifying JWT route protection. Password encryption was verified within MongoDB.

The explicit test scenarios and status outcomes are detailed in Table 2.
The development and evaluation of the Smart AI Invoice Generator produced positive outcomes, demonstrating the effectiveness of the system in addressing the limitations of manual invoicing. The integration of the Google Gemini API successfully minimized the manual input bottleneck. Manual calculations were entirely automated, eliminating the risk of arithmetic calculation errors. The centralized MongoDB server ensured physical files are no longer required, solving the risk of document damage or loss. The interactive dashboard provided instant visibility into outstanding invoices and monthly revenue. Additionally, the PDF export functionality allowed small, local businesses to produce standardized, professional invoices, significantly enhancing transaction trust and business branding. Secure JWT authorization successfully restricted access to verified users, preserving data privacy.

5. CONCLUSION

This study successfully designed and developed a Smart AI Invoice Generator to address the challenges associated with manual invoice processing among small and local businesses. The existing manual system was found to be time-consuming, error-prone, and inefficient in managing customer records, sales transactions, and invoice generation. By

integrating Artificial Intelligence through the Google Gemini API, this web-based system enables business owners to generate professional, multi-item invoices from simple natural language prompts. Developed using the Waterfall SDLC and built with the MERN Stack (React.js, Node.js, Express.js, MongoDB) and Tailwind CSS, the system has proven to be an effective, secure, and highly reliable alternative to traditional paper-based invoicing, dramatically reducing manual data-entry effort and improving the efficiency of small business operations.

6. FUTURE RECOMMENDATIONS

To further enhance the capabilities of the Smart AI Invoice Generator, the following recommendations are proposed:
1. Implement Customer User Accounts: Provide a portal for customers to log in, view historical invoices, and track outstanding balances.
2. Integrate Invoice Sharing Features: Support automated PDF invoice delivery directly through email or instant messaging platforms (such as SMS and WhatsApp).
3. Include Data Visualization: Incorporate interactive graphical reports (bar charts and pie charts) on the dashboard to visualize sales performance and financial trends.
4. Support Online Payment Integration: Integrate secure online payment gateways (e.g., Paystack, Flutterwave) to allow electronic invoice settlement.
5. Develop a Mobile Application: Create native mobile applications for iOS and Android platforms to facilitate invoice management on-the-go.

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Biochar Effectiveness for Organic Wastewater Decontamination

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ABSTRACT

Agro-based industries are characteristically associated with the generation of large amounts of biomass residues, which pose disposal challenges and strain their profitability. Current advancements in biomass conversion technologies hold potential benefits for industries through biomass conversion into value-added products. Accordingly, there is increasing interest and attention on producing biochar from the residues for a variety of applications, most notably, the treatment of industrial effluents. To date, several lignocellulosic-based biomass residues have been considered for biochar production: date stones, olive stones, almond shells, orange seeds and pulp, groundnut shells, banana peels, and oil palm biomass. Despite their abundance, selecting biochar with a high adsorption capacity for effective treatment of agro-industrial effluents has always been challenging. Overcoming this limitation, therefore, requires knowledge of the prevailing adsorption mechanisms between the biochar surface and organic contaminants. Although the literature covers a wide variety of such investigations, this review offers further insight into the contributory effects of adsorption mechanisms and conditions on the performance of pristine biochar in treating agro-industrial wastewater. The review indicates that tailoring biochar through controlled pyrolysis and feedstock selection can enhance its structural and chemical properties, thereby improving adsorption capacity for specific organic pollutants like phenol and tannic acid. Biochar adsorption performance depends on multiple interrelated factors, including biochar properties (surface area, pore size distribution, and surface functionality), properties of the contaminant, and adsorption medium conditions such as pH and temperature.

Keywords: biochar, adsorption capacity, contaminants, adsorption mechanism

INTRODUCTION

In effluents from many agro-based industries, organic compounds are usually the predominant contaminants that contribute to wastewater turbidity and toxicity, and if discharged into the aquatic environment, they can lead to eutrophication. Because of its universal nature, simplicity, and lowest cost of treatment per unit volume of wastewater, adsorption using a variety of novel adsorbents has been considered as the best wastewater treatment method (Ali *et al*., 2012). Although biochar is among the cheapest adsorbents for treating industrial effluents, its adsorption capacity for organic contaminants is usually low, leading to a large dosage requirement for effective treatment. Therefore, selecting an effective biochar requires adequate understanding of the influential factors encouraging interactions between the adsorbent and the adsorbate.

Effective adsorptive removal of a contaminant in an aqueous phase considerably depends on the positive interactions between the properties of the adsorbent and the adsorbate (Weber & Vliet, 1981). The large surface area, volume, and distribution of nanopores, and surface functional groups of biochar determine to a greater extent its adsorption capacity and spectrum of adsorbability. Molecular size, polarizability, ionizability, and hydrophobicity are properties of organic

compounds relevant in many aspects of adsorption, including size exclusion effect, hydrophobic effect, dispersive, electrostatic, and π interactions, and H-bonding (Kah *et al*., 2017; Pignatello *et al*., 2017). Accordingly, producing biochar with tailored properties suitable for effective wastewater treatment will require knowledge of both physical and chemical properties of the targeted contaminant. Therefore, this paper reviews current studies on adsorption interaction mechanisms and performance of biochar in removing organic contaminants from aqueous solutions.

ADSORPTION MECHANISMS

To achieve effective wastewater treatment using biochar, identifying the underlying mechanism of the adsorption process will be useful for analyzing the efficacy of biochar in terms of the extent of adsorption and spectrum of adsorbability (Tan *et al*., 2015). The adsorption behaviour of biochar for different organic compounds differs and strongly depends on the properties of the biochar, organic compound, and adsorption media, such as solution pH and temperature (Weber & Vliet, 1981). Several adsorption mechanisms that are likely to encourage interactions between biochar and organic contaminants are: (i) nonspecific interactions, (ii) hydrogen bonding, (iii) chargeassisted hydrogen bonding, (iv) electron donor-acceptor interaction, (v) electrostatic interaction, (vi) ligand exchange, and (vii) covalent bonding and oxidative coupling (Kah *et al*., 2017).

Nonspecific or hydrophobic adsorption is often used to describe the combination of solvophobic effects and van der Waals forces, which is expected to operate to a certain extent for all forms of organic contaminants. Adsorption mechanism initiated by the solvophobic effect occurs due to the repulsive behaviour of water to nonpolar organic contaminants, resulting in the formation of homogeneous partitioning of hydrophobic domains and when in close contact with hydrophobic groups on biochar surface, the organic contaminants interact with the surface by van der Waals forces (Keiluweit & Kleber, 2009). The contribution of solvophobic effect to adsorption has been attributed to the existence of a significant correlation between adsorption capacity and hydrophobicity indices of contaminants such as solubility and octanol-water partitioning coefficient. The van der Waals forces with low binding energy in the range between 0.4 and 4 kJ/mole are the weakest intermolecular attractive forces due to temporary and induced dipole and quadrupole interactions (Kah *et al*., 2017). Polar organic contaminants are also influenced to a certain extent by van der Waals forces operating between the contaminants and surfaces of biochar. The extent of adsorption can be related to the molecular size and polarizability of the contaminant, and the polarity index of biochar surface (Kah *et al*., 2017; Weber Jr. and van Vliet, 1981).

Specific interactions are believed to be invoked by the presence of polar or charged groups on organic contaminants. A hydrogen bond is anticipated to contribute to the adsorption of polar organic contaminants by the polar regions on the surface of biochar (Sun *et al*., 2011). The H-bond adsorption mechanism occurs as a result of the attraction between electronegative atoms and the electropositive H nucleus. A positive correlation between the extent of adsorption and the polarity index of biochar could indicate the contribution of H bonds to the adsorption process. The binding energy of the H bond ranges between 4 and 17 kJ/mole depending on the difference in proton affinity between the H donor and H acceptor, as indicated by the difference in their pK_a (Gilli *et al*., 2009). The formation of exceptionally strong H bond that exceeds those between water molecules and various organic functional groups, known as negative charge-assisted H bonds, was proposed as a likely interaction between weak acids and acidic oxygen groups on the surface of biochar (Teixidó *et al*., 2011). This type of H bond is distinguished by the close similarity in proton affinities pK_a of the proton donor and acceptor groups. An increase in solution pH after adsorption of ionic forms of weak acids at circumneutral pH is also proposed as an indication of the contribution of charged-assisted H-bond to the adsorption process. The rise in solution pH at equilibrium suggests that water supplied the proton for a charge-assisted H bond to occur between the capable organic compounds and oxygen groups on biochar surface having similar pK_a values. Consequently, the solution pH will rise after adsorption due to increased OH concentration, as expressed in Equation 1 (Pignatello *et al*., 2017):

$$X^- + H_2O + O^- \leftrightarrow (X \cdots H \cdots O)^- + OH \qquad (1)$$

The role that aromatic components play in the adsorption of organic compounds is recognized by the existence of the so-called electron-donor acceptor (EDA) interactions, which appeared to be the most favourable under certain circumstances (Tang *et al*., 2018). The EDA adsorption mechanism is based on the attractive forces between electron-rich (donors) and electron-deficient (acceptors) components (Keiluweit & Kleber, 2009). Consequently, organic

contaminants with an aromatic entity can engage in π-EDA interactions with the biochar surface. In this case, contaminants with electron-rich aromatic π-systems acting as π-donors or electron-deficient aromatic πsystems acting as π-acceptors interact noncovalently with the biochar surface possessing complementary functionality. The biochar surface could possess different forms of surface functionalities leading to different categories of EDA interactions. The most notable EDA interactions occurring between organic contaminants and the biochar surface area are: (i) π-π EDA interaction, (ii) cation-π interaction, (iii) anion-π interaction, and (iv) Hπ interaction.

Biochar shows high potential for π-π EDA interaction with aromatic organic contaminants due to its high proportion of graphene sheets, which serve as high π-donors or acceptors. The content of graphitic carbons and surface functional groups attached to the edge of the graphene sheet greatly influence the π-donor and acceptor properties of the biochar. Biochar with a high content of polyaromatic hydrocarbons is considered a strong πdonors, whereas highly functionalized biochar, specifically π-electron withdrawing groups, is expected to be strong π-acceptors (Kah *et al*., 2017). Regions on biochar polyaromatic hydrocarbons that are π-accepting are assumed to engage in π-π EDA interaction with π-donating aromatics such as benzene, toluene, and polyaromatic hydrocarbons (Keiluweit & Kleber, 2009). Evidence of the opposite interaction is also presented, where a πaccepting heteroaromatic amine interacts with the π-donating surface of biochar (Xiao & Pignatello, 2015). Apart from the graphene sheets, the presence of minerals on the biochar matrix and surface functional groups provides for the possibility of polar or charged groups to interact with the aromatic π-system of organic contaminants.

The cation-π interaction is a noncovalent attractive force between a cation on the biochar surface and the π-donor of an aromatic contaminant. Cation-π interaction is reported to account for up to 72.6 % of the total adsorption of ciprofloxacin by pyrogenic carbonaceous materials (Zhao *et al*., 2017). Deprotonated functional groups such as carboxyl groups (COO^-) and hydroxyl groups (O^-) are assumed to serve as strong anion-donors. In this case, deprotonated functional groups on the biochar surface or organic contaminants are likely to engage into anion-π interaction with π-systems having energy strength ranging between 20 – 50 kJ/mole (Schottel *et al*., 2008). The existing line of evidence for the occurrence of anion-π interactions was revealed by a strong adsorptive interaction between hydroxyl-substituted aromatics and graphite, mainly due to the electron-donating effect of hydroxyl groups and the π-accepting effect of graphene surface (W. Chen *et al*., 2008). Polarized X-H groups of amino acid and amine groups could serve as a potential electron acceptor, where the interaction between a π-donor entity and H result to week H bond with energy between 6 and 17 kJ/mole (Keiluweit & Kleber, 2009).

Charged entities on the biochar surface and organic compounds can interact electrostatically by ion exchange or ion bridging. Electrostatic attraction is considered the dominant mechanism for adsorbing ionizable organic contaminants on the biochar surface (Tan *et al*., 2015). The surface of biochar contains functional groups with charges that depend on its pH. In most cases, the surface is positively charged at solution pH < biochar pH_{PZC}, which gradually changes to the negatively charged surface at solution pH > pH_{PZC} of biochar. Electrostatic attraction involving interaction between an anion and the positively charged surface of biochar is referred to as anion exchange. At solution pH > pK_a, most ionizable organic acids are negatively charged; as such, anion exchange can play a role when in close contact with positive sites on the biochar surface (favourably when solution pH < biochar pH_{PZC}) (Kah *et al*., 2017). Anion exchange is only relevant in adsorption processes involving organic contaminants that are permanent anions or ionizable at low pK_a values and biochar with high pH_{PZC}, as illustrated for adsorption of benzoic acid, salicylic acid, nicotinic acid, and 4-aminobenzoic acid on activated carbon (Ayrancı́ & Duman, 2006).

Cation exchange is another form of electrostatic interaction involving the attraction of cationic organic contaminants to negative surface of biochar. At solution pH > pH_{PZC}, biochar surface carries negatively charged functional groups mostly provided by dissociated carboxyl (COO^-) and hydroxyl groups (OH^-), which can engage in cation exchange with positively charged organic contaminants. Consequently, this adsorption mechanism is relevant for organic contaminants with pK_a > pH_{PZC} of biochar. In addition, the contribution of cation exchange to adsorption can be inferred from the variation of adsorption as a function of medium pH and ionic strength, as demonstrated by the adsorption of methylene blue onto biochar (Inyang *et al*., 2014).
The contribution of ligand exchange, Lewis acid-base reaction, covalent bond, and oxidative coupling to the extent of biochar performance in terms of the removal of organic acid is difficult to estimate and considered negligible. For instance, there is no evidence supporting the occurrence of the ligand exchange mechanism, while the covalent bond is generally not considered as an adsorption mechanism (Kah *et al*., 2017). Lewis acid-base interaction appeared to be

part of the adsorption mechanism for organic contaminants with -NH_2 groups. The mechanism is useful for explaining the adsorption of several basic organic compounds on acid functional groups of biochar.

ADSORPTION MODELS

Adsorption equilibrium has been approached from different concepts (i.e., kinetic consideration, thermodynamic principles, potential theory), and the corresponding theories proposed have been used to develop isotherm equations that are used for experimental data representation (Tien, 1994). The equilibrium isotherm equations are important for the selection of appropriate biochar and optimum process conditions, because it can serve as an analytical tool for understanding the biochar-contaminant interaction mechanisms, surface properties and affinity of biochar, and estimating adsorption capacity (Bulut *et al*., 2008). The models for adsorption at equilibrium are categorized based on single-component adsorption onto a homogeneous or heterogeneous surface. Some models assume monolayer adsorption of contaminants on the biochar surface and constant heat of adsorption, while others assume multilayer adsorption of contaminants on the biochar surface with exponentially distributed heat of adsorption (Foo & Hameed, 2009). The equations listed in Table 1 are some of the famous equilibrium isotherm equations typically employed for mechanism elucidation and capacity estimation in an aqueous system.

Being the most widely used equilibrium isotherm equation, the Langmuir model assumes the occurrence of only monolayer adsorption of contaminants on energetically identical adsorption sites and negligible lateral interactions between neighbouring adsorbed contaminants. Information about the theoretical monolayer saturation capacity and affinity of binding sites (adsorption energy) can be deduced from the relevant parameters of the Langmuir equation (Bulut *et al*., 2008). Freundlich model is the simplest isotherm equation for experimental data representation and was formulated to describe non-ideal adsorption on energetically heterogeneous surfaces as well as multilayer adsorption. Herein, adsorption depends on the contaminant's concentration, where adsorption proceeds by first occupying the energetically stronger sites until the adsorption energy decreased exponentially upon reaching equilibrium (Foo & Hameed, 2009). The linearity parameter of the Freundlich equation, $1/n$, provides insight into the surface heterogeneity and likely adsorption mechanism, whereas information related to capacity affinity is obtained from the K_F parameter (Lattao *et al*., 2014). Dubinin-Radushkevich isotherm equation was formulated based on potential theory postulating that the mechanism of adsorption in micropores is that of pore filling – condensed adsorption film – rather than layer-by-layer formation of adsorbate on the wall of the micropores (Hutson & Yang, 1997). The magnitude of adsorption energy, *E*, is used for estimating the type of adsorption mechanism. The values that lie in the range 1 to 8 kJ/mole indicate the physical adsorption mechanism. Ion-exchange mechanism is deduced from values ranging from 8 to 16 kJ/mole, and when values lie between 20 and 40 kJ/mole indicates chemisorption (Mohammed *et al*., 2018). Temkin isotherm model describes adsorption on a heterogeneous surface by assuming that adsorption on such a surface is characterized by a uniform distribution of binding energies and the heat of adsorption decreases linearly with coverage (Günay *et al*., 2007).

Redlich-Peterson isotherm expression is a three-parameter hybrid isotherm that can behave like Langmuir isotherm at low concentration, and at high concentration, it features Freundlich isotherm (Foo & Hameed, 2009). This isotherm can describe adsorption on either homogeneous or heterogeneous surfaces, as it contains a heterogeneity factor, *g*. Thus, surface approaches homogeneity as *g* approaches 1 (Haghseresht & Lu, 1998). Another three-parameter isotherm equation that combines aspects of Langmuir and Freundlich equations is the Tóth isotherm expression. It was originally developed to improve Langmuir isotherm fitting for describing adsorption on heterogeneous surfaces, satisfying adsorption at both concentration extremes, which feature a linear isotherm in the Henry's law region and a highly nonlinear isotherm in the high-concentration region (Foo & Hameed, 2009).

When two or more different adsorbed species interact, adsorption equilibrium becomes more complicated because of competition for adsorption sites. Though models establishing isotherm expressions for predicting adsorption of multiple adsorbates at equilibrium are based on adsorbed solution theories, modified isotherm expressions for single adsorbates have proven to predict adsorption of multiple adsorbates effectively (Table 1). The adsorbed solution theory is based on the assumption that the adsorbed species mixture forms an ideal solution on the surface at constant spreading pressure (Noroozi & Sorial, 2013).

Table 1: List of isotherm adsorption models

Model	Mathematical expression	References
Single component		
Langmuir	$\frac{qmaxKLCe}{1 + K_L C_e}$	(Foo & Hameed, 2010)
Freundlich	$q_e = K_F Cn$	(Foo and Hameed, 2010)
Dubinin-Radushkevich, (D-R)	$\frac{RT \ln(1+(\frac{1}{C_e})^2}{qe = qmaxe^{-2E2}}$	(Günay *et al*., 2007)
Temkin	$q_e = \frac{RT}{bTe} \ln(A_{Te}C_e)$	(Günay *et al*., 2007)
Redlich-Peterson, (R-P)	$K_{RP}C_e$	(Haghseresht and ~~Lu, 1998~~)
	$qe = 1 + (a C)^g$	
Tóth	$K_T C_e$	(Foo and Hameed, 2010)
	$qe = \frac{1}{(a_T + C_e)^{tT}}$	
Multiple components		
Extended Langmuir	$KL,$	(Noroozi and Sorial, 2013)
	$qe,1 = 1 + \sum KL,i\ Ce,i$	
JP extended Langmuir	$qmax,2KL,2Ce,2$	(~~Noroozi and Sorial, 20~~13)
	$q_e,1 = \frac{}{1 + K_L,1C_e,1 + K_L,2C_e,2}$	
Binary Freundlich	$\frac{1}{\sum Nj=1 (q\ i)}\ ni$	(LeVan *et al*., 1999)
	$Ci = \sum \frac{}{(\ n_i\ )} Nj=q\ 1\ i\ qj\ (\ )\ nj$	
Modified Freundlich	$q_e = \frac{K_F Cn}{D_o}$	(Summers and Roberts, 1988)
Ideal adsorbed solution theory	$\frac{\pi A}{RT} = q_i \ln(1 + K_i C_i)^{ref}$	(LeVan *et al*., 1999)

The combined effect of both equilibrium and rate factors determines the performance of the adsorption process. The rate factors determine the efficiency of the apparent adsorption process related to the ideal adsorption process performance (LeVan *et al*., 1999). Adsorption kinetics describe the rate of contaminant uptake by biochar, which in turn controls the time for adsorption to reach equilibrium (Tan *et al*., 2009). Rate of adsorption is a function of (i) film diffusion, where contaminants travel toward the external surface of the biochar; (ii) particle diffusion, where contaminants travel within the pores of the biochar to reach adsorption sites; (iii) adsorption of the contaminants on biochar adsorption sites (Tan *et al*., 2009). Adsorption of contaminants on the surface of biochar is very fast and is

therefore usually not considered the rate-limiting step. The adsorption rate is controlled by film diffusion, particle diffusion, or both. The rate of adsorption of a contaminant is governed by film diffusion if the resistance for the contaminant to travel from liquid to the external surface of biochar is greater than the resistance for the contaminant to travel within the biochar pore (i.e., film *diffusion* > particle diffusion) and vice versa (Tan *et al*., 2009).

Several kinetic models have been used to estimate the adsorption rate and predict the rate-limiting step. The most popular models are listed in Table 2. The pseudo-first-order rate equation is considered the earliest model regarding adsorption rate based on adsorption capacity. It has been widely used to describe the adsorption of organic contaminants in wastewater using biochar. The pseudo-second-order model postulates that the rate of adsorbate adsorption depends on the number of active sites on the adsorbent's surface, which is the rate-controlling step (Dinari *et al*., 2017). The Elovich equation is a chemisorption model that assumes the rate of contaminant adsorption decreases exponentially with increasing adsorbed amount (H. Qiu *et al*., 2009).

Table 2: List of kinetic adsorption models and thermodynamic parameters

Model	Mathematical expression	References
Pseudo first order	$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303}t$	(Y. Qiu *et al*., 2009)
Pseudo second order	$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$	(Y. Qiu *et al*., 2009)
Intraparticle diffusion	$q_t = k_{pi}t^{\frac{1}{2}} + C_i$	(Hameed *et al*., 2009)
Elovich	$q_t = \left(\frac{1}{\beta}\right)\ln(\alpha\beta) + \left(\frac{1}{\beta}\right)\ln(t)$	(Mohammed *et al*., 2018)
Thermodynamics	$\ln K_D = \frac{\Delta G^0}{RT} = \frac{\Delta S^0}{R} - \frac{\Delta H^0}{RT}$	van't Hoff (Suresh *et al*., 2011)

Thermodynamic parameters provide additional information on the adsorption mechanism. The classical thermodynamics of the adsorption process has been determined using the van't Hoff relationships among Gibbs free energy (ΔG^0), enthalpy change (ΔH^0), entropy change (ΔS^0) and equilibrium adsorption constant (K_D) given in Table 2. The values of Gibb's free energy provide information on the spontaneous nature and affinity of the adsorption process; values between –20 and 0 kJ/mole and between –400 and –80 kJ/mole indicate physisorption and chemisorption, respectively. The value of the enthalpy parameter indicates whether the adsorption process is endothermic or exothermic; lower values from 5 to 10 kJ/mol reflect the existence of physisorption, and generally higher values between 30 and 70 kJ/mole suggest the chemisorption process (Suresh *et al*., 2012). The degree of disorder of the adsorption process is given by the change in entropy (ΔS^0), where positive values correspond to an increase in the degree of freedom of the adsorbed contaminant. In contrast, negative values indicate uniformity and weaker activity of the adsorbed contaminant on the adsorbent surface (Suresh *et al*., 2012).

PERFORMANCE OF BIOCHAR

Selecting appropriate biochar for wastewater treatment requires critical evaluation of several factors to optimize the adsorption process. A review of the factors that can influence the adsorption capacity of biochar for organic contaminants is given in the following subsections.

Effect of biochar dosage

The optimum dosage of biochar is one of the most important factors to consider for an adsorption system, as it relates to the operational cost and feasibility of adsorption systems. Biochar with higher adsorption capacity requires a lower dosage for a given volume of wastewater treatment. The general trend is that the removal efficiency of biochar increases with increasing dosage due to increased available adsorption sites, and it also corresponds to increasing

adsorption capacity to a point at optimum dosage. This claim was supported by the work of (S. Fan *et al*., 2017), where they reported increasing methylene removal efficiency to 98% as the dosage of sludge-derived biochar increased from 2 g/L to the optimum dosage of 8 g/L. However, as the dosage further increased, removal efficiency remained stable while adsorption capacity began to decrease. In contrast, (W. Huang *et al*., 2018) reported a simultaneous increase and decrease of methylene blue removal efficiency and adsorption capacity, respectively, with increasing dosage of biochars prepared from sheep, rabbit, and pig manure. The reduction of adsorption capacity was attributed to excessive dosage. The excessive dosage could result in incomplete coverage of adsorption sites due to an insufficient solute concentration in the solution, and high dispersive forces emanating from the excess adsorption sites. To fully utilize the capacity of biochar and achieve efficient removal of organic contaminants, Ibrahim *et al*. (2017) employed a consecutive dosage treatment technique to remove chemical oxygen demand from palm oil mill effluent final discharge using biochar derived from oil palm mesocarp fiber. They achieved 50 % removal efficiency using optimum dosage (10 g/L) applied consecutively four times, as against 33.4 % removal efficiency using a single dosage of 40 g/L. Thus, utilizing optimum biochar dosage (i.e., dosage at maximum adsorption capacity) is a necessary first step toward achieving efficient adsorption treatment.

Effect of Biochar Properties

As mentioned earlier, both the physical and chemical properties of biochar have a profound effect on the effective adsorption treatment of organic wastewater. The physical properties with significant importance are the specific surface area, nanopore volume, and nanopore size distribution, of which specific surface area is presumably the key parameter. It was found that specific surface area correlates well with the adsorption capacity of biochar for organic contaminants. (Wang & Xing, 2007) investigated the adsorption capacity of biochars produced from the pyrolysis of chitin and cellulose at 250, 320, and 400 °C. They found that the specific surface area increased with increasing pyrolysis temperature and the maximum adsorption capacity for naphthalene and phenanthrene positively correlated with biochar specific surface area. (Chun *et al*., 2004) reached a similar conclusion of greater adsorption capacity for benzene and nitrobenzene with increasing surface area for a series of biochars derived from pyrolysis of wheat crop residue at 300 to 700 °C. Most studies have reached a similar conclusion: surface area increase provide additional sites that took an active role in the adsorption of organic contaminants by biochar (Ahmad *et al*., 2013; B. Chen *et al*., 2008; Chen and Chen, 2009; Graber *et al*., 2012; Trigo *et al*., 2016; Zhang *et al*., 2013; Zhou *et al*., 2010). However, this is not usually the case in certain circumstances, as biochar porosity tends to play a vital role in accessing adsorption sites on the surface area.

The biochar pore size distribution is known to be an important physical property that affects the adsorption capacity for organic contaminants. Since nanopore sizes are broadly distributed, organic contaminants with different sizes and conformations will be limited to specific subsets of nanopore regions due to the molecular sieving effect (Pignatello *et al*., 2017). Ding *et al*. (2008) reported no clear trend between the adsorption capacity for atrazine and the surface area of five activated carbons. They observed that the adsorption capacities of three activated carbons having different magnitudes of surface area were similar. In contrast, activated carbon with the largest surface area had moderately lower adsorption capacity compared with the three activated carbons and slightly higher adsorption capacity compared with activated biochar with the smallest surface area. They found no direct correlation between adsorption capacity and surface area and concluded that nanopores within the micropore regions contributed substantially to the adsorption of atrazine because of its small size. Li *et al*. (2017) studied the adsorption behaviour of metolachlor, atrazine, and isoproturon on six biochars with different BET surface areas and reported that the increase in adsorption capacity for each of the organic compounds deviates from the BET surface area but correlates well with the surface area within mesopores (1.7–50 nm), reflecting the molecular size exclusion effect. A similar conclusion was reached for adsorption of several organic contaminants from the aqueous phase (Li *et al*., 2015; Xiao and Pignatello, 2015a), emphasizing the importance of utilizing mesoporous biochar for effective treatment of organic wastewater containing large-sized organic contaminants.

Upon accessing the adsorption sites, the affinity with which a contaminant will be adsorbed depends mainly on the surface area functionality. The biochar molecular structure comprises the graphene sheet, oxygen functional groups, and mineral complex that contribute to the surface area functionalization. It is generally assumed that the adsorption of aromatic organic contaminants by biochar can be enhanced by increasing the fraction of polyaromatic hydrocarbons. Chen and Chen (2009) investigated the adsorption mechanisms and adsorption capacity of naphthalene

and 1-naphthol on biochars with an increasing degree of carbonization, where the highest adsorption capacity for the aromatic contaminants was obtained on biochar with the highest degree of carbonization. They attributed the enhanced adsorption capacity to π-π interaction due to the dominance of the surface coverage mechanism. In addition to the π-π interaction, there are shreds of evidence establishing the contribution of interaction between the surface graphene sheet and cation or anion moieties of organic contaminants to the adsorption capacity (Chen *et al*., 2008; Xiao & Pignatello, 2015b). The adsorption of polar organic contaminants by biochar can be enhanced by increasing the polarity of the biochar surface. The higher adsorption capacity for polar organic compounds (nitrobenzene and m-dinitrobenzene) on the biochar surface with relatively higher polarity was observed compared to nonpolar compound (naphthalene) (Chen *et al*., 2008). This could probably be due to interaction between the acid functional groups (carboxyl and phenolic groups) on the biochar surface and the basic organic compounds (Kah *et al*., 2017). In general, a positive correlation between adsorption capacity and biochar polarity index indicates the likely contribution of oxygen functional groups via several interaction mechanisms. Though their contribution to the adsorption capacity for organic compounds is minimal, the mineral compounds on biochar surface could interact with organic compounds by cation-π mechanism (Keiluweit & Kleber, 2009).

Effect of Adsorption Medium

Solution pH is one of the critical parameters for optimizing the adsorption process. The solution pH determines the nature and strength of the electrostatic charge of the biochar surface and the dissociation state of ionizable organic compounds (Tan *et al*., 2015). Because biochar carries various functional groups, the behavior of the functional groups changes with increasing solution pH. Most biochar surfaces are positively charged at lower solution pH (i.e., pH < pH_{PZC}), which changes to the negatively charged surface at high solution pH (i.e., pH> pH_{PZC}). The surface charge interacts with organic contaminants electrostatically, and it is assumed to contribute substantially to the adsorptive removal of ionizable organic contaminants. Mohammed *et al*. (2018) evaluated the effect of solution pH (2.0, 6.5, and 10.0) on the adsorption of phenol (p*K*a 9.95) by biochar prepared from the pyrolysis of pine fruit shell. Their result showed that the biochar had high phenol adsorption capacity at acidic solution pH and dropped substantially at alkaline pH due to electrostatic repulsion between the negatively charged dissociated phenol and the negatively charged biochar surface. (Ahmed & Hameed, 2018) studied the effect of solution pH (3 to 11) on salicylic acid (p*K*a 2.98) by biochar produced from barley straw. The adsorption capacity of the biochar was highest at pH 3 and dropped significantly from pH 4 despite the biochar having a positive surface up to pH 7. They assume the H bond to be the main adsorption mechanism, as salicylic acid is neutral at pH 3, and it is not repelled by the positive surface of the biochar. Conversely, the adsorption capacity of basic compounds and cationic dyes increases with increasing solution pH due to the electrostatic attraction between the positively charged organic contaminants and negative charge biochar surface at alkaline pH (Jia *et al*., 2013; Parshetti *et al*., 2014; Xu *et al*., 2011).

The effect of the adsorption medium on adsorption capacity is more than identifying optimum solution pH. The solution temperature also influences the adsorption capacity to a considerable extent. Most studies on adsorption of organic contaminants by biochar have demonstrated that adsorption capacity increased with increasing medium temperature (Ahmed and Hameed, 2018; Dawood *et al*., 2017, 2016; Mohammed *et al*., 2018; Parshetti *et al*., 2014; Sarıcı-Özdemir and Önal, 2010; Suresh *et al*., 2011; Vunain *et al*., 2018). Suresh *et al*. (2011) studied the effect of medium temperature (at 15, 30, and 45 °C) on catechol and resorcinol adsorption on granular activated biochar derived from coconut shell and determined the thermodynamic parameters. The negative values and increase in absolute values of ΔG^0 with increasing temperature suggested that the adsorption of the phenolic compounds onto the adsorbent was spontaneous and more favourable at higher temperatures. The positive values of ΔH^0 indicated that the adsorption was endothermic. Vunain *et al*. (2018) reported similar thermodynamic conditions. Though their result showed that the adsorption capacity of biochars prepared from pine fruit shell for phenol increased with increasing medium temperature, Mohammed *et al*. (2018) found that the adsorption of phenol was not favorable at higher temperatures, as suggested by the decreasing absolute values of ΔG^0. The negative values of ΔH^0 indicated that the adsorption was exothermic.

Adsorptive Removal of Phenol and Tannic Acid

Biochar from agricultural residues can be an effective adsorbent for treating phenolic-contaminated wastewater.

High biochar adsorption capacity has been reported for phenol. Adsorption capacity values of 26.5 mg/g (Mohammed *et al*., 2018), 15.8 mg/g (Komnitsas and Zaharaki, 2016), 30.1 mg/g (Shin, 2017), 62.9 mg/g (Lawal *et al*., 2021), and 105.4 mg/g (Yakout, 2017) have been recorded for phenol removal in aqueous solutions. Biochar can engage in a range of interaction mechanisms that maximize adsorption capacity. Because of their diverse surface functionalities, biochar and phenolic compounds such as phenol and tannic acid tend to engage in van der Waals forces, specific π-π interactions, hydrogen bond, and electrostatic interactions, which can improve the overall adsorption performance. Some studies suggest that not all biochars are effective in the removal of phenolic compounds (Alam *et al*., 2009). However, if a suitable biomass feedstock, an effective production method, and appropriate adsorption conditions are selected, biochar from agricultural residues can be an effective adsorbent.

CONCLUSION

Biochar demonstrates significant potential as a cost-effective and sustainable adsorbent for the removal of organic contaminants from agro-industrial wastewater. Its adsorption performance depends on multiple interrelated factors, including biochar properties (surface area, pore size distribution, and surface functionality), properties of the contaminant, and adsorption medium conditions such as pH and temperature. Various adsorption mechanisms—such as hydrophobic, hydrogen-bonding, electrostatic, and π–π electron donor–acceptor interactions—govern the extent and efficiency of contaminant removal. The adsorption behaviour can be effectively interpreted using established isotherm, kinetic, and thermodynamic models to optimize process parameters and understand mechanism types (physisorption or chemisorption). The review indicates that tailoring biochar through controlled pyrolysis and feedstock selection can enhance its structural and chemical properties, thereby improving adsorption capacity for specific organic pollutants like phenol and tannic acid. Ultimately, developing engineered biochars with targeted functional groups and pore structures offers a promising pathway for efficient, low-cost treatment of organic-laden wastewater in sustainable environmental management.

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Water Management and Nutrient Leaching in Rice Production in Nigeria: A Review

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ABSTRACT
Rice-based agro-ecosystems in Nigeria operate under increasingly fragile hydrological conditions characterized by climatic variability, inefficient water management systems, soil structural degradation, and nutrient losses. Although substantial research has examined water-saving irrigation and nutrient management, much of the available evidence originates from Asian rice systems, with limited synthesis of the interconnected water–soil–nutrient processes under Nigerian conditions. This review critically synthesizes evidence on water management, soil-water dynamics, nutrient leaching, hydrological variability, and environmental implications in Nigerian rice production, drawing comparative insights from sub-Saharan Africa and Asia. A structured narrative review was conducted using peer-reviewed literature and relevant technical publications identified through keywords related to rice irrigation, Alternate Wetting and Drying (AWD), evapotranspiration, water productivity, nutrient leaching, nitrogen loss, soil-water dynamics, and eco-hydrology. Studies were screened for relevance and synthesized under four themes: irrigation and water-use dynamics; soil-water and hydrological processes; nutrient transport and leaching; and environmental sustainability. The review indicates that continuous flooding can cause substantial water losses through evaporation, seepage, and percolation, while inappropriate irrigation and fertilizer management may enhance nutrient movement below the root zone. Nitrogen is particularly vulnerable to leaching, denitrification, and runoff. The principal novelty of this review is its Nigeria-focused integration of irrigation management, soil-water dynamics, nutrient transport, leaching processes, water productivity, and environmental implications within a unified rice-production framework. Unlike reviews that primarily examine AWD, water productivity, or nutrient management independently, this review explicitly identifies the gap in quantitative understanding of irrigation interval–agrochemical interactions under Nigerian soil, climatic, hydrological, and management conditions and highlights lysimeter experimentation and process-based modelling as complementary approaches for addressing this gap.

KEYWORDS: Water management; rice irrigation; nutrient leaching; soil-water dynamics; eco-hydrology; Nigeria; sustainable rice production

INTRODUCTION

Rice has become an increasingly important component of Nigeria's food system, with production occurring under rain fed lowland, and irrigated lowland, upland, and other production environments. Expansion of irrigated rice production provides an important pathway for increasing national rice supply; however, intensification also increases pressure on freshwater resources and may accelerate nutrient losses where irrigation and fertilizer application are poorly synchronized (Sokoto and Muhammad, 2014).

Water management in lowland rice is traditionally associated with maintaining ponded or saturated soil conditions. Although continuous flooding can suppress weeds and provide relatively stable water conditions, it may involve considerable water consumption through evapotranspiration, seepage, percolation, and other non-beneficial losses. Previous studies have demonstrated that improved field water management can reduce irrigation water requirements while maintaining rice yield and improving water productivity (B.A.M. Bouman, 2007).

The hydrological implications of rice production extend beyond irrigation water consumption. The timing and magnitude of irrigation influence soil moisture, hydraulic gradients, redox conditions, percolation, and the movement and transformation of nutrients within the soil profile (Bwire, Saito, Sidle, and Nishiwaki, 2024). Nitrogen, in particular, may be lost through leaching, denitrification, volatilization, and surface runoff. Consequently, water management cannot be considered independently from nutrient management (Abubakar *et al*., 2023).

Climate variability further complicates these interactions. Changes in rainfall patterns, temperature, evapotranspiration demand, drought occurrence, and flooding can affect irrigation requirements and alter the timing of agricultural operations. Evidence from Nigerian irrigation schemes has demonstrated vulnerability of agricultural water resources to climatic variability. These conditions create a need for management approaches that simultaneously consider water availability, crop water requirements, soil-water dynamics, and nutrient fate (Adegbehin, Iguisi, Yusuf, and Dauda, 2021).

Several reviews have examined AWD, rice water productivity, and nitrogen management at international scales (Bouman and Tuong, 2001; Ishfaq *et al*., 2020; Bwire *et al*., 2024). However, the evidence remains fragmented when considered from the perspective of Nigerian rice agro-ecosystems. Studies addressing irrigation, soil-water behaviour, nutrient losses, climate vulnerability, and environmental sustainability are often treated as separate research areas. There is therefore a need to bring these components together within a single analytical framework.

The novelty of this review lies in its Nigeria-focused integration of water management, soil-water dynamics, nutrient transport, leaching processes, and environmental implications within a single rice-production framework. Previous reviews have largely examined alternate wetting and drying, rice water productivity, or nutrient management as separate topics or have focused predominantly on Asian rice production systems. In contrast, this review brings these processes together to explain how irrigation timing and water availability influence soil-water behaviour, percolation, nutrient movement, and potential environmental losses under Nigerian rice-production conditions. A further contribution is the explicit identification of the research gap between general water-saving irrigation recommendations and their quantitative evaluation under Nigerian soil, climatic, hydrological, and management conditions**.** The review therefore moves beyond a general description of AWD and nutrient management by identifying the need for integrated lysimeter measurements and process-based modelling to quantify irrigation interval–agrochemical interactions and their effects on soil-water retention and cumulative leaching losses. This synthesis provides a conceptual basis for developing site-specific water and nutrient-management strategies for sustainable rice production in Nigeria.

REVIEW METHODOLOGY

A structured narrative review approach was adopted to synthesize available evidence on the interconnected relationships among irrigation management, soil-water dynamics, nutrient transport and leaching, hydrological variability, and environmental sustainability in rice production. Particular emphasis was placed on integrating Nigerian-specific evidence with findings from comparable rice-producing regions where direct evidence from Nigeria was limited.

Relevant literature was identified through structured searches of Google Scholar, Science Direct, Springer Link, MDPI, and relevant peer-reviewed journal websites and scientific publisher platforms. The search strategy employed combinations of keywords and Boolean operators related to the principal concepts of the review, including rice irrigation, water management, alternate wetting and drying (AWD), soil-water dynamics, soil-water retention, nutrient transport, agrochemical leaching, hydrological variability, rice production, and environmental sustainability. The search was complemented by screening the reference lists of key review articles and highly relevant primary studies to identify additional publications not retrieved through the initial database searches.

The literature considered in the review covered the period 1999–2024. The 1999 publication was retained as a foundational reference because of its direct relevance to water-resource management in rice production, while greater emphasis was placed on recent studies addressing contemporary challenges in irrigation management, soil-water processes, nutrient and agrochemical transport, and environmental sustainability. Earlier or later publications were considered only where they provided essential foundational concepts or methodological information relevant to the review.

To improve transparency and reproducibility, the review process was organized around predefined review scope, search concepts, eligibility considerations, thematic classification, and evidence-synthesis procedures. Retrieved studies were screened for relevance to the review objectives and subsequently grouped into major thematic areas reflecting the principal components of the study. These included (i) rice irrigation and water-management practices, (ii) alternate wetting and drying and soil-water dynamics, (iii) nutrient and agrochemical transport and leaching, and (iv) hydrological and environmental sustainability considerations. Evidence from the selected studies was then critically synthesized to identify established findings, areas of agreement and disagreement, methodological limitations, and research gaps relevant to irrigated rice production and the present lysimetric investigation.

2.1 Water management terms:
"rice irrigation", "rice water management", "continuous flooding", "alternate wetting and drying", "AWD", "irrigation scheduling", "water productivity", "evapotranspiration", and "percolation".

2.2 Soil-water and hydrological terms:
"soil water dynamics", "soil moisture", "hydrological variability", "infiltration", "seepage", "drainage", "soil structure", "paddy hydrology", and "eco-hydrology".

2.3 Nutrient-loss terms:
"nutrient leaching", "nitrogen leaching", "nitrogen loss", "fertilizer-use efficiency", "nutrient transport", "denitrification", "runoff", and "agrochemical transport".

2.4 Geographical and production terms:
"Nigeria", "Nigerian rice", "West Africa", "sub-Saharan Africa", "irrigated rice", "lowland rice", and "paddy production".

The search strategy was designed to identify literature addressing at least one of the major components of the review while allowing subsequent integration of evidence across the four thematic areas.

2.5 Eligibility and selection of studies

Studies were considered relevant when they provided evidence on one or more of the following: rice irrigation and water management; water productivity; soil-water behaviour; nutrient transport or leaching; hydrological variability; nutrient-use efficiency; environmental impacts of rice production; or modelling of water and nutrient processes.

Priority was given to peer-reviewed studies, review articles, authoritative technical publications, and studies conducted in Nigeria, sub-Saharan Africa, and other rice-producing regions with environmental and management conditions relevant to Nigerian production systems.

Studies were excluded where their subject matter had little relevance to rice water management, nutrient dynamics, agricultural hydrology, or environmental sustainability. Where Nigerian-specific evidence was unavailable, studies from other regions were retained as comparative evidence rather than direct representations of Nigerian conditions.

2.6 Literature screening and synthesis procedure

The retrieved records were screened in stages to improve consistency and reduce the inclusion of irrelevant evidence. First, titles and abstracts were examined against the predefined eligibility criteria. Records that were clearly unrelated to rice water management, soil-water dynamics, nutrient transport, leaching, agricultural hydrology, or environmental sustainability were excluded. Duplicate records identified across databases were removed before full-text assessment. The remaining studies were assessed based on their relevance to the review objectives and the availability of information concerning irrigation management, soil-water behaviour, nutrient movement, leaching, water

productivity, environmental impacts, or related modelling approaches. Where studies from Nigeria were available, they were prioritized for interpretation of the Nigerian context. Evidence from sub-Saharan Africa and other rice-producing regions was used for comparison and to provide broader scientific context where Nigerian evidence was limited.

Following screening, the selected literature was classified into four thematic categories: (i) irrigation and water-use dynamics; (ii) soil-water and hydrological processes; (iii) nutrient transport and leaching; and (iv) environmental sustainability and adaptation. Findings were then compared across studies to identify areas of agreement, contrasting results, methodological limitations, and unresolved research gaps. Particular attention was given to the influence of irrigation regime, soil characteristics, fertilizer or agrochemical management, and hydrological conditions on water movement and nutrient losses. The final synthesis was narrative rather than quantitative because of differences among studies in experimental design, environmental conditions, irrigation practices, measured variables, and reporting methods.

3. WATER MANAGEMENT AND NUTRIENT LEACHING CHALLENGES IN RICE-BASED SYSTEMS IN NIGERIA

Rice production in Nigeria is closely dependent on effective management of water and soil nutrients, particularly in lowland and irrigated rice systems where water availability and fertilizer inputs strongly influence crop productivity (Chapagain and Hoekstra, 2011). However, inefficient irrigation practices, inadequate drainage infrastructure, climatic variability, and inappropriate fertilizer application can disrupt soil-water dynamics and increase nutrient losses from the root zone (Mojid, Ahmed, and Rahman, 2020). Excessive or poorly timed irrigation may increase seepage, percolation, and drainage, creating pathways for dissolved nutrients, particularly nitrogen, to move beyond the crop root zone and potentially contaminate surrounding water resources. Conversely, insufficient or irregular water supply can reduce crop water availability and alter soil redox and nutrient transformation processes (Njuki and Bravo-Ureta, 2018). These interactions indicate that water management and nutrient leaching are not independent challenges but closely coupled processes within rice-based agro-ecosystems. Understanding this water–soil–nutrient interaction is therefore essential for developing efficient irrigation and nutrient-management strategies capable of improving rice productivity while reducing water consumption and environmental losses under Nigerian conditions.

In recent years, declining freshwater availability has become a critical engineering and water-resources management challenge, with an estimated four billion people globally affected by water stress due to increasing demand, climate variability, and inefficient allocation of available supplies (Materu, Shukla, Sishodia, Tarimo, and Tumbo, 2018). Projections indicate that by 2025, approximately 20% of irrigated rice production areas will face physical water scarcity, where water resources are insufficient to meet crop water requirements, while about 29% will experience economic water scarcity, arising from limitations in irrigation infrastructure, water conveyance systems, and management capacity (Mekonnen and Hoekstra, 2016).

From an engineering perspective, rice is classified as a high water-demand crop because it is conventionally cultivated in lowland irrigated systems under continuous flooding (Sun, Young, McFarlane, and Chambers). This production system is designed to maintain a standing water layer to minimize percolation losses, suppress weeds, and stabilize crop establishment. However, such systems are characterized by low irrigation water-use efficiency, as substantial volumes of water are lost through evaporation, seepage, and deep percolation (Aliku, Oshunsanya, and Aiyelari, 2022).

The traditional rice cultivation practice involves transplanting 30–35-day-old seedlings into puddled soils, a process that requires repeated tillage and large irrigation inputs to create saturated soil conditions. While the CF system delivers high yield stability and effective weed control, it is increasingly unsustainable under conditions of limited water supply. Moreover, the engineering practice of puddling induces adverse soil physical changes, including soil

particle dispersion, reduction in macroporosity, and formation of a subsurface plough pan. These changes impair soil hydraulic conductivity and root penetration, thereby reducing the productivity and irrigation performance of subsequent non-rice crops (Carrijo, Lundy, and Linquist, 2017) .

In response to these constraints, modern irrigation and soil-water management strategies emphasize the adoption of resource-efficient rice production technologies capable of reducing irrigation demand while maintaining yield. Such approaches aim to improve water productivity, system resilience, and long-term soil physical integrity, making rice production more compatible with sustainable water-resources engineering and integrated agricultural water management under increasing water scarcity.

More than 97 percent of the world's water resources are in the oceans and seas and are too salty for most production uses. Two-thirds of the remainder is locked up in ice caps, glaciers, permafrost, swamps and deep aquifers. Every year, about 108 000 billion m3 precipitates on to the earth's surface. About 60 percent of this (61 000 billion m3) evaporates directly back into the atmosphere, leaving an annual water resource of 47 000 billion m3. If this amount were distributed evenly across the world's population, there would be approximately 9 000 m3 per person per year (Baig, 2024). However, water availability varies across continents, with North and South America being better watered than Africa, Asia and Europe. Furthermore, much of Africa and Asia's potential supply is lost through runoff caused by heavy seasonal rains. It is estimated that only 9 000 to 14 000 billion m3, or about a quarter of the annual water resource, may ultimately be controllable. At present, an estimated 3 400 to 3 700 billion m3 is utilized (Barker, Dawe, Tuong, Bhuiyan, and Guerra, 1999).

Agriculture is the largest consumer of water, using 72 percent of the total worldwide and 87 percent in developing countries. With growing demand for water for non-agricultural uses (domestic, municipal, industrial and environmental), the proportion available for agriculture is projected to decline to 62 percent worldwide and 73 percent in developing countries. In developing countries, the growth in water demand for industrial and municipal uses, in absolute terms, is expected to exceed the growth in water demand for agriculture between 1995 and 2020 (Baig, 2024).

A shift in the future allocation of water among competing uses is inevitable. The global trend will reduce the share of water for agricultural use. The growth in irrigated area has slowed in the past decade and is projected to increase at an annual rate of less than 1 percent between 1995 and 2020. Thus, new investments in irrigation and water supply systems will be inadequate for meeting the growing non-agricultural demand for water and for mitigating the impact of water withdrawals from agriculture. Major changes in practices, policies and institutions will be required to ensure that limited water resources are appropriately managed to increase the productivity of water in irrigated agriculture. If these steps are not taken, rice will be the crop most affected, as it depends most heavily on irrigation (Baig, 2024).

Alternate wetting and Drying (AWD), subject fields to alternating flooding and drying, rather than continuous flooding throughout the crop season. Fields are re-flooded when soil surface attains the aerobic state, as water is allowed to subside via percolation and evapotranspiration. It means, that instead of keeping the paddy field continuously flooded, the paddy fields are subjected to dry/wet cycles (Facon, 2000). Though, there are numerous potential benefits of using the AWD irrigation technique but it is not easy for farmers to use it practically; as without developing simple irrigation indices, it is hard for them to choose the best time for irrigation application. IRRI and Institute for Agro-Environmental Science (IAES), Japan established a set of easy guidelines for AWD application, using a field water polyvinyl chloride (PVC) tube as a device to monitor the field water level (Ishfaq *et al*., 2020). Figure1 below.

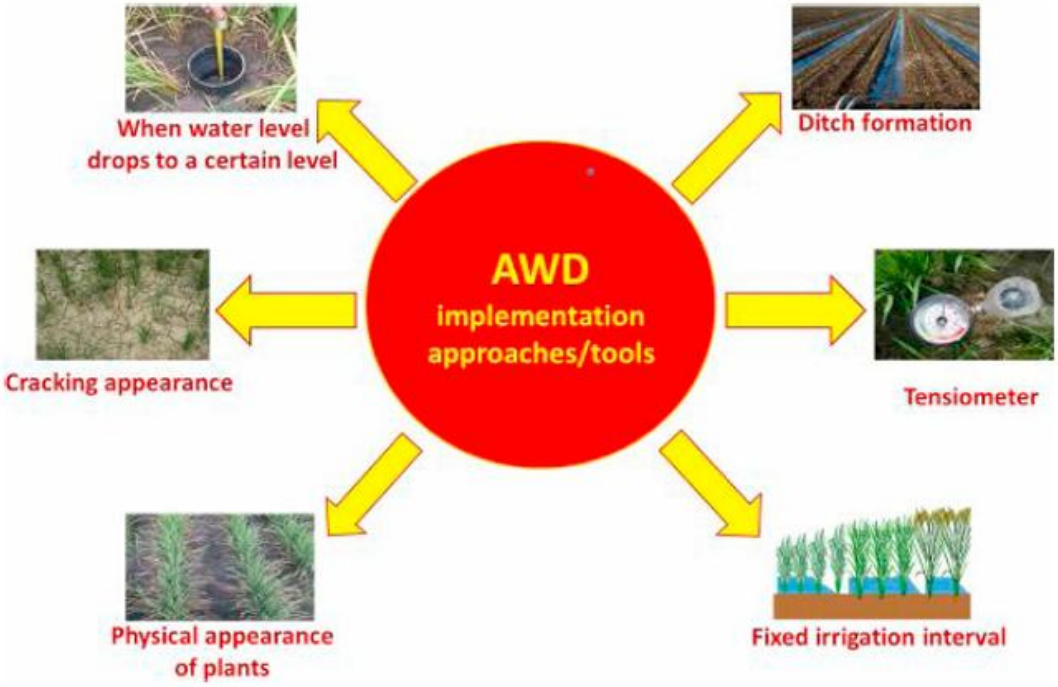

Figure 1: Indices of alternate wetting and drying implementation in paddy fields.
Source: (Ishfaq *et al*., 2020)

4. ECO-HYDROLOGICAL SETTING OF RICE PRODUCTION IN NIGERIA

Rice is a major staple food in Nigeria and plays a key role in food security and economic development. Its production occurs across diverse agro-ecological and hydrological environments, where water availability, soil characteristics, rainfall patterns, irrigation practices, and field-water management collectively influence crop productivity. Understanding how water moves through rice fields and interacts with soil and crop processes is therefore fundamental to understanding the eco-hydrological conditions governing rice production in Nigeria.

Nigeria is an independent sub-Saharan West African country since 1st October 1960. It borders the Gulf of Guinea and shares boundaries with Benin to the west and Cameroon to the east. The country has a land area of 910,768 km² and a water area of approximately 13,000 km². Agricultural, arable, permanent crops, permanent pasture, forest, and other land uses account for 78%, 37.3%, 7.4%, 33.3%, 9.5%, and 12.5% of the total land-use areas, respectively. Within this environmental context, Nigeria is biocapacity-deficient, with its ecological footprint exceeding its biocapacity by 58% (Obekpa *et al*., 2025). This condition highlights the importance of efficient management of the country's land and water resources, particularly within water-intensive agricultural systems such as rice production.

Rice is cultivated across diverse ecological zones in Nigeria, including irrigated lowlands, rainfed lowlands, uplands, and floodplains. Irrigated lowland rice is cultivated in areas such as Kano, Jigawa, and Kebbi, where rice is generally grown in bunded fields to facilitate the production of one or more crops per year. Farmers commonly maintain approximately 5–10 cm of standing water in these fields. Rainfed lowland rice is cultivated in areas such as Bauchi, Taraba, and Adamawa, where bunded fields are flooded with rainfall for at least part of the cropping season. In both irrigated and rainfed lowland systems, paddy fields are commonly puddled before rice transplanting to facilitate crop establishment. Upland rice is cultivated predominantly in the South-West and South-East, while floodplain rice

production occurs in areas such as the Hadeja-Jama'are and Lake Chad basins. In flood-prone areas, paddy fields periodically experience excess water resulting from uncontrolled flooding in Nigeria (Tiamiyu *et al*., 2016). These diverse production environments are characterized by variations in evapotranspiration, percolation, infiltration, rainfall, and soil-water dynamics (Aminu and Eze, 2019).

Paddy-field preparation is one of the most important operations influencing rice production and field-water management. In recent years, field preparation has become increasingly mechanized in developed and many developing countries due to the availability of power tillers and compatible implements. Field preparation commonly involves bund shaping and puddling at the onset of the paddy season. Bunds are shaped uniformly to the desired height and may be plastered with mud to improve water retention (Ranjan and Pranav, 2021). These practices facilitate weed control, maintain ponded conditions during the rainy season, and reduce seepage losses. However, irrigated paddy fields are also cultivated in relatively dry regions, where substantial quantities of water may be required to maintain flooded conditions. In such environments, evaporation from ponded water can be high, while seepage losses may also exceed those observed in wetter regions.

The hydrological response of paddy fields is largely governed by rainfall, irrigation management, and soil conditions (Bwire *et al*., 2024). During rice cultivation, farmers regulate the quantity of water retained within paddy fields according to crop requirements and prevailing environmental conditions. In addition, rainwater can be temporarily stored in ponds located near paddy fields. Consequently, paddy fields can function as temporary buffers against flooding, depending on their water-storage capacity. This storage capacity can influence flood discharge through changes in the field water balance and associated water-management practices (Kim *et al*., 2007).

The eco-hydrological characteristics of Nigerian rice production are therefore shaped by the interaction among climatic variability, soil properties, rainfall, irrigation, drainage, field preparation, and crop water requirements. Paddy fields are influenced not only by the amount of water supplied but also by how effectively irrigation and drainage systems regulate water movement into, within, and out of the soil profile. Effective planning and design of irrigation and drainage canals are consequently essential for maintaining appropriate field-water conditions, ensuring adequate drainage, and supporting rotational crop production. Although the delivery of irrigation water through pipelines can be relatively expensive, it can reduce maintenance requirements and enhance the reliability and stability of water supplies. Collectively, these factors define the eco-hydrological setting within which Nigerian rice production operates and provide an important basis for evaluating water productivity, nutrient movement, and environmental sustainability in rice-based systems.

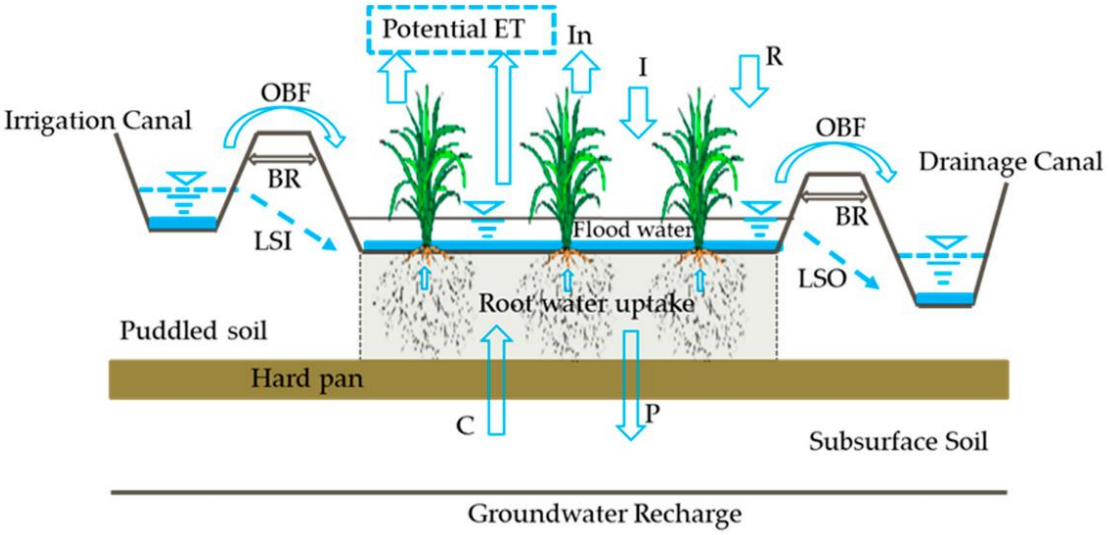

Figure 2: Hydrological Response in Paddy Filed.

Source: (Bwire *et al* ., 2024).

*C: capillary rise; Potential ET: evaporation and transpiration; In: interception loss by canopy; I: irrigation; OBF: over-bund flow; P: percolation; R: rainfall; LSI: lateral seepage inflow from irrigation canal; LSO: lateral seepage outflow to drainage canal; BR: bund/ridge.

5. ECO-HYDROLOGICAL FRAMEWORK FOR RICE PRODUCTION

An eco-hydrological framework for rice production optimizes water use, soil health, and ecosystem services by balancing, or reducing, the high water needs of traditional, continuously flooded systems 3,000 – 5,000 liters per kg of rice). This approach integrates modern techniques like Alternate Wetting and Drying (AWD) to reduce water usage by 25-70 lower methane emissions, and increase water productivity (Ishfaq *et al*., 2020). Eco-hydrology integrates hydrological processes, such as rainfall, infiltration, runoff, and evapotranspiration with ecological processes such as nutrient cycling, soil biota activity, and plant water interactions. In rice systems, this framework helps explain how water management decisions influence soil fertility, nutrient availability, greenhouse gas emissions, and long-term system resilience (Yimer*, 2022). Understanding these linkages is essential for diagnosing environmental problems and designing sustainable interventions. Water resource management in agriculture is a critical contributor to the economic and social development of Nigeria, and if successful, irrigation in Nigeria could represent a cornerstone of the agricultural development of the country (Ukpai, Ezeh, and Effam, 2020). There are high expectations for the potential of improved water management to drive agricultural growth and poverty reduction. These expectations are understandable; most regions include major farming systems and have a high likelihood of drought occurrence due to temperature increase and soil nutrient depletion caused by human-induced factors and climate change (Yimer*, 2022). A systems approach that identifies and assesses the roles of multiple actors is required to achieve sustainable development outcomes.

6. **HYDROLOGICAL VARIABILITY AND ITS EFFECTS ON RICE PRODUCTION**

Hydrological variability driven by climate change, irregular rainfall, and fluctuating river flows significantly affects rice yields. Delayed onset of rains causes transplanting challenges, while extreme events such as floods wash away seedlings or damage irrigation infrastructure. Extended dry spells reduce soil moisture and reservoir levels. Moreover, seasonal variability affects water tables, influencing nutrient diffusion, redox reactions, and root-zone aeration. Assessment of the effects of rainfall variability on rice yield would assist in formulating policy that would help rice stakeholders to properly adapt rice farming to maximize rice production and consequently raise national output of rice to the level of self-sufficiency. Rainfall and water requirement for rice and tomatoes during growing periods revealed

that the optimal amount of water for rice is 711.45mm and that of tomatoes 786mm in a total growing period (Adegbehin *et al*., 2021). This implies that any excess or deficit from this, will likely affect the yields of these crops. Similarly, the seasonal and long-term variations in the flow of rivers in the area underline the importance of large storage as a means of making optimum use of the water resources.

7. SOIL WATER INTERACTIONS AND THEIR INFLUENCE ON PRODUCTIVITY

Waterlogged rice soils undergo dynamic changes in physical, chemical, and biological properties. Prolonged flooding promotes reduced soil conditions, influencing nutrient solubility, microbial processes, and the cycling of nitrogen, phosphorus, and micronutrients. Poor drainage leads to excess water retention, while sandy or degraded soils exhibit rapid percolation and minimal nutrient retention. In many Nigerian rice fields, soil structure decline, compaction, and organic matter loss intensify nutrient leaching and reduce water-use efficiency (Bouman and Tuong, 2001). Crop productivity and sustainability are integrally linked to the optimal use of natural resources, including water. Water is not just an essential input for plant growth but also a bottleneck in several agro-ecosystems, especially in arid and semi-arid environments (Russo, *et al* ., 2014). As world agriculture continues to grapple with escalating population pressures, shifting climatic regimes, and declining freshwater resources, maximizing water use has emerged as a key element of sustainable crop production systems (Mehta, 2024). The soil-plant-water interaction is the fundamental foundation of agricultural water management (Horel, 2024). This three-way interaction regulates the storage of water in the soil, uptake by plant roots, and use for physiological processes like transpiration, nutrient transport, and photosynthesis (Kirkham, 2023). The soil properties of texture, structure, porosity, and organic matter content affect water infiltration, retention, and movement within the profile (Franzluebbers, 2002). These factors regulate the soil's water-holding capacity and its capacity to deliver moisture to plants during critical development phases (Bhattacharya, and Bhattacharya, 2021). precision irrigation equipment provide new means of monitoring and optimizing water use (Bwambale *et al* ., 2022). Knowledge of the soil–plant–water continuum and the complex interrelationships between its constituents is essential for evaluating its wider influence on ecosystems (Gavrilescu, 2021). A thorough understanding of these relationships is necessary for formulating effective mitigation measures towards sustainable land management (Wang, *et al* ., 2019). These include the effective management of water and nutrients, optimization of crop yields, enhancement of biodiversity, and assessment of environmental footprints (Penuelas, and Sardans, 2021). Soil ecosystems are very intricate and dynamic networks that are controlled by multi-faceted interactions, especially the interchanges of carbon, nutrients, and water between soils, plants, and the atmosphere (Hillel, 2007). They are controlled by both natural and human-induced factors and are very important for maintaining soil health and facilitating plant growth.

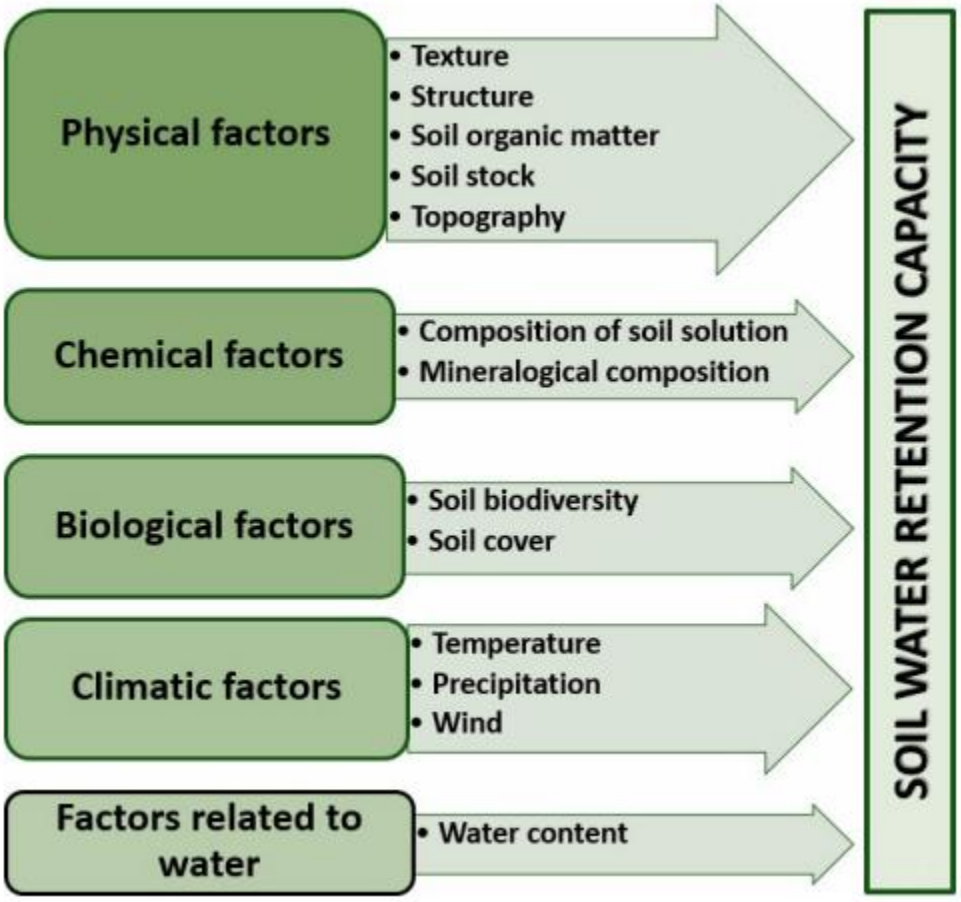

Figure 3: Soil Water Retention Capacity.
Source: (B.A.M. Bouman, 2007).

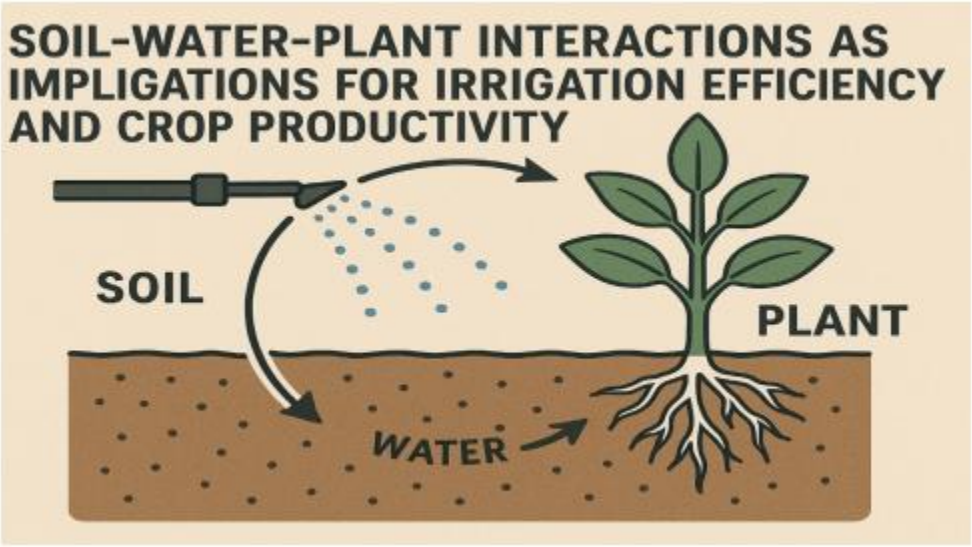

Figure 4: Soil-Water –Plant interactions
Source: (B.A.M. Bouman, 2007).

Availability of water in soil is one of the key factors that determine plant physiological processes (Williams *et al* ., 2007). It has a direct influence on nutrient and water uptake by plant roots, as well as the activity and richness of microbial communities in the soil (Van Der Heijden *et al* ., 2008). Microorganisms, in return, are involved in cycling nutrients and decomposing organic matter, further impacting soil fertility and plant health (Hawkes, *et al* ., 2007).

- **NUTRIENT MANAGEMENT REQUIREMENTS IN RICE ECOSYSTEMS**

Rice requires significant quantities of nitrogen, phosphorus, potassium, and micronutrients. Farmers often rely on inorganic fertilizers without considering soil conditions or hydrological cycles. As a result, nutrient application frequently does not match crop demand or soil retention capacity. Rainwater runoff and vertical percolation transport nutrients beyond the root zone, reducing fertilizer-use efficiency and raising production costs. These issues highlight the need for integrated, eco-hydrological nutrient management (Alam, Khanam, and Rahman, 2023).

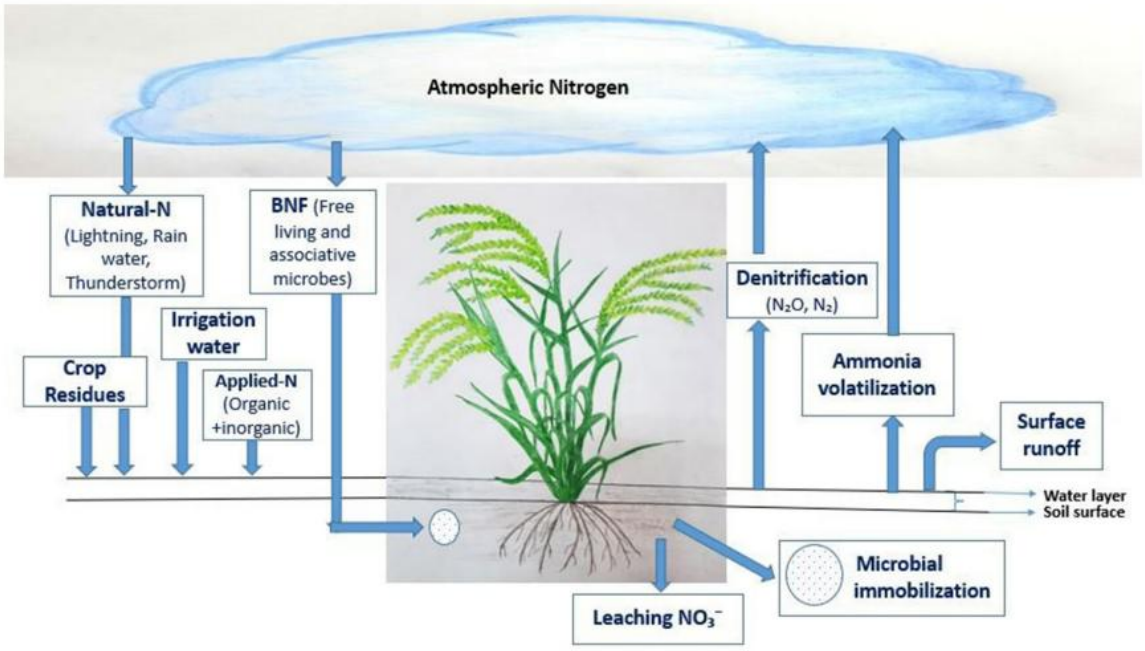

Figure 5: Source of Nitrogen in Wetland rice eco-system.
Source: (Alam *et al*., 2023).

- **MITIGATION AND ADAPTATION STRATEGIES**

Solutions to eco-hydrological challenges must integrate water, soil, and nutrient management:

1. Alternative Wetting and Drying (AWD) to reduce water use and limit nitrate losses.
2. Improved irrigation infrastructure to minimize conveyance losses.
3. Good field leveling to ensure uniform water distribution.
4. Integrated Soil Fertility Management (ISFM) combining organic matter, inorganic fertilizers, and site-specific nutrient application.
5. Use of controlled-release fertilizers or deep placement techniques to reduce leaching.
6. Construction of buffer strips and sediment traps to protect water bodies.
7. Climate-smart practices, such as drought-tolerant varieties and improved scheduling.

These strategies require extension support, farmer training, and investment in water management systems.

- **POLICY AND INSTITUTIONAL CONSIDERATIONS**

Addressing eco-hydrological constraints requires supportive institutional frameworks. Policies promoting efficient irrigation schemes, water-saving technologies, and soil conservation are essential. Strengthened river basin authorities, sustainable land-use regulations, and incentives for good agronomic practices can enhance environmental resilience. Research extension linkages must be improved to close knowledge gaps and promote evidence-based management.

- **RESEARCH GAPS AND FUTURE DIRECTIONS**

Key areas that require further study include:

6. Quantifying nutrient leaching under local hydrological regimes using lysimeters and modeling tools.
7. Assessing long-term impacts of water management strategies on soil health.
8. Developing region-specific water productivity benchmarks.
9. Evaluating the ecological consequences of fertilizer pollution in Nigeria's wetlands and lakes.
10. Integrating remote sensing for water-use monitoring.

These gaps highlight the need for multidisciplinary eco-hydrological research.

- **CONCLUSION**

Water management and nutrient leaching represent interconnected challenges for sustainable rice production in Nigeria. The literature demonstrates that irrigation practices influence not only crop water availability but also soil-water dynamics, percolation, nutrient transformation, and the movement of dissolved nutrients below the root zone. Consequently, improving rice sustainability requires management strategies that jointly address water and nutrient processes.

Alternative Wetting and Drying, improved irrigation scheduling, integrated soil fertility management, and improved irrigation infrastructure offer promising pathways for reducing unnecessary water consumption and improving resource-use efficiency. However, their effectiveness depends on local soil, climatic, hydrological, and management conditions.

The key research priority emerging from this review is therefore not simply to determine whether water-saving irrigation is beneficial, but to quantify how irrigation intervals interact with fertilizer and agrochemical application rates to control soil-water retention, drainage, nutrient transport, and cumulative leaching losses under Nigerian conditions. Addressing this gap through controlled lysimeter experiments, field validation, and process-based modelling will provide the evidence required for site-specific and environmentally sustainable rice-water management in Nigeria.

- **.ACKNOWLEDGEMENT**

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Effects of Stem Characteristics and Blade Speed on the Cutting Force Required for Cassava Stems

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ABSTRACT
Stem characteristics and blade speed are very important parameters in the design and development of agricultural machinery, especially in computer-aided design (CAD) and discrete element modelling (DEM). To examine the effects of stem characteristics and blade speed on the cutting force required for cassava stems, four locally available cassava varieties (TMS 30572, TMS 4(2) 1425, TME 419, and TMS 30555) were examined at a mean moisture content of 35.2% and a mean stem diameter of 23.7 mm to determine the influence of cassava variety on the cutting force. The effect of stem diameter on the cutting force was examined using TMS 30555 stems with diameters ranging from 18.5 to 27.2 mm at a mean moisture content of 35.5%. The influence of stem moisture content was examined using stems with moisture contents ranging between 35.2 and 37.3% at a blade speed of 23 rpm and a mean stem diameter of 23.2 mm. The influence of blade speed on the cutting force was also examined at blade speeds of 23, 39, and 50 rpm, a mean moisture content of 37.0%, and a mean stem diameter of 23.2 mm. The experiments were conducted in three replicates. The results showed significant varietal differences in cutting force, with TMS 30555 requiring the highest cutting force (654.91 N) and TME 419 the lowest (122.20 N). Cutting force increased with increasing stem diameter, exhibiting a positive nonlinear relationship with a diminishing rate of increase. Stem moisture content showed a significant quadratic relationship with cutting force, characterized by a concave downward trend and a peak cutting force at an intermediate moisture content. Blade speed also showed a quadratic relationship: the minimum cutting force occurred at 249 N at a blade speed of 39 rpm, while both lower and higher blade speeds required greater cutting forces. The study indicated that cutting force is significantly influenced by stem diameter, stem moisture content, and blade speed. This study provides valuable engineering data to optimize cassava stem-cutting mechanisms that improve the development and performance of cassava planting and harvesting equipment. Based on the results of this study, a blade speed of 39 rpm and stem moisture of 35.2% at stem diameters between 20 and 30 mm are recommended for optimum stem cutting.

***Keywords**:* Characteristics, cutting force, effect, speed, stem.

1. INTRODUCTION

Development of indigenous machinery for agricultural production in this era of food scarcity is very important, especially for crops that are very indigenous to Africa. A good example of such a crop is Cassava. Though Nigeria has in the past recorded the highest cassava production (ref. yr), this production was mainly carried out using manual and other crude implements. Given the current food demand driven by population growth, rural-urban drift, and ongoing economic reform, there should be strong demand for mechanization of agriculture that is self-reliant and sustainable through local development and the production of machinery and other agricultural technologies.

To design and develop appropriate farm machinery for the production of crops, the characteristics of the crops and the components of the machines are essential requirements. These characteristics usually vary from one place to another because of soil variability, soil conditions, and crop types, and cassava is not an exception. Research in this area is limited, especially regarding the specific physical properties of cassava stems and their effects on the cutting force requirement. Stem cutting is an important action in the production of cassava. It occurs in cassava planting, harvesting, and biomass processing of cassava stems for fuel and energy production. It is therefore important to assess the effects of stem characteristics as a crop variable and blade speed as a machine variable on the force required to cut cassava stems.

According to Oupathum et al. (2021), a chopping device with two blades and a cutting blade linear velocity of 5.03 m/s could produce 115.30 kg/hr, consume 1.28 kW of power, produce 11.06 W/hr/kg of specific energy, and distribute 69.6% of cassava sized 1–10 mm. Oupathum et al. (2019) investigated how the moisture content and knife bevel angles affected the shearing characteristics of cassava stems. It was found that when the knife bevel angle was increased from 20 to 40 degrees, the shearing stress and specific shearing energy increased and the moisture content dropped from 64.27 to 17.67% w.A b. It was discovered that the highest shearing force, shearing stress, and specific shearing energy were 2.16 kN, 4.62 MPa, and 55.58 mJ/mm2, respectively. Abisuwa et al. (2026) showed in a study that cassava stem recorded the highest cutting force of 654.91 N against other agricultural stems, like stubborn grass (11.81 N), at moisture contents ranging from 18.3% to 39.0%. The result showed that woody stems required greater cutting forces than herbaceous grasses.

It was found by Atsyo et al. (2020) that cutting shear stress and force increased with an increase in cassava tuber age because of an increase in density and starch content. 515 rpm blade speed at a cutting efficiency above 80%, with a cutting time of 3 seconds were observed in another study by Nwaeche et al. (2022). The report also showed that cutting efficiency increased with an increase in blade speed, and it was also reported that an increase in residence time had a significant impact on the cutting efficiency of cassava stems with variable stem diameters. The results analysis by Ikejiofor (2012) established that at cutting velocities of 1.2 and 1.32 m/s and corresponding cutting efficiencies of 99.42 and 94.71%, the cutting velocity had a very highly significant effect on the efficiency of a cassava cutting machine, whereas stem size had no significant effect at the 5% level. Despite these studies, there is a need for more detailed information serving as a link between the physical and mechanical characteristics of cassava stems and cutting-force requirements at different blade speeds, particularly for cassava varieties cultivated under Nigerian conditions. Existing studies have examined various aspects of stem cutting, including moisture content, bevel angle, blade configuration, cutting velocity, and cutting efficiency, but there is limited information on the combined effect of specific stem characteristics and blade speed on the force required to cut cassava stems. Such information is important for determining the appropriate power and torque requirements and for optimizing the design of locally developed cassava production and processing machines. Therefore, this study was carried out to determine the effects of selected cassava stem characteristics and blade speed on the cutting force required to sever cassava stems. The findings are expected to provide useful engineering data for the design and development of efficient indigenous cassava stem-cutting machinery for applications in cassava planting, harvesting, and biomass processing.

2. STEM CUTTING AND CUTTING FORCE THEORY

Cutting is defined as the process of mechanically separating a solid body along a predetermined line using a blade. In most cases, the original body is divided into two portions that create new surfaces. Cutting has been given other names for special tasks like chopping, mowing, sawing, splitting, slicing, dicing, chipping, etc. (Lungkapin et al. 2007)
The cutting force theory of cassava stems analyzes the mechanical interaction between a cutting blade and the stalk tissue to optimize agricultural machinery like planters and harvesters. The required cutting force, energy, and stress depend heavily on stem geometry, moisture content, and blade parameters (PrasanthKumar and Saravanakumar, 2020). Cutting force depends on stem diameter, Stem moisture content, Stem density, Stem variety/characteristics, and blade speed.

Koloor and Borgheie (2018) investigated the static and dynamic cutting force of Iranian rice stems to construct rice harvesting devices. In the study, they constructed a static and dynamic shear test device to test the cutting force of rice stems. The effects of moisture content, stem cross-sectional area, stem variety, blade angle, blade type, and blade speed on shearing strength were assessed. The findings revealed that as the cross-sectional area increased, so did the cutting force, but as the moisture content increased, it dropped. The static test yielded maximum and minimum shearing strengths of 1629 and 1429 kPa, respectively, whereas the dynamic test yielded 187.4 and 144 kPa. There are equations for the determination of the cutting force, the blade speed, and moisture content (equations 1,2, 3, and 4)

The cutting force (F) required to sever a plant stem can be determined using sensor-based instrumentation, and the cutting energy can be estimated using equation 1 as expressed by Preethi et al. (2021).

$$E_c = F_c \times D \quad (1)$$

where E_c is the cutting energy, F_c is the cutting force, and D is the diameter of the stem material.

The blade speed (crank) and the linear speed can be determined using equations 2 and 3 as expressed by Preethi et al. (2021).

$$n(rpm) = \frac{V \times 1000}{\pi D} \quad (2)$$

where V is the linear speed in meters per minute (m/min), and D is the outer diameter of the blade in millimeters (mm).

$$V = \frac{S \times n}{30} \quad (3)$$

Where V is the blade speed, S is the length of stroke in m, and n is the crank speed in rpm

Stem moisture content can be determined using equation 4 as expressed by Preethi et al. (2021).

$$Moisture\ Content = \frac{W_s - W_d}{w_s} \times 100 \quad (4)$$

Where W_s is the weight of the stem before drying in g, and Wd is the weight of the dried stem in g

3. MATERIALS AND METHODS

TMS 4(2) 1425, TME 419, TMS 30572, and TMS 30555 cassava varieties were used in this study. The stem varieties were obtained from the Teaching and Research Farm of the Department of Agricultural and Bio-Environmental Engineering Technology, Rufus Giwa Polytechnic, Owo, Nigeria, during the rainy season. The stem of TMS 4(2) 1425 is silver-brown, slightly thick and robust, and has a staggered arrangement of nodes; TME 419 has a brown/green colour with a rough and woody texture, and its nodes are moderately spaced; TMS 30572 is also silver-brown, but its brownish color is lighter than that of TMS 4(2) 1425, and its nodes are correctly arranged with shorter internode spacing. TMS 30555 is erect, silver-green/brown, with short to intermediate spacing.

3.1 Sample Preparation and the Cutting Force Measuring System

The samples used for the study were prepared from freshly cut 12-month-old cassava stems. They were carefully selected and cut into 1000 mm long using a hacksaw and a steel measuring tape. The moisture content of the cassava stems was measured with a digital wood moisture meter, and the stem diameter was taken with a digital vernier caliper. The blade speed was varied using different pulleys of varying diameters. A cutting force measuring system (Figure 1) consisting of a cutting unit, a transmission unit, crank mechanisms for motion conversion, a sensor-based instrumentation and data acquisition system, a 1-horsepower electric motor, a supporting frame was used for measuring the cutting force.

Figure 1: The Cutting Force Measuring System

3.2 Experimental Procedure

Four experiments were conducted in this study: cassava variety versus cutting force, stem diameter versus cutting force, stem moisture content versus cutting force, and blade speed versus cutting force. In the cassava variety experiment, TMS 4(2) 1425, TME 419, TMS 30572, and TMS 30555 were used with a mean moisture content of 35.2**%**, a mean stem diameter of 23.7 mm, and a blade speed of 23 rpm to determine the influence of cassava variety on the cutting force. The effect of stem diameter on the cutting force was investigated using TMS 30555 stems with varying diameters of 18.5, 20.3, 21.4, 24.2 and 27.2 mm at a mean moisture content of 35.5%. The influence of stem moisture content was evaluated using stems at varying moisture contents of 35.2, 35.8, 36.2, 36.7 and 37.3**%** at a blade speed of 23 rpm and a mean stem diameter of 23.2 mm. The influence of blade speed on the cutting force was also determined at blade speeds of 23, 30, 39, 45 and 50 rpm, a mean moisture content of 37.0%, and a mean stem diameter of 23.2 mm. The experiments were carried out in three replicates.

3.3 Data Acquisition and Analysis

The cutting force was automatically collected using the sensor-based instrumentation system (Figure 2). The instrumentation was later connected to a laptop computer to download the data and generate the mean values of the cutting force downloaded. The data generated were later analyzed using descriptive statistics in Microsoft Excel 2024.

Figure 2: Data Acquisition System, the Load Cell and the Power Bank

RESULTS AND DISCUSSION

Cassava Variety and the Stem Cutting Force

Figure 3 presents the relationship between cassava variety and cutting force. The results showed that TMS 30555 required the highest cutting force (654.91 N) among the four selected varieties, and TME 419 had the lowest cutting force (122.20 N). The force value for TME 4(2) 1425 had a close and second-highest value of 637.74 N. The variation in force requirement may be due to differences in the mechanical properties, particularly the fibre/tissue structure. Literature for comparing the cutting force of these specific cassava varieties is limited; therefore, the observed differences can be discussed in relation to the known variation in the physical and mechanical properties of cassava stems. Kaewwinud et al. (2017) reported that the physical and mechanical properties of cassava stalks depend on factors including stalk diameter, average length, mass, moisture content, and region of cut.

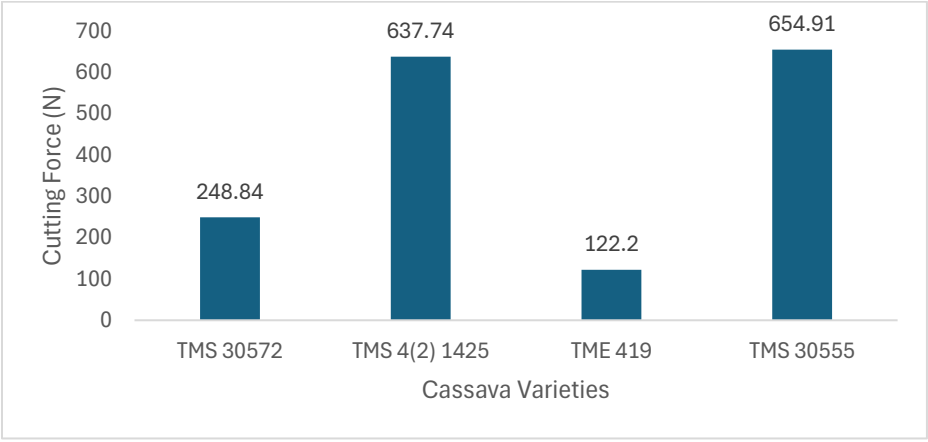

Figure 3: Cassava Cutting Force

Stem Diameter and the Cutting Force

Figure 4 presents the influence of stem diameter on cutting force. The result showed a linear relationship between the stem diameter and the cutting force with a coefficient of determination R^2 of 0.9672. In the study, cutting force increased as stem diameter increased. The highest cutting force of 257.33 N was recorded with a stem diameter of 27.2 mm, and a stem diameter of 18.5 mm had the lowest cutting force of 222.5 N. This is in agreement with Wang et al. (2017), who reported a similar relationship between stem cutting force and the stem diameter. In their study, it was concluded that stems with larger diameter generally required greater forces.

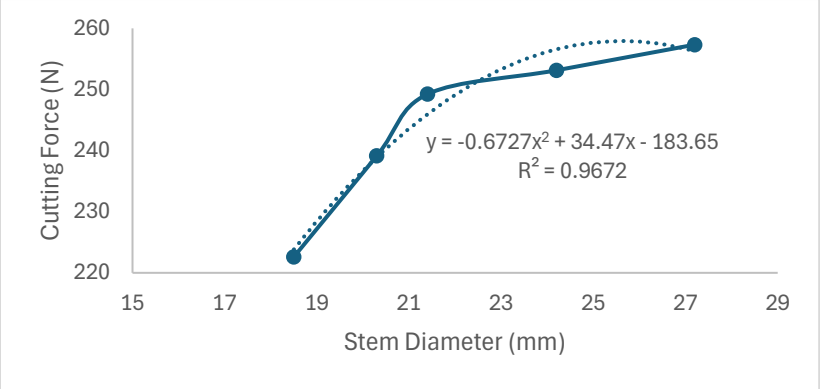

Figure 4: Diameter versus Cutting Force

Effect of Stem Moisture Content on the Cutting Force

The polynomial relationship presented in Figure 5 showed that the cutting force recorded in this study increased with an increase in stem moisture content and later decreased with further increase in the stem moisture content. This conforms with Singh et al. (2019), who reported that the cutting strength of a henna stem increased up to a point and later declined with further increase in the stem moisture content. This polynomial model is also supported by Kaewwinud et al. (2017), who concluded that cassava stalks with higher moisture content required less cutting energy than the drier stalks.

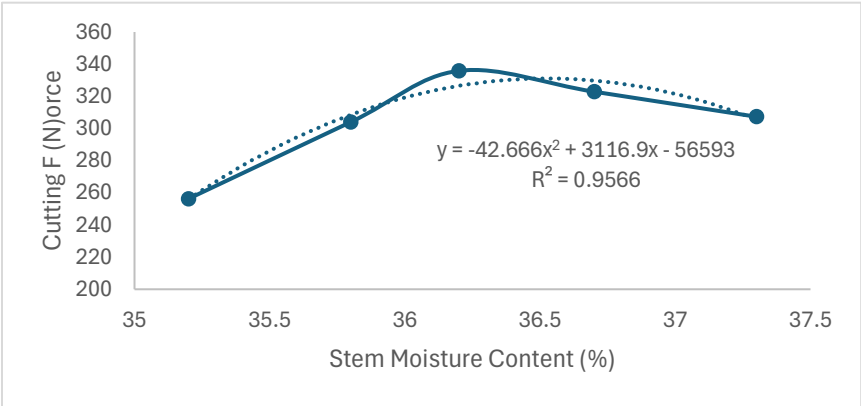

Figure 5: Stem Moisture Content Versus Cutting Force

Effect of Blade Speed on the Cutting Force

The U-shape polynomial model observed between the blade speed and the cutting force is presented in Figure 6. The results showed that cutting force initially decreased with increasing blade speed and later increased with further increase in the blade speed. This indicates that blade speed had a non-linear influence on the cutting force required to cut the cassava stem. The minimum cutting force obtained at the intermediate blade speed suggests the existence of

an optimum operating speed at which the resistance of the cassava stem to cutting was minimized. The U- shape model can be attributed to the dynamic behaviour of the cassava stem during cutting. This conforms with wang et al. (2017), who reported that cutting force is influenced by cutting speed in addition to stalk diameter, cutting position, and cutting angle, and that higher blade speed produced greater impulsive force, based on momentum considerations.

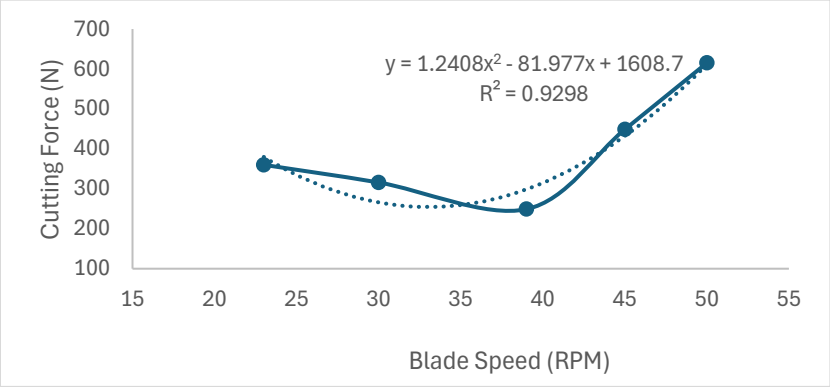

Figure 6: Blade Speed versus Cutting Force

CONCLUSIONS

The following conclusions were drawn from this study:

1. Cassava variety influenced cutting force requirement, and the cutting force varied among the selected cassava varieties; TMS 30555 exhibited the highest value of 654.92 N, and TME 419 had the lowest value of cutting force of 222.6 N.
2. Stem diameter had a significant effect on the force required to cut cassava stems. The cutting force increased with increasing stem diameter, with a maximum cutting force of 257.33 N at a stem diameter of 27.2 mm.
3. Stem moisture content and blade speed had a non-linear relationship with cutting force. The relationship of the cutting force with the stem moisture content and the blade speed can be described as quadratic, but the blade speed is inversely related with a U-shape curve.
4. The findings have relevant implications for design, development, and mechanization of cassava production. The study has provided useful data for determination of power requirements, blade specifications and configurations, and operating conditions of machines used in cassava mechanization.

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Paper ID 20:
Enhancing Farmers Safety Using Levy Flight Whale Optimization Algorithm in Wireless Sensor Networks

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ABSTRACT
The increasing occurrence of insecurity affecting farming communities in Nigeria has created a critical need for intelligent monitoring systems capable of detecting threats and providing timely alerts to enhance farmer safety. Wireless Sensor Networks (WSNs) have emerged as an effective technology for real-time environmental monitoring because of their distributed sensing capability and efficient wireless communication. However, WSN performance is constrained by limited energy resources, inefficient cluster head selection, uneven energy consumption, and unreliable communication, which reduce network lifetime and monitoring effectiveness. This study proposes an enhanced Levy Flight Whale Optimization Algorithm (LWOA)-based framework to improve WSN performance for farmer safety monitoring in insecurity-prone agricultural environments. The proposed approach integrates the global search capability of the Levy Flight mechanism with the Whale Optimization Algorithm to optimize cluster head selection, balance energy utilization, and enhance network exploration. A simulation model comprising 100 sensor nodes randomly deployed over a 100 m × 100 m agricultural field was developed using MATLAB R2024a. The proposed model was evaluated against the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol and the standard Whale Optimization Algorithm (WOA) using Packet Delivery Ratio, network lifetime, residual energy, sensing coverage, and Farmer Safety Index (FSI) as performance metrics. Simulation results showed that the proposed LWOA achieved the highest FSI of 98.4%, outperforming WOA 94.9% and LEACH 92.0%. The findings demonstrate that integrating Levy Flight with WOA significantly improves energy efficiency, network reliability, sensing coverage, and monitoring effectiveness, making it a promising solution for enhancing farmer safety in insecure agricultural environments.

KEYWORDS: Wireless Sensor Networks, Farmer Safety, Levy Flight, Whale Optimization Algorithm, Smart Agriculture

1. INTRODUCTION

In Nigeria, especially in rural areas, agriculture continues to be a significant source of income. However, farmer safety and agricultural output have been severely impacted by insecurity brought on by banditry, insurgency, and other illegal activities. Because farming areas encompass a wide geographic area and have limited security resources, traditional surveillance methods are frequently insufficient. In the area where the study is conducted, almost 87 percent of the populaces are farmers (United Nations, 2022). The insurgency cause has severely affected agricultural productivity, leading to major losses, displacement of people, and devastation of farmland. This ongoing insurgency, which has persisted for seven years, has crippled the agricultural sector the economic backbone of Yobe State and worsened food insecurity, particularly in Yobe, Borno and Adamawa states due to reduced land farming, lack of access to seeds, and farming tools (Babagana et al., 2018).

In response to these challenges, the researcher aims to develop a model designed to mitigate the risks faced by farmers in the region by investigating the impact of Boko Haram on food production in Yobe State, Nigeria. The aim of the model is to increase safety and security for farmers by providing an additional layer of protection. It will allow for real-time monitoring of the areas, giving soldiers the ability to assess potential threats and alert farmers and commuters to the presence of approaching attackers.

Through distributed sensing and transmission, Wireless Sensor Networks (WSNs) offer an affordable way to monitor huge agricultural landscapes. Despite their benefits, WSNs have problems with communication dependability,

network lifetime, and energy usage (Heinzelman et al., 2000). (Samara & Al-Okour,2020), (Jadhav & Shankar, 2017) Although clustering procedures like LEACH have been widely used to increase energy efficiency, their random cluster head selection frequently results in uneven energy depletion.

To overcome these restrictions, this research offers a Levy Flight Whale Optimization Algorithm (LWOA) for cluster head optimization and farmer safety enhancement. The proposed framework strives to increase monitoring efficacy, communication dependability, and overall network performance (Gimba et al.,2022).

2. THEORETICAL ANALYSIS

2.1 Optimization Principle

The proposed LWOA enhances the traditional WOA by introducing the long-range movements inspired by Levy Flight. While the classical WOA efficiently exploits local search spaces by it encircling and the spiral updating mechanisms, it often suffers from early convergence when optimizing Cluster Head selection in Wireless Sensor Networks.

The integration of Levy Flight enables candidate solutions to escape local optima by introducing irregular long-distance movements. Therefore, the search process will then balance the exploration and the exploitation more effectively, which will lead to improved Cluster Head selection.

2.2 Cluster Head Selection Analysis

Suppose that,

$$N\{n_1, n_2, n_3 \dots, n_{100}\}$$

Represents all of the sensor nodes in the area, each of the sensor nodes has a residual energy, communication distance and a neighborhood density

The optimization objective then is given as;

$$max\ F(x)$$

This is subject to

$$E_i > E_{threshold}$$

E_i is the initial energy

E_{res} residual energy

Where

$$F(x) = \frac{E_{res}}{d+1}\ (1 + 0.1L)$$

The optimization chooses the Cluster Heads that simultaneously increases the remaining energy while reducing the communication distance.

2.3 Energy Consumption Analysis

The total network energy consumed is

$$\mathrm{E_{total}} = \sum_{i=1}^{N} (E_{Tx} + E_{Rx})$$

E_{Tx} is the transmitting energy

E_{Rx} is the receiving energy

Since Cluster Heads aggregate data, that helps in reducing the redundant transmissions.

$$E_{aggregation} < E_{direct}$$

2.4 Network Lifetime Analysis

The lifetime of the network depends on balanced energy utilization.

If

$$\Delta E = E_{\max.} - E_{\min.}$$

Is minimized,

Then,

$$Lifetime \propto \frac{1}{\Delta E}$$

The proposed LWOA attempts to minimize energy difference among nodes, thereby procrastinating the node failures.

2.5 Communication Reliability Analysis

The Packet Delivery Ratio is modeled as

$$PDR = 1 - P_{loss}$$

Where

$$P_{loss} = f(d, E, Interference)$$

Since the proposed LWOA minimizes communication distance,

$$d_{LWOA} < d_{LEACH}$$

Therefore

$$PDR_{LWOA} > PDR_{LEACH}$$

2.6 Farmer Safety Analysis

Farmer safety depends on three major factors, the threat detection, successful packet delivery and network availability

Therefore

$$FSI = 0.4(DR) + 0.3(PDR) + 0.3(NA)$$

The theoretical upper bound is

$$FSI_{\max.} = 100\%$$

The simulation results indicate that the proposed LWOA achieves a Farmer Safety Index of 98.4%, outperforming LEACH 92.0% and WOA 94.9%, demonstrating that the integration of Levy Flight with WOA improves monitoring effectiveness for farmer safety applications.

3. MATERIALS AND METHODS

3.1 Study Area

This study was conducted by considering Gujuba Local Government Area, Yobe State, Nigeria; the region was significantly affected by insurgency, and attacks on farming communities. The numerous security threats in the region have led to the reduction in agricultural productivity and restricted farmer's access to their farmlands. Accordingly, an intelligent monitoring framework capable of providing unbroken surveillance and early threat detection is required. The proposed Wireless Sensor Network (WSN) framework is designed to monitor farming environments and improve the safety of farmers through timely detection and communication of suspicious activities.

3.2 Research Design

This research adopted a simulation-based quantitative experimental design. A homogeneous Wireless Sensor Network was modeled in MATLAB R2024a to test the effectiveness of the proposed LWOA. The performance of the proposed algorithm was compared with two benchmark clustering algorithms; LEACH and WOA. The comparison focused on energy efficiency, communication reliability, network lifetime, coverage sensing and Farmer Safety Index.

3.3 Materials

The following hardware and software resources were used.

Hardware

An Intel(R) Celeron(R) Processor, 4GB RAM, 512 GB SSD and 64bit Windows 10 Operating System computer was used in running the simulation.

Software

A MATLAB R2024a with MATLAB Wireless Sensor Network Toolbox and Optimization Toolbox was used.

3.4 Wireless Sensor Network Model

A homogeneous Wireless Sensor Network that consists of 100 sensor nodes was randomly deployed within a 100 m × 100 m agricultural field, the network assumptions are show in the table below;

Table 1 shows the simulation parameters used during the implementation.

Parameter	Value
Simulation Tool	MATLAB R2024a
Network area	100m x 100m
Number of nodes	100
Initial energy	0.5J
Packet length	4000bits
Sink position	(50,50)
E_{Rx}	50nJ/bit
E_{Tx}	50nJ/bit
$\mathcal{E}_{fs}$	10 pJ/bit/m^2

$\mathcal{E}_{mp}$	0.0013 pJ/bit/m^4
EDA	5 nJ/bit
Maximum Simulation Rounds	3000

Each sensor continuously monitors environmental activities and forwards collected information to the sink through the selected Cluster Heads (CHs).

3.5 Energy Consumption Model

The first-order radio energy model was adopted in the computation.

The Transmission Energy is given as,

$$E_{Tx}(k,d) = \{kE_{elec} + k\mathcal{E}_{fs}d^2, d < d_0 \;\; kE_{elec} + k\mathcal{E}_{mp}d^4, d \geq d_0$$

Where

- k = packet size
- d = transmission distance
- E_{elec} = electronic energy
- $\mathcal{E}_{fs}$ = free-space amplifier
- $\mathcal{E}_{mp}$= multipath amplifier

The Receiving Energy is defined as,

$$E_{Rx} = kE_{elec}$$

The remaining energy after the whole communication is

$$E_{res} = E_{initial} - E_{consumed}$$

3.6 Proposed Levy Flight Whale Optimization Algorithm

The proposed method combines the exploration ability of Levy Flight with the exploitation capability of the Whale Optimization Algorithm.

The optimization process passes through six steps.

Step 1Random deployment, of the sensor nodes.

Step 2 Initialization of the whale population, each whale represents an entrant Cluster Head configuration.

Step 3 Evaluation of the fitness function.

The fitness function considers the residual energy, communication distance and Levy Flight exploration which is given by,

$$fitness = \frac{residual\ energy}{distance + 1} * (1 + 0.1 * levy)$$

Higher fitness values correspond to better Cluster Head entrants.

Step 4 Position update

Updating the whale positions was done using,

$$X(t+1) = X^*(t) - A.D$$

Where

$$D = |CX^*(t) - X(t)|$$

$$A = 2ar - a$$

And

$$C = 2r$$

Where

r is a random number

a decreases from 2 to 0

Levy Flight Update, in other to prevent early convergence, the whale positioning is modified using Levy Flight.

$$X_{new} = X + \alpha * Levy(\lambda)$$

Where

α Is the step size and $Levy(\lambda)$ Follows a heavy tailed probability distribution

Which enables long distance, searching and improves global optimization.

Step 5 Cluster Head Selection, in selecting the CH, the sensor node with the highest fitness value within each cluster becomes the Cluster Head.

Step 6 Data Transmission, each cluster members will transmit it sensed data to the Cluster Head, then the Cluster Head will aggregate the data before forwarding it to the sink.

3.7 Performance Evaluation

The proposed algorithm was evaluated using:

Packet Delivery Ratio

$$PDR = \frac{Packet\ Received}{Packets\ Sent} * 100$$

Residual Energy

$$RE = \sum_{i=1}^{N} \mathrm{E_i}$$

Network Lifetime

The network life time was measured using

- First Node Dead (FND)
- Half Node Dead (HND)
- Last Node Dead (LND)

Coverage Ratio

$$Coverage = \frac{CoveredArea}{Total\ Area} * 100$$

Farmer Safety Index

The proposed Farmer Safety Index is defined by the equation below

$$FSI = 0.4(DR) + 0.3(PDR) + 0.3(NA)$$

Where

DR is the Detection Rate

PDR is the Packet Delivery Ratio

NA is the Network Availability

4 RESULTS AND DISCUSSION

The Table 1 below presents the performance comparison of the evaluated protocols.

Table1. Performance Comparison

Metric	LEACH	WOA	LWOA
Safety Index (%)	92.0	94.9	98.4
FND	1348	1326	1299
HND	1839	1967	1814
LND	2472	2460	2410

Table 1 Compares LEACH, WOA, and the proposed LWOA based on Farmer Safety Index (FSI), First Node Dead (FND), Half Nodes Dead (HND), and Last Node Dead (LND). The results show that LWOA achieved the highest FSI of 98.4%, compared to 94.9% for WOA and 92.0% for LEACH, demonstrating its superior effectiveness in supporting farmer safety monitoring. Although LEACH recorded the highest FND and LND, while WOA achieved the highest HND, these metrics mainly reflect network lifetime. In general, the higher FSI achieved by LWOA indicates that the proposed algorithm was more effective and reliable for monitoring and detecting threats while supporting timely safety

alerts. Therefore, LWOA demonstrates greater suitability for farmer safety applications despite the slight trade-off in network lifetime.

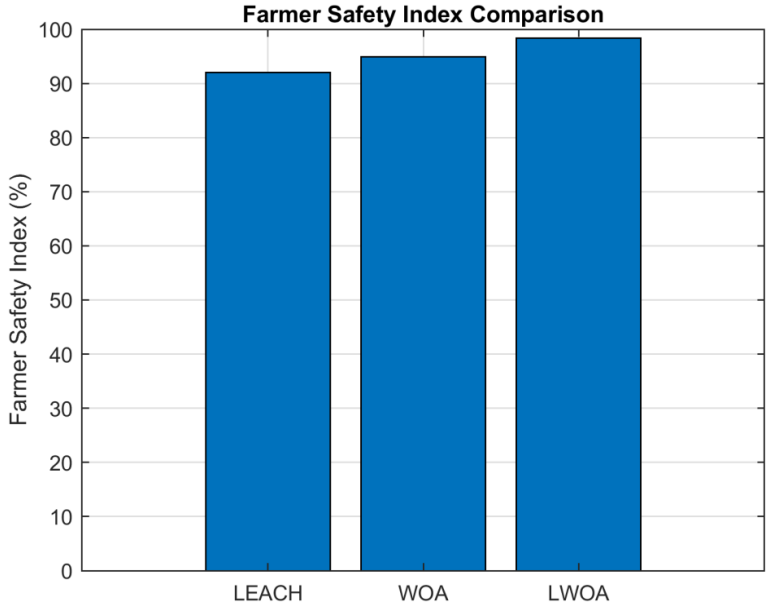

Figure 1 Farmer Safety Index Comparison

Figure 1 illustrates the comparison of the Farmer Safety Index among LEACH, WOA, and LWOA. LEACH achieved a Safety Index of 92.0%, while WOA improved the performance to 94.9%. The proposed LWOA achieved the highest Safety Index of 98.4%, representing an improvement of 6.4% over LEACH and 3.5% over WOA. This result demonstrates that uniting the Levy Flight mechanism into WOA improves the optimization process and enhances the effectiveness of the WSN for farmer safety monitoring. The higher Safety Index indicates that LWOA provides great reliable monitoring and supports, improved threat detection and safety alert delivery in insecurity prone agricultural environments.

5 CONCLUSION

The conclusion should be a brief summary of findings. It should clearly state the contributions, relevance of the findings and recommendations, as appropriate. This study demonstrated that the proposed Levy Flight Whale Optimization Algorithm (LWOA) can effectively enhance farmer safety monitoring using Wireless Sensor Networks. The Simulation results obtained using MATLAB R2024a showed that LWOA achieved the highest Farmer Safety Index of 98.4%, outperforming WOA 94.9% and LEACH 92.0%. Although LEACH and WOA achieved better performance in some network lifetime measures, LWOA provided superior safety-oriented performance. Therefore, LWOA is a promising approach for reliable threat monitoring and alert communication in insecure agricultural environments. Future work should focus on improving its network lifetime and energy efficiency while maintaining its high safety performance.

ACKNOWLEDGEMENTS

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included on the title page, as a footnote to the title or otherwise
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Paper ID 22:
Development and Evaluation of an Automated Soil Macro Nutrient Testing Device under Tropical Soils

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ABSTRACT
Effective soil nutrient management is essential for optimizing crop yield and promoting sustainable agricultural practices. Conventional methods for analyzing soil macronutrients are often costly. An automated soil macronutrient detection device was developed and evaluated, to measure, process and display soil nutrients of N, P, K, pH, temperature, and soil moisture content. The device's performance was evaluated in a field experiment by monitoring the growth of cowpea (beans) under both fertilized and unfertilized conditions. The results confirmed the device's capacity to accurately monitor nutrient changes in the soil. The device measured the initial concentration of Nitrogen(N) from 970 mg/kg in week 1 down to 725 in week 6; Phosphorus(P), 8.30, to 2mg/kg; while Potassium(K) ranged from 190.50 to 91.48 mg/kg. On the control plot, Nitrogen (N) measured from 970mg/kg in week 1, down to 700mg/kg in week 6, Phosphorus (P): 8.30, to 1mg/kg, Potassium (K) ranges from 190.50mg/kg to 83.48 The soil pH ranged from 6.32 to 6.1.The simulation results demonstrate that the developed device is highly responsive to increasing concentrations of nitrogen, shows maximum range limitation for phosphorus and potassium sensors, and effectively detects pH variations associated with fertilizer dissolution. These findings confirm the device's functionality under controlled conditions and provide baseline calibration data necessary for interpreting its behaviour when deployed in field soil conditions. The developed automatic soil nutrient detection device offers a low-cost, rapid, and user-friendly alternative to traditional testing by enabling real-time nutrient monitoring and data-driven decisions.

Keywords: Micronutrients, Sensors, Soils

1.0 INTRODUCTION

1.1 Soil Nutrients

Effective soil nutrient management plays a vital role in modern agriculture, significantly influencing crop yield, soil health, and sustainable farming practices (Smith *et al*., 2020). Plants needs about 16 essential elements for their growth, which are; carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and chlorine (Cl). Carbon, hydrogen, and oxygen are obtained from the air and water, while the remaining 13 mineral elements are absorbed from the soil, often requiring fertilizers to supplement what is naturally available (Uchida, 2000; Oyetunde *et al.*, 2024).

Soil nutrients are categorized into Primary (Macro) Nutrients **(**macronutrients), Secondary Nutrients Calcium (Ca), Magnesium (Mg), and Sulphur (S) are required in lesser amounts than macronutrients, but each is equally important to the crop, and Micronutrients which includes Boron(B), Zinc (Zn), Copper (Cu), Manganese (Mn), Iron (Fe), Chloride (CI^-) and Molybdenum (Mo)(ACES, 2025).

For macronutrients, Nitrogen is necessary for the formation of amino acids, proteins, DNA and RNA, synthesis of amino acids, nucleic acids, cell division and chlorophyll, vegetative growth, leaf development, and crop yield (Sun *et al.,* 2023). Phosphorus promotes early root formation and growth, and is involved in photosynthesis, respiration, energy storage and transfer, cell division and enlargement. Deficiency Symptoms of Phosphorus (P) include; leaves of plants turning blue or purple and stunting occurs, it also leads to poor root development, delay and reduction in flowering and fruiting, the crops also take much time to ripen and also deficiencies can be seen in the shape and size of fruits as a result.

Potassium is involved in carbohydrate metabolism and the break down and translocation of starch and regulates stomatal function, water balance, and resistance to stress. Deficiency Symptoms of potassium (K) causes; Stunted growth resulting in shorter plants, leaf tip and edge scorching or "burning" appearance, reduced sweetness and juice content in fruits, increased susceptibility to water stress during mild drought conditions, higher incidence of branch breakage, imbalance and disease resistance (FAO, 2021; García,(2024).).

For Secondary Nutrients; Calcium increases fruit set and quality, continuous cell division and formation (regulates hormonal activity). Magnesium, the centre molecule of chlorophyll, and a cofactor for many enzymes, improves utilization and mobility of phosphorus and Sulphur is an integral part of amino acids and protein synthesis, formation of certain vitamins and coenzymes, oil contents, and aids in seed formation (Bindraban *et al*., 2020;

ACES, 2025).

Micronutrients are used in minute amounts but are just as important to plant growth and development as the major nutrients.Some of the essential micronutrients are Boron, Zinc,Copper, Manganese, Iron, Chloride and Molybdenum (ACES, 2025). In recent years, the challenge of maintaining macronutrient balance has grown due to soil degradation, intensive farming, and climate resilient-related shifts in nutrient availability. Studies show that precision nutrient management is now essential to optimize fertilizer use efficiency, minimize environmental impacts such as eutrophication, and sustain long-term soil fertility (Zhang *et al*., 2021). These considerations are especially relevant for irrigation farms, where water movement can alter nutrient distribution and exacerbate leaching losses.

1.1.2 pH Effects on Nutrient Availability

Soil pH has a direct impact on the chemical composition of the soil, particularly in terms of nutrient availability. Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are most accessible to plants within a pH range of 6.0 to 7.0. Outside this range, nutrient availability can be significantly altered (Omya, 2025). For instance, pH effect can be classified in two-way extremes, in strongly acidic soils and strongly alkaline soils (Yun *et al.,* 2024; Lakesh *et al.,* 2024(Figure 1):

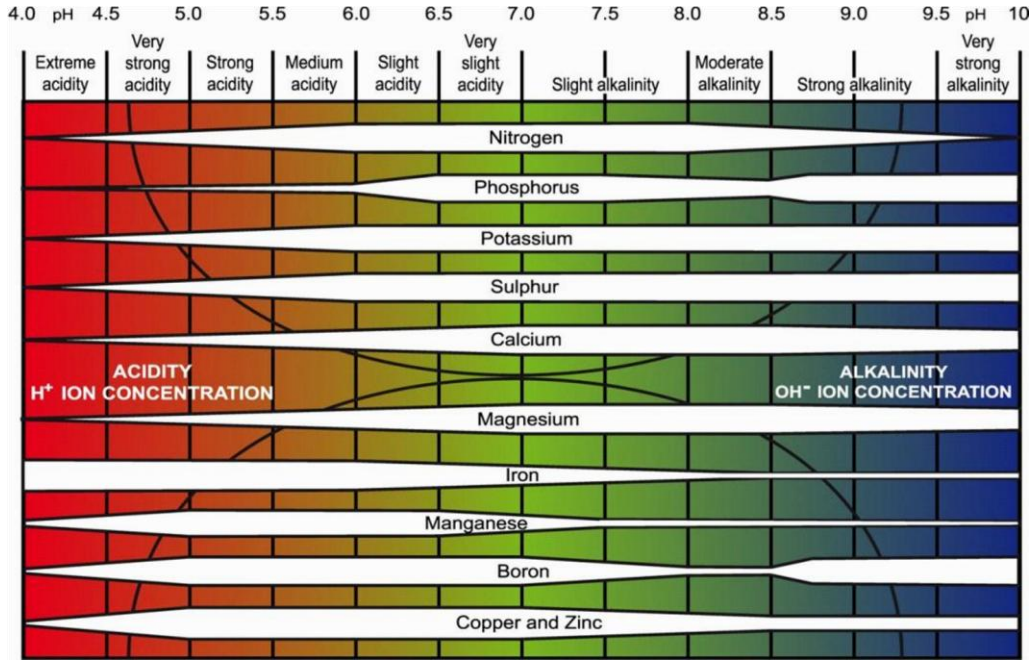

Figure 1: Effect of pH on Nutrient Availability in Soils (The Wider the Bar, the More Available is the Nutrient) Source(Lakesh *et al.,* 2024).

In Strongly Acidic Soils (pH < 5.5)

Macronutrient Lockout: Phosphorus becomes chemically bound to iron and aluminum, forming insoluble compounds that plants cannot absorb.

Micronutrient Toxicity: High acidity dissolves naturally occurring aluminum, manganese, and iron to levels that are highly toxic to plant roots.

Nutrient Depletion: Essential elements like calcium, magnesium, and potassium are easily leached away by water. Microbial Stagnation: Beneficial bacteria that decompose organic matter and release nitrogen are heavily hindered, causing a buildup of un-decomposed organic material. (Donald, 2026).

In Strongly Alkaline Soils (pH > 7.5)

Macronutrient Lockout: Phosphorus reacts with calcium to form insoluble calcium phosphate.

Micronutrient Deficiencies: Micronutrients like iron, zinc, copper, and manganese precipitate (solidify) into forms that plant roots can no longer extract, frequently leading to iron chlorosis (yellowing leaves) (Horiba, 2026). To manage Soil pH for better yields when the soil pH is unbalanced, amendment can be done to restore nutrient solubility (Donald, 2026; Horiba, 2026).

1.2.1 IoT-based soil sensors

Internet of Things (IoT) technology has revolutionized soil nutrient monitoring by enabling continuous, real-time data collection and remote management. IoT-based soil sensors are embedded devices that measure key soil parameters

such as moisture, temperature, pH, electrical conductivity (EC), and nutrient levels (e.g., nitrate, potassium) and transmit this data wirelessly to cloud platforms for analysis and visualization. (Kumar and Lee,2020; Zhang 2023).

IoT-based soil sensors represent a transformative technology for smart agriculture, promoting sustainability and profitability in farm management systems that optimize inputs and reduce environmental impact (Singh *et al*., 2023). Advancements in soil nutrient detection technologies including electrochemical sensors and remote sensing are enabling more accurate and real-time monitoring of macronutrient availability, supporting site-specific nutrient management (SSNM) strategies (Chen and Zhang, 2021).As global food demand continues to rise, (UNEP, 2020) the proper management of soil macronutrients becomes increasingly critical for ensuring food security, environmental sustainability, and economic viability of farming systems.

Conventional methods for analyzing soil nutrients typically involve laboratory testing, causing delays in nutrient assessment and subsequent decision-making (Patel *et al*., 2021).

An automatic soil macronutrient detection device for irrigation farms seeks to overcome these challenges by offering an on-site monitoring system capable of analyzing soil nutrient levels in real time (Li *et al.,* 2022; Gonzalez *et al.,* 2023).

This study developed an automated soil nutrient detection system that is precise, cost-effective, and user-friendly. The research utilized suitable sensor technologies, data processing devices and communication methods for relaying real-time soil nutrient information to farmers and agricultural management systems. By enhancing soil nutrient monitoring, this innovation can promote sustainable farming practices, optimize fertilizer usage, and boost agricultural productivity, benefiting both small- and large-scale irrigation farms. When integrated with an irrigation system, it can further enhance resource efficiency by ensuring that water and fertilizers are applied based on actual soil conditions, minimizing waste and improving plant health.

2.0 MATERIALS AND METHODS

2.1 Study Area

The study was conducted at Joseph Sarwuan Tarka University, Makurdi, situated in Makurdi Local Government Area, Benue State, Nigeria. Formerly known as the Federal University of Agriculture, Makurdi, the institution lies in the North-Central region of Nigeria.

Makurdi is located approximately between latitudes 7°35N and 7°50′N and longitudes 8°22′E and 8°40′E (Ibrahim and Anthony. (2026). Geologically, the soils around Makurdi is derived from sedimentary formations, notably the Makurdi sandstone and related formations. Soils vary across slope positions: upland soils tend to be coarser (sandyto-sandy loam), while lower slopes, floodplains, and near-river areas have more clay and silt content. Organic matter tends to be low to moderate depending on land use, and many soils show moderate to low fertility in terms of macro-nutrients and micro-nutrients, often requiring supplemental inputs for optimal crop growth (NGSA,2020).

Because of this variability in soil texture, drainage, nutrient content, and moisture availability, Makurdi represents a suitable location for assessing and validating an automated device for detecting soil macro- and micro-nutrients in irrigation farm settings. The diversity in soil conditions within the area will allow for robust testing across a range of realistic agricultural scenarios.

Makurdi, the location of Joseph Sarwuan Tarka University, experiences a tropical savanna climate, which is characterized as tropical wet and dry. Wet or rainy season lasts from April to October with rainfall amount varying between 900 mm to 1500 mm and the dry season spans from November to March (Johnson *et al.,* 2025).

2.2 Experimental Site

The experiment was carried out at the Meteorological Station of the Department of Agricultural and Biosystems Engineering, Joseph Sarwuan Tarka University, Makurdi, Benue State, Nigeria.

2.2.1 Soil preparation

Appropriate tools were used for soil preparation, planting and measurement in the study Area.

2.2.2 Determination of site soil samples

The soil used for the experiment was collected from the same source to ensure uniformity and filled into twenty experimental bags. A composite soil sample was obtained by collecting equal portions of soil from each of the filled bags, thoroughly mixed to form a unit sample, and then taken to the laboratory for analysis. The laboratory analysis was conducted to determine the physical and chemical properties of the soil using standard laboratory methods. **Physical parameters:** Physical parametres determined are: soil texture, moisture content, organic carbon, organic content, soil temperature.

Chemical parametres: soil pH, nitrogen (N), phosphorus (P), potassium (K), Zinc (Z), iron (Fe), manganese (Mg), boron (B), cupper (Cu), exchangeable acid **(**EA), exchangeable base (EB**))**, cation exchange capacity (CEC) base saturation (BS).

2.2.3 Design of experimental plots

The experimental plot was designed**,** to accommodate a total of twenty (20) washed cement bags; ten (10) for the control treatment and ten (10) for the fertilized soil treatment. for the planting of the evaluation crop (cowpea). Each bag was filled with soil to a depth of 30 cm to support plant growth. The bags were placed 75cm between rows to allow free movement and prevent shading, and 40cm between bags to ensure each plant gets adequate sun light.

2.2.4 Crop Planting

Cowpea (Vigna unguiculata) was selected as the test crop for evaluating the developed automated soil nutrient detection device. The seeds were planted in the twenty (20) experimental bags filled with same amount soil. Planting was done at the middle soil in the bags, one seed per bag. Ten (10) bags were applied a measured quantity of 15g of NPK (15-15-15) mix ratio fertilizer as treatment, while the remaining ten (10) served as the control (unfertilized).

2.3 Smart Agricultural Components (IoT) used to develop the Automated Device

The development of the project device involved the integration of several electronic and IoT components, each performing a specific function essential to the overall operation of the system before they coupled to perform the required task. The major components used are Arduino Nano, Analog-to-Digital Converter (ADC), Switch,Wires, Six-in-One Soil Sensor, Dry Cell Batteries, OLED Display, Vero Board**, (**Table 2) and (Plate 1).

2.3.1 Device coupling and performance

The various components of the automated device were systematically integrated in accordance with schematic circuit shown in Figure (2) forming the corresponding block diagram illustrated in Figure (3). These interconnected units collectively function to detect and monitor key soil parameters of pH, NPK, temperature and moisture content, and their various readings were displayed by the OLED (Plate 2e).

2.3.2 Testing of simulated fertilizer (NPK)

Also, a known quantity of NPK 15:15:15 fertilizer was measured using a digital weighing balance at different levels (5g, 6g, 7g, 8g, 9g, 10g). Each quantity was separately dissolved in 200 milligrams of distilled water to prepare five standard solutions of increasing nutrient concentrations. The solutions were thoroughly stirred until the fertilizer was completely dissolved to ensure homogeneity, and each was appropriately labelled according to its concentration (5g, 6g, 7g, 8g, 9g, 10g), and the concentration was monitored weekly.

For sensor calibration and measurement, the automated device was powered on and allowed to stabilize before use. The six-in-one sensor probe was then immersed sequentially into each prepared solution. A stabilization period of approximately 20–30 seconds, was allowed for each reading to ensure accuracy. The displayed values for nitrogen (N), phosphorus (P), potassium (K), pH, temperature, and moisture index were subsequently recorded.

2.3.3 Weekly testing of soil nutrients after planting

Weekly testing of soil nutrients was carried out throughout the experimental period to monitor variations in soil fertility parameters resulting from fertilizer application and crop uptake. The assessment was performed using the developed automated soil macronutrient detection device, which was designed to measure essential soil properties, pH, nitrogen (N), phosphorus (P), potassium (K), temperature, and moisture content.

Soil samples were taken from each of the experimental bags, ten (10) fertilized and ten (10) unfertilized—to ensure consistent monitoring across treatments. The six-in-one soil sensor was inserted into the soil at a uniform depth of approximately 10 cm to obtain readings. Data from the sensor were transmitted to the device's microcontroller and displayed on the OLED screen for immediate recording.

Table 2: IoT Components Uses and Specifications

Materials	**Uses**	**Specification**
Analog digital converter ADC	Convert analog signals (continuous values, like voltage from the sensor)	RS485 TTL Converter
Electrolyte battery	Supply consistent power to the device components	12V battery
Wires	Connects the various components of the device to together	150mm breadboard jumper wires
Power Switch	Used for switching the device on and off	Voltage: 210 V Body : Plastic
Six in one soil sensor	Detects soil nutrients (N.P.K) ,soil moisture, soil ph., and soil temperature	RS485 5V
OLED Display	OLED display shows data from the microcontroller for easy monitoring and interaction.	3.3V-5V
Arduino Nano	It is the heart of the system and controls all the system operations.	5v model Maximum voltage =20v Maximum current =40mA
Vero Board	Organizes and secures the electronic connections and circuitry of the system	1.6mm thick with copper thickness of 35um whole grid. 2.54 x 2.54mm. Hole diameter is 1.02mm

3.0 RESULTS AND DISCUSSION

3.1 Results

The physical and chemical properties of the soil used for the experiment were determined in the laboratory through standard methods and procedures. The physical and chemical properties of the experimental soil are presented in (Table 3**).** The result served as the initial data used for subsequent comparison with results of the developed automated soil nutrient detection device test, after planting and during the agronomic development of the beans crop. In the results: Nitrogen (N) was expressed as a percentage (%), Phosphorus (P) in (mg/l), while Potassium (K), Magnesium

(Mg), and Calcium (Ca) were measured in centimoles of charge per kilogram of soil (cmol/kg). To ensure uniformity and comparison, all values were converted to a common unit of milligrams per kilogram (mg/kg) using formulae (1, 2 and 3) for Nitrogen, phosphorus and potassium respectively. To convert nitrogen content from percentage to milligrams per kilogram (mg/kg), the following relationship is applied (Havlin *et al.*, 2014; FAO, 2022):

1% = 10,000 mg/kg1

Hence the conversion formula is given as:

$$N\left(\frac{mg}{kg}\right) = N\,(\%) \times 10{,}000 \qquad (1)$$

Plate 1a: six in one soil sensor

Plate 1b:Dry cells

Plate 1c:Jumper wires

Plate 1d: OLED display

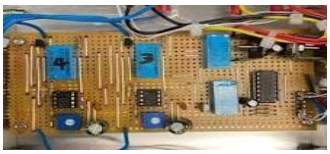

Plate 1e: Vero board

Plate 1f: Switch

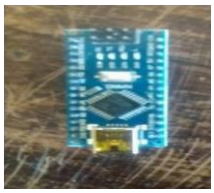

Plate 1g: Arduino Nano

Plate 1h: Analog digital converter

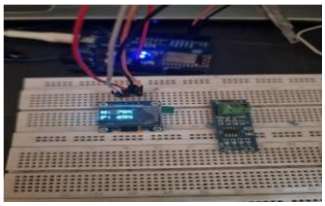

Plate 1i: Breadboard

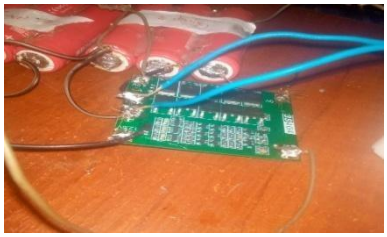

Plate 1j: BMS

Plate 1: IOT Components

Phosphorus is commonly measured in milligrams per liter (mg/l**)** of soil extract, especially when using extraction methods such as Bray-1**,** Olsen**,** or Mehlich-1. Since one liter of soil extract approximately represents one kilogram of soil under standard laboratory conditions, the conversion is expressed as (FAO,2021):

$$1\ mg/L \approx 1\ (mg/kg) \quad (2)$$

Thus, the concentration of phosphorus in the soil is calculated using the formula by Cole and Marshall (2025):

$$P\ (mg/kg)\ = P\ (mg/l)$$

Potassium is usually reported in centimoles of positive charge per kilogram of soil ($cmol^{+}$/ kg)**,** representing its exchangeable cation concentration. Conversion to milligrams per kilogram (mg/kg) is derived from the atomic weight and valency of potassium, expressed as (Brady and Weil, 2019; Bindraban *et al.*, 2020):

$$K(mg/kg) = K\ (cmol^{+}/kg) \times 391$$

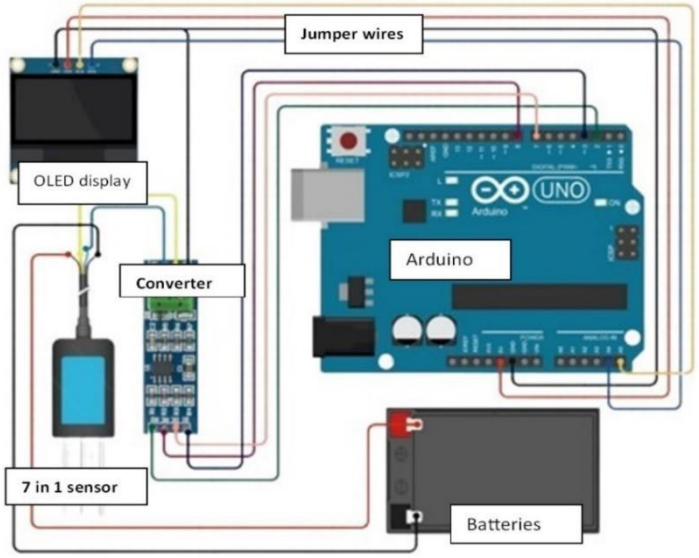

Figure 2: Schematic circuit diagram of the automated device

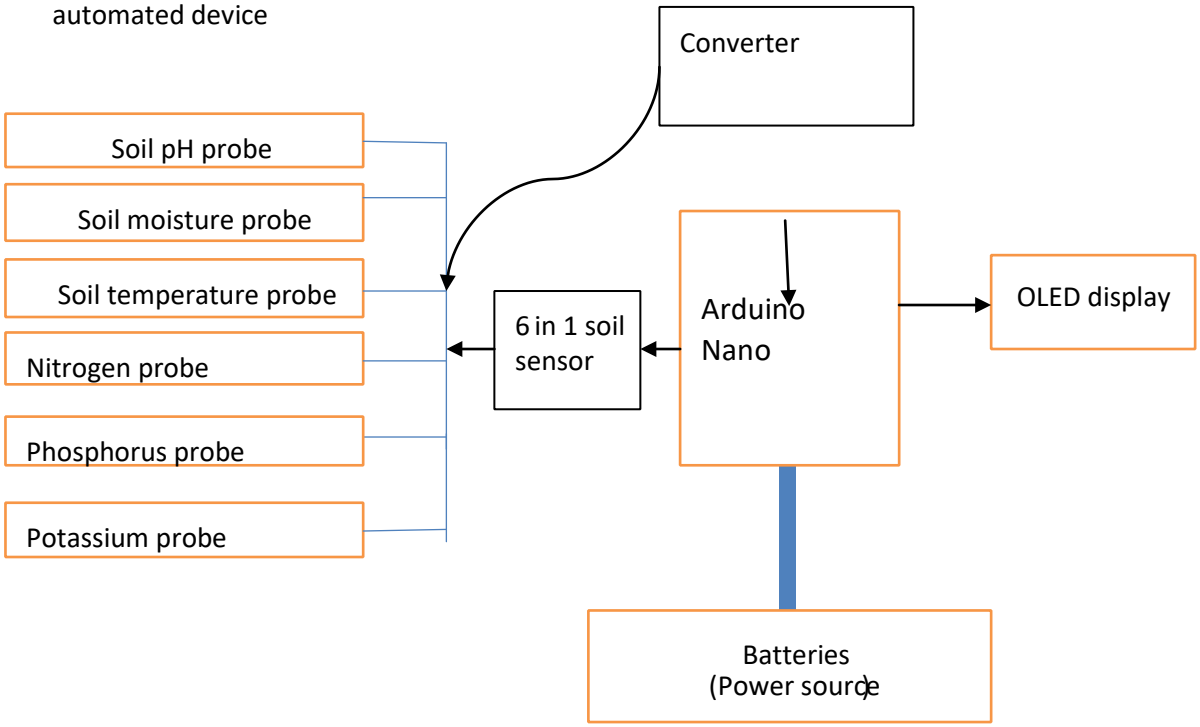

Figure 3: Block diagram of the automated device

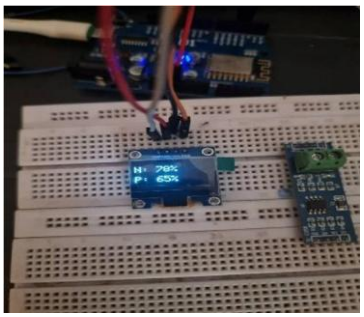

Plate 2aconnecting components

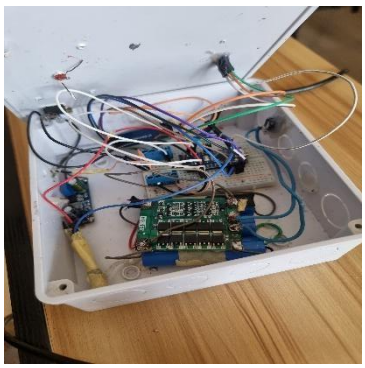

Plate 2b: Device interior

Plate 2c: Complete Automated Device

Plate 2d: Temperature reading

Plate 2e: Device showing NPK readings

Plate 2f: pH reading

Plate2g:Testing of soil nurients

Plate 2h: Weekly testingof soil nutrients on experimental site.

before planting

Plate 2: Coupling and Testing of the Automated Device

To evaluate the performance and sensitivity of the developed automated soil nutrient detection device, a controlled simulation was conducted using NPK (15-15-15) ratio fertilizer of varying concentrations levels. The fertilizer was

dissolved in 500ml of distilled water at different weight levels of 5 g, 6 g, 7 g, 8g, 9g, and 10 g, representing a gradient of nutrient concentrations.

The developed device was dipped in each solution to detect and display the concentrations of Nitrogen (N), Phosphorus (P), and Potassium (K) in each prepared solution. The readings obtained were automatically processed and recorded in real time, showing a consistent increase in nutrient detection values with increasing fertilizer concentration.

Table 3: Soil Physical and Chemical Properties of Experimental Site

S/NO	Soil Properties	Value	Conversions(mg/kg)	Remarks
1	Sand	11.00 (%)		
2	Clay	68.80 (%)		
3	Silt	20.20 (%)		
4	Moisture	13 (%)		
5	Temperature	29˚C		Optimal range
6	O.C	0. 87 (%)		
7	O.M	1.6 (%)		
8	pH	6.32		Slightly acidic
9	N	0.097 (%)	970.0	
10	P	8.30 (mgl-1)	8.30	
11	K	0.28 (Cmolkg-1)	109.50	
12	Ca	3.15(Cmolkg-1)		
13	Mg	2.90(Cmolkg-1)		
14	Zn	4.65 (mg/Kg)	4.65	
15	Cu	4.9 (mg/kg)	4.9	
16	Mn	1.7 (mg/kg)	1.7	
17	Fe	8.70 (mg/kg)	8.70	
18	B	0.034(mg/Kg)	0.034	
19	EB	6.58 (%)		
20	EA	1.12 (%)		
21	CEC	7.70 (%)		
22	BS	85.45 (%)		

Key
O.C = Organic content (%),O.M = Organic matter (%), EB = Exchangeable base (Cmol/kg)EA = Exchangeable acidity (Cmol/kg), CEC = Cation exchange capacity (Cmol/kg), BS = Base saturation (%)

The results, presented in Table (4), indicate a direct proportional relationship between fertilizer concentration and nutrient values detected by the system, demonstrating the accuracy, linearity, and responsiveness of the device across varying NPK concentrations. This confirms that the developed system effectively detects changes in nutrients concentration. We observed that an increase in fertilizer concentration from 5 to 6 g per 500 mL resulted in a marked increase in phosphorus and potassium concentrations, getting up to 1999 mg/kg at pH of 6.7. As we further increased fertilizer concentration, the accompanying decline in pH to 5.2 did not produce additional increases in the measured phosphorus and potassium concentrations, indicating that the sensor response had reached its peak. The repeated maximum value of 1999 mg/kg for phosphorus, potassium, and eventually nitrogen strongly suggests that this value represents the upper detection limit of our sensing device rather than the true nutrient concentration. The weekly nutrient monitoring results for the control plot are presented in Table (5) and the nutrient monitoring results for the fertilized plots in Tables (6).

The results obtained from the growth evaluation of cowpea (Vigna unguiculata**)** cultivated under both fertilized and control (unfertilized) conditions in a rain fed field was conducted weekly over a period of six (6) weeks. **Table 4:** Simulation of NPK (15-15-15) Fertilizer Solutions

Solution	**N**	**P**	**K**	**pH**	**Temperature**	**MC (%)**
(mg/l)	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(%)**	
A (5g/500ml)	785	1810	1816	6.9	25.4	100
B (6g/500ml)	829	≥1999	≥1999	6.7	25.4	100
C (7g/500ml)	995	≥1999	≥1999	5.9	25.4	100
D (8g/500ml)	1460	≥1999	≥1999	5.9	25.4	100
E (9g/500ml)	≥1999	≥1999	≥1999	5.8	25.4	100
F (10g/500ml)	≥1999	≥1999	≥1999	5.20	25.4	100

Table 5: Weekly N, P, K (mg/kg) Concentration in Control Plot Soil

Week No	**N (mg/kg)**	**P (mg/kg)**	**K (mg/kg)**	**pH**	**SMC (%)**
0(Base line)	970.0	8.30	109.50	6.32	13.40
1	920.0	6.30	104.48	6.3	51
2	870.0	4.30	99.48	6.4	55
3	830.0	2.30	94.48	6.3	26
4	790.0	2	90.48	6.2	45
5	750.0	1	86.48	6.3	57
6	700.0	1	83.48	6.3	60

Table 6: Weekly N, P,K (mg/kg) Concentration in Fertilized Plot

Week	N (mg/kg)	P (mg/kg)	K (mg/kg)	pH	SMC (%)
0 (Baseline)	970.0	8.30	109.50	6.32	13.40
1	1,050.0	18.30	169.48	6.33	51
2	960.0	10.30	144.48	6.2	55
3	880.0	5.3	124.48	6.1	26
4	810.0	3.3	109.48	6.2	45
5	755.0	2	99.48	6.21	57
6	725.0	2	91.48	6.3	60

3.2 Discussion

3.2.1 Soil physical and chemical properties

The soil physical and chemical analysis presented in Table (3) provides essential baseline information for interpreting the nutrient dynamics, crop performance, and sensor readings obtained during the experiment. The particle size distribution shows that the soil consisted of 11.00% sand**,** 68.80% clay**,** and 20.20% silt**,** classifying it as a clayey soil**.** Clay soils are characterized by high nutrient-holding capacity due to their large surface area and negative charge, but they often exhibit poor aeration and drainage. This property is particularly important for cowpea cultivation and for evaluating the responsiveness of the developed device, as high clay content influences ion mobility and moisture retention-factors that affect sensor performance.

High clay content restricts ion mobility in soils by increasing the specific surface area and net negative charge, which enhances cation exchange capacity (CEC). This results in strong adsorption and immobilization of essential nutrients and heavy metals, preventing them from leaching into groundwater (Abdulgadir *et al.,* 2023). The soil recorded a moisture content of 13% and a temperature of 29°C**,** both within favorable ranges for cowpea germination and early growth. The organic carbon (0.87%) and organic matter (1.6%) were relatively low, indicating limited natural nutrient mineralization potential. Organic matter plays an important role in soil structure, cation exchange capacity, and long-term nutrient supply. Thus, the low values imply the need for supplemental fertilization to support optimal crop growth. The soil pH of 6.32 falls within the slightly acidic range, which is suitable for most tropical legumes, including cowpea. This pH favours the availability of essential nutrients such as nitrogen, phosphorus, and micronutrients. Slight acidity also ensures better microbial activity, promoting root development and nutrient uptake. The pH range further supports the accuracy of sensor readings since extreme pH values can affect ion concentration and sensor response. The macronutrient values showed 0.097% nitrogen (equivalent to 970 mg/kg)**,** which falls within the medium fertility range for agricultural soils but may still be inadequate for vigorous cowpea production. Phosphorus (8.30 mg/kg) was in the low category, indicating limited availability due to fixation in clay-rich soils. Exchangeable potassium**,** converted from 0.28 cmol/kg to 109.50 mg/kg**,** lies in the low-to-medium range, suggesting that K supplementation would be beneficial. These values justify the application of NPK fertilizer in the experiment and provide a strong baseline for evaluating the device's performance in detecting nutrient changes. The exchangeable cations of Ca (3.15 cmol/kg) and Mg (2.90 cmol/kg)—indicate moderate levels typical of tropical soils with significant clay content. Micronutrient concentrations, including Zn (4.65 mg/kg)**,** Cu (4.90 mg/kg)**,** Mn (1.70 mg/kg)**,** Fe (8.70 mg/kg)**,** and B (0.034 mg/kg)**,** fall within acceptable ranges for legume cultivation. These values confirm that the soil does not suffer major micronutrient deficiencies, allowing the experiment to focus primarily on macronutrient (NPK) dynamics. The fertility indices of exchangeable bases (EB = 6.58%)**,** exchangeable acidity (EA = 1.12%)**,** and cation exchange capacity (CEC = 7.70%) indicate a moderate nutrient retention capacity**,** consistent with clayey soils. A base saturation

of 85.45% suggests that most exchange sites are occupied by essential base cations rather than acidic ions, providing a favorable chemical environment for crop growth.

Thus, baseline of the soil properties demonstrated that while the soil is structurally rich in clay and capable of holding nutrients, its macronutrient levels especially phosphorus and potassium are marginal and require supplementation. These characteristics provided a suitable test environment for the developed automated nutrient detection device, allowing assessment of its ability to track nutrient changes accurately under real cultivation conditions.

3.2.2 Calibration and response behaviour of the device under (NPK 15-15-15) solutions

The nutrient solution analysis presented in Table (9) demonstrates the concentration of nitrogen (N), phosphorus (P), and potassium (K) detected by the developed automated soil nutrient device when different quantities of NPK 1515-15 fertilizer of 5 to 10 g were dissolved in 500 ml of distilled water. The results provide important insight into the device's sensitivity, linearity,and response behaviour under controlled conditions.

A key observation is that nitrogen levels showed a progressive increase from 785 mg/kg in Solution A (5 g) to 1999 mg/kg in Solution E and F (9–10 g)**.** This indicates that the device effectively detected the increase in N concentration as fertilizer quantity increased. The sharp rise at higher concentrations suggests that nitrogen was more freely soluble and more easily detected in solution form, validating the functionality of the nitrogen sensor component.

Phosphorus and potassium values reached maximum detectable limits of 1999 mg/kg, beginning from Solution B (6 g) through Solution F. This concentration mesa indicates that the device readings for P and K reached the upper detection threshold of the sensor at approximately 1999 mg/kg. This behaviour is characteristic of sensors that have a fixed maximum measurable concentration, meaning that beyond this point, increases in fertilizer concentration do not reflect proportionally in the output. This finding is important for calibration, as it defines the upper limit at which the device can accurately quantify P and K.

The pH values showed a gradual decline from 6.9 in Solution A to 5.20 in Solution F, demonstrating the acidifying effect of higher fertilizer concentrations. NPK fertilizers, especially those containing ammonium-based nitrogen, are known to reduce pH as solubility increases. This confirms that the device correctly captures pH variations associated with nutrient concentration changes, which is essential for understanding soil acidity responses during real field use. Temperature remained constant at 25.4°C, and moisture was at 100% in all solutions because these were controlled solution-based tests rather than soil tests. This stability validates that fluctuations in NPK values were not influenced by temperature or moisture interference, ensuring that readings reflected true nutrient responses. Thus, the simulation results demonstrate that the developed device is highly responsive to increasing concentrations of nitrogen**,** shows maximum range limitation for phosphorus and potassium sensors, and effectively detects pH variations associated with fertilizer dissolution. These findings confirm the device's functionality under controlled conditions and provide baseline calibration data necessary for interpreting its behaviour when deployed in field soil conditions.

4.0 CONCLUSION

This study successfully developed and evaluated an automated device capable of detecting key soil macronutrients of Nitrogen (N), Phosphorus (P), Potassium (K), and pH, temperature, and soil moisture content. The device demonstrated strong sensitivity, accuracy, and reliability in both controlled fertilizer simulations and real soil conditions. Laboratory analysis showed that the experimental soil was clay-rich with low macronutrient levels particularly phosphorus and potassium highlighting the need for fertilizer supplementation.

The NPK fertilizer simulation confirmed the device's responsiveness, with nutrient readings increasing in line with fertilizer concentrations and accurately identifying the detection thresholds for phosphorus and potassium sensors. When tested in field soil during cowpea cultivation, the device effectively tracked weekly nutrient changes, showing clear nutrient decline patterns as plants absorbed available N, P and K.

The overall results showed that the developed automated soil nutrient detection system is a practical, low-cost, and reliable tool for real-time soil fertility monitoring. Its ability to track nutrient dynamics throughout the crop cycle makes it valuable for farmers, agronomists, and researchers. The device supports precision agriculture by improving fertilizer decision-making, enhancing nutrient use efficiency, and promoting sustainable crop production.

Its recommended further improvements should incorporate data logging and expanded micronutrient detection (e.g.,Zn, Fe, B, Mn), cation exchange capacity (CEC), and electrical conductivity (EC) to broaden its diagnostic capabilities in one operation.

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Paper ID 24:
Expanded Polystyrene Packaging for Cold Chain Applications: Performance, TradeOffs, and Alternatives-A Review

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ABSTRACT

Expanded polystyrene (EPS) is the default choice wherever packaging needs to be light, cushioning, and thermally resistant, fitting a wide range of food and temperature-sensitive distribution systems. Yet its fossil origin, environmental persistence, and the patchy state of recovery infrastructure in many regions raise real questions about how sustainable its choice is. Rather than judging EPS as a standalone material, this review treats it as an integrated postharvest packaging system, shaped as much by package design, commodity behavior, cooling arrangements, and transport conditions as by the polymer itself. EPS is compared against moulded-fibre, biobased, agro-residue-derived, mycelium-based, and reusable alternatives on criteria that matter in practice. examined. The study examined thermal protection, mechanical performance, moisture response, structural integrity, material efficiency, logistics, reuse and recycling potential, life-cycle impact, and economic feasibility. Evidence drawn from peer-reviewed literature and authoritative technical sources on fresh produce, fish and seafood distribution, cold chain logistics, and circular packaging systems points to a consistent conclusion: EPS earns its keep when properly designed and paired with adequate pre-cooling, but its environmental performance depends on collection, transport, recycling, reuse, and disposal conditions. None of the alternatives escape this logic; judge a material as sustainable not by what it is made of, but by how it performs against EPS under matched commodity and supply-chain conditions. A performance-resource-environment framework is proposed to guide decisions on when to select, redesign, reuse, recycle, or replace EPS in climate-resilient postharvest systems.

***KEYWORDS**:* sustainability; life-cycle assessment; circular economy; agricultural value chains; alternative packaging.

1. INTRODUCTION

There is no amount of successful agricultural production that guarantees food security if a meaningful share of what's grown deteriorates or is lost before it ever reaches a plate (Food and Agriculture Organization of the United Nations [FAO], 2011; Hodges et al., 2011). Postharvest losses don't just shrink food availability and farmer income; they waste every input, land, water, energy, and labour that went into producing the food in the first place. That's precisely why postharvest technologies sit at the centre of any serious conversation about climate-resilient food systems, particularly in developing countries where better handling, packaging, storage, and distribution can meaningfully cut avoidable losses and strengthen agricultural value chains, as reported by Kitinoja et al. (2011). It's also directly relevant to building climate-resilient and smart agricultural systems for sustainable food security and agro-industrial growth. Packaging does more engineering work in a postharvest system than it often gets credit for. Depending on the commodity and the distribution environment, it provides containment, mechanical protection, thermal resistance, moisture control, and logistical efficiency. Impact, compression, and vibration during handling and transport can quietly erode the quality and marketability of fresh produce, which is exactly why package design and cushioning deserve to be treated as genuine engineering interventions rather than afterthoughts. (Al Dairi et al.,2022); Lin et al.,2023). Expanded polystyrene (EPS) has earned its place in this space largely because its cellular structure combines low density, energy absorption, and insulation in one material, a useful trifecta for protective and temperature-sensitive packaging (Lu et al., 2023; Seid et al., 2025). But it would be a mistake to read EPS's performance straight off its intrinsic material properties. What actually happens to a shipment depends on package geometry, wall thickness, foam density, closure design, how the product is loaded and stacked, the cooling setup, and the realities of the supply chain it travels through (Kassim et al., 2023)

At the same time, EPS carries sustainability baggage that's hard to ignore. Its fossil origin, its tendency to linger in the environment, and the practical difficulty of collecting and recovering it have all added up to growing pressure to cut back on or replace it. Recycling pathways, both mechanical and chemical, do exist. But whether they translate into real circularity depends on collection, sorting, contamination levels, densification, processing infrastructure, and the economics of what comes out of the other end, as reported by Ragaert et al. (2017). In other words, EPS's sustainability credentials can't be settled by material classification alone; they have to be evaluated at the system level. A growing set of alternatives such as moulded fibre, bio-based polymers, agricultural-residuederived materials, mycelium-based packaging, and reusable containers are being developed and tested in response. But being biodegradable, recyclable, or plant-derived doesn't automatically make a material environmentally superior. What matters is whether it can deliver the packaging function required under the commodity, environmental, and logistical conditions at hand. The

comparative life-cycle evidence bears this out: reusable systems and bio-based alternatives can outperform single-use EPS in some contexts. Nevertheless, the outcome hinges on the functional unit chosen, the material quantities involved, transport, reuse cycles, dimensions, and end-of-life scenario (Enarevba & Haapala,2023; Hilmarsdóttir et al.,2024). This nuance matters especially in tropical, resource-constrained postharvest systems, where packaging has to cope with high ambient temperatures, long transport distances, rough handling, cold chains that cut in and out, and recycling infrastructure that may barely exist (Hoffmann et al., 2025). So, the real engineering question isn't whether EPS "works" or whether it's "bad for the environment rather, *"Under what postharvest and cold chain conditions does EPS packaging provide sufficient functional benefit to justify its environmental burden, compared with technically feasible alternatives?"* With that question as the anchor, this review sets out to:

i. examine the thermal, mechanical, moisture-related, and logistical properties of EPS relevant to cold chain packaging
ii. evaluate how package design and supply chain conditions shape EPS performance in practice;
iii. weigh the environmental and end-of-life trade-offs that come with EPS use;
iv. compare EPS against selected alternative packaging systems on functionally relevant engineering criteria; and
v. build a performance-resource-environment framework for application-specific postharvest packaging decisions.

The central contribution here is treating EPS as an integrated postharvest packaging system, not merely as a material to be praised or condemned in isolation.

MATERIALS AND METHODS

Review design

This article follows a structured critical review design, examining the engineering performance, sustainability trade-offs, and alternatives associated with EPS packaging in temperature-controlled food distribution systems. The evidence was considered at three linked levels: material properties, package performance, and supply chain outcomes. Because the studies reviewed varied widely in commodity, package design, test conditions, functional units, and outcome measures, this was never going to work as a systematic review or meta-analysis, and it wasn't attempted as one.

Research question

The primary research question guiding the review was:

Under what postharvest and cold chain conditions does EPS packaging provide sufficient functional benefits to justify its environmental burdens compared with technically feasible alternatives?
Five subsidiary questions shaped the inquiry:

1. Which engineering properties of EPS contribute to thermal buffering and mechanical protection?
2. How do package design and supply chain conditions influence EPS performance?
3. Which environmental and end-of-life factors limit EPS sustainability?
4. Which alternative packaging systems offer comparable functions?
5. What criteria should guide the decision to retain, redesign, reuse, recycle, or replace EPS?

Literature identification

Literature was identified through searches of Scopus, Web of Science, and Google Scholar up to August 2026, using combinations of the following terms: "expanded polystyrene" OR EPS; packaging OR container OR box; postharvest OR fresh produce OR fresh cut OR fruit OR vegetable; food OR fish OR seafood; cold chain OR transport OR logistics; thermal insulation; mechanical protection; recycling; circular economy; and sustainable packaging. Searches were restricted to English-language publications. Supplementary searches through institutional repositories and the reference lists of key reviews helped catch relevant studies the main database searches missed.

Eligibility criteria

Sources were included if they examined EPS or a functionally comparable packaging system; addressed thermal, mechanical, moisture-related, structural, environmental, or logistical performance; related to food, agriculture, postharvest handling, or temperature-controlled distribution; provided enough methodological or analytical detail to be useful; and were either peer-reviewed publications or authoritative institutional sources. Duplicate publications, promotional material presented as scientific evidence, incomplete or unverifiable references, studies unrelated to packaging function, and unsupported claims about material performance were all excluded.

Evidence synthesis

Information was extracted under three evaluation dimensions. Functional performance covered thermal resistance, temperature history, cooling retention, impact protection, compression resistance, stacking strength, vibration response, moisture resistance, and structural integrity. Resource and operational performance covered material quantity, package mass and volume, logistics efficiency, durability, reuse potential, availability, scalability, and economic feasibility. Environmental performance covered life-cycle impacts, fossil-resource dependence, collection, recycling, circularity, environmental leakage, and realistic end-of-life pathways. Given how much the reviewed studies differed in commodities, package designs, test conditions, functional units, and outcome measures, the findings were synthesized narratively rather than pooled statistically. Where the evidence base is indicative rather than exhaustive, this is flagged with language such as "the reviewed literature suggests."

RESULTS

EPS as an engineered packaging system

EPS is a lightweight cellular polymer whose behavior comes largely from its foam structure. Low density keeps package mass down; the cellular architecture supplies thermal resistance and energy absorption. Together, these properties explain why EPS has become so widespread in packaging and insulation (Lu et al.,2023; Seid et al..2025). But its relevance to postharvest systems really plays out at three levels. At the material level: density, cellular structure, thermal conductivity, compressive behavior, moisture response. At the package level: wall thickness, geometry, closure design, stacking configuration, product loading, cooling setup. At the supply chain level: ambient temperature, storage duration, transport vibration, handling, commodity characteristics, stack height, and cold chain conditions. A good material property, in other words, doesn't automatically hand you good package or postharvest performance.

Thermal performance

EPS's core thermal job is to slow heat transfer. It shouldn't be described as something that "maintains temperature" or actively cools a product, because it does neither. What happens to temperature inside an EPS package depends on insulation thickness, foam density and thermal properties, package geometry, the product's starting temperature, ambient conditions, how much refrigerant or ice is used, product loading, air movement, and how long the journey takes Kucharek et al.,2020). Cevoli and Fabbri (2017) used experimentally validated finite element modelling to show that the thermal behavior of insulated food packages tracks material properties, geometry, dimensions, and boundary conditions together, not any one of them alone. For perishable commodities, cutting heat transfer can help keep a product closer to its target temperature range for longer, but only when adequate pre-cooling and cooling resources are already in place. EPS on its own cannot rescue an inadequately pre-cooled shipment or paper over a broken cold chain. The engineering indicators worth tracking, then, are thermal resistance, heat transfer rate, temperature rise rate, cooling retention time, and the product's actual temperature history.

Mechanical protection

Fresh commodities take a beating during handling and transport: impact, compression, vibration, and abrasion, damage that can quietly undercut both marketability and quality (Al Dairi et al., 2022; Lin et al., 2023). EPS cushions because its cellular structure deforms and absorbs some of the energy from impact and loading. But three distinct functions get lumped together too often: impact cushioning, compression and stacking resistance, and vibration response. Lu et al. (2023) tested EPS boxes at densities of 22 and 23 kg/m³ and found that even small density increases produced substantial gains in material-level modulus and compressive strength, though the link to whole-box stacking strength was less direct. The practical takeaway for postharvest package design isn't "pick the strongest EPS available," but rather to tune foam density, wall thickness, geometry, and loading configuration together for the right balance of protection, structural performance, and material efficiency.

Moisture resistance and package stability

Yuan et al. (2026) reported that EPS is relatively insensitive to moisture compared to more hydrophilic packaging materials, but "relatively insensitive" is a long way from "waterproof." Water absorption shifts with density, cellular structure, specimen geometry, exposure duration, and testing conditions (Gnip et al., 2006). In real postharvest systems, package performance can also hinge on joints, closures, liners, and drainage, details that matter most in high-humidity environments, under condensation, or wherever melted ice and wet handling are routine (Lufu et al., 2021). The whole package system, not the foam alone, needs to be evaluated under conditions that resemble actual service.

Lightweight design and logistics

Low density lets EPS packages offer relatively large protective or insulating volumes without much material weight, which helps with manual handling and can improve transport efficiency wherever mass is the limiting factor. But low package mass isn't automatically good news environmentally or logistically. Transport performance depends on mass and volume together, plus cube utilization, stacking efficiency, transport distance, the product-to-package ratio, and return logistics (He et al., 2018). Hilmarsdóttir et al. (2024) found that reusable tubs showed lower environmental impacts than single-use EPS boxes in a specific fresh-fish export scenario, though that result was tied closely to the system studied, shaped by material mass, package dimensions, and how many times the tubs were actually reused. The lesson is to optimize packaging mass rather than chase minimization for its own sake.

Fresh fruits and vegetables

Fresh fruit and vegetables face mechanical damage, temperature swings, and water loss during distribution (Gbabe et al., 2025). Dunno et al. (2021) compared moulded-fibre and EPS trays for whole apples and found that, under the conditions tested, EPS trays cut impact acceleration and bruise susceptibility substantially more than moulded fibre did. Tray position still mattered, though, which is the important caveat here: EPS can cushion effectively, but the choice of material alone doesn't eliminate mechanical damage. Package geometry, how the product is arranged, and the hazards of the distribution route all still count. Because the study used whole apples, its findings shouldn't be lifted wholesale and applied to tropical fruit without commodity-specific validation.

Fish and seafood distribution

EPS boxes turn up frequently in temperature-sensitive fish and seafood distribution, particularly in export-oriented and industrial supply chains, largely because they insulate well while still accommodating ice or other cooling media. Tryggvason et al. (2020) tested insulated containers of varying depths alongside EPS boxes for iced and superchilled Atlantic salmon, and found that container configuration and cooling conditions together shaped quality and yield outcomes. EPS's job here is really just to slow heat transfer and offer physical protection; it doesn't supply cooling capacity on its own. Passive EPS packaging, in other words, only works where it's paired with an appropriate cooling system whenever low product temperatures are required.

Cold chain systems

EPS commonly forms part of passive insulated packaging systems, and how well such a system performs thermally depends on the interplay between insulation, refrigerant, package geometry, product loading, transport duration, and outside conditions. So the useful engineering question isn't "Is EPS a good insulator?" but rather: "Can the complete packaging system hold the required product temperature for as long as the distribution actually takes?" That distinction matters most in tropical supply chains, where high ambient temperatures, patchy electricity supply, and unpredictable transport duration are the norm rather than the exception.

Life cycle perspective

Desole et al. (2024) noted that life cycle assessment gives a structured way to evaluate environmental impact across defined stages of a product or packaging system, from raw material production and polymer manufacture through transport, use, collection, recycling or recovery, and final disposal. But packaging shouldn't be assessed in isolation from the food it protects. Hemachandra et al. (2024) reviewed food packaging life-cycle assessments that explicitly accounted for packaging-related food waste, and showed why the relationship between packaging function and food waste needs to be folded into sustainability assessments rather than treated as a footnote. So the environmental burden of packaging has to be weighed alongside its function and its demonstrated effect on product protection. Comparisons need a clearly defined functional unit: comparing one kilogram of EPS with one kilogram of an alternative material can be scientifically misleading when the two materials need different masses to deliver the same protective function.

A more defensible comparison looks at the packaging required to protect a defined quantity of a specified commodity through a defined storage and distribution scenario.

Packaging and food loss prevention

Cutting avoidable food loss improves resource-use efficiency, since every unit of food embodies land, water, energy, labour, and other inputs that went into producing it. Packaging can contribute to that goal when it genuinely prevents mechanical damage, thermal deterioration, or quality loss that would otherwise occur. But that environmental benefit can't just be assumed; it depends on how the environmental burden of the packaging stacks up against the quantity and type of loss it actually prevents. Licciardello (2017) made a similar point, arguing that both packaging's own impacts and its potential role in preventing food waste need to be weighed together. EPS, in short, shouldn't be credited with automatically reducing food loss or extending shelf life; that contribution has to be demonstrated under defined conditions of commodity, package design, loading, temperature, humidity, handling, and distribution duration.

Circular economy and end-of-life management

EPS draws a sharp line between technical recyclability and practical circularity. What actually happens at end of life depends on collection, sorting, contamination control, transport, densification and processing infrastructure, the quality of recovered material, and market demand for it. EPS's low bulk density adds its own wrinkle here: large volumes of lightweight material can be awkward and costly to collect and transport before any processing even begins. Kulakovskaya et al. (2023) applied an integrated environmental-economic circular-economy assessment to the EPS value chain, combining material flow analysis, life cycle assessment, life cycle costing, and scenario development, and found that recycling can deliver environmental and economic benefits, but only under particular conditions. Fitriasari et al. (2025) reached a similar conclusion evaluating chemical recycling pathways, finding potential economic and environmental benefits under the specific process configurations they modelled. Neither result should be read as evidence that EPS recycling is uniformly beneficial; the outcome depends on collection distance, feedstock quality, contamination, energy use, processing yield, plant scale, and downstream markets. The right end-of-life strategy, in other words, is always application-dependent.

Functional equivalence as the basis for comparison

A packaging alternative doesn't earn the label "sustainable" simply by being bio-based, biodegradable, recyclable, or fibre-derived, according to Moshood et al. (2022). The question that actually matters is whether the alternative can deliver the required function with acceptable environmental, technical, and economic performance. A material with a smaller environmental footprint per kilogram might need far more material to provide equivalent protection; conversely, a material with heavier manufacturing impacts might offer a longer service life, better reuse potential, or stronger product protection. Comparisons, then, need to rest on functional equivalence, not on material mass or material identity alone.

Mycelium-based packaging

Mycelium-based composites have emerged as one of the more interesting alternatives to petroleum-based packaging. Enarevba and Haapala (2023) compared EPS and hemp–mycelium packaging inserts through life cycle assessment and found that mycelium packaging performed better on some indicators, including energy demand and global warming potential, while trade-offs remained on others. That's a useful reminder that alternative materials need to be judged across multiple impact categories, for a clearly defined function, not on a single favourable metric. It's also worth noting that the study looked specifically at shipping-box inserts, not the full range of postharvest applications, so its conclusions shouldn't be generalized automatically to insulated food or fresh-produce containers.

Fibre-based and agro-residue packaging

Moulded pulp, paperboard, and other fibre-based materials are increasingly in the running as alternatives to conventional plastic packaging. Semple et al. (2022) reviewed moulded pulp for disposable food packaging and highlighted the growing use of non-wood fibres such as bagasse, wheat, and bamboo, alongside persistent challenges around processing, additives, moisture performance, and finding viable end-of-life pathways. For postharvest use, fibre-based and agro-residue packaging need to be judged on their ability to maintain structural integrity, mechanical protection, moisture resistance, and overall performance under the actual storage and transport environment they'll face. In tropical conditions especially, moisture uptake and loss of stiffness can become limiting factors unless coatings or hybrid designs are used to compensate.

Reusable packaging systems

Reusable packaging can lower environmental burdens per use, but only once enough service cycles are actually achieved. Its real-world performance depends on durability, cleaning requirements, reverse logistics, transport, how often packages get lost, reuse frequency, and energy use. Hilmarsdóttir et al. (2024) showed reusable packaging outperforming single-use EPS in a defined fresh-fish export scenario, but that doesn't make reusable systems universally superior; the outcome stays system-specific and application-dependent.

Performance-resource-environment framework

Deciding whether to keep or replace EPS calls for an integrated engineering framework built around three questions. Performance: can the packaging deliver adequate thermal protection, mechanical protection, moisture resistance, structural integrity, and safe, reliable containment? Resource: does it achieve these functions efficiently in terms of material consumption, mass, transport, durability, reuse, cost, and availability? Environment: what are the consequences for life-cycle impacts, fossil-resource use, collection, recycling, environmental leakage, and realistic end-of-life management? Framed this way, the decision was never really "EPS versus biodegradable packaging." It's EPS versus a functionally equivalent packaging system, operating under the same commodity, environmental, and logistical conditions (Kim et al., 2023).

Table 1. Comparative engineering criteria for postharvest packaging selection

Evaluation dimension	Key engineering question	Recommended assessment	Reference
Thermal performance	Can the package maintain the required product temperature?	Temperature profile, heat transfer rate, thermal resistance	Wang et al., 2020
Mechanical protection	Can it withstand impact, compression, and vibration?	Impact, compression, and vibration testing	Kim, et al. 2025
Moisture performance	Can it perform under expected humidity and wet conditions?	Water absorption, moisture resistance, dimensional stability	Mohammed et al., 2022
Structural performance	Can the package withstand stacking and handling?	Stacking and structural testing	Kueh et al., 2023
Material efficiency	How much material is required?	Mass and volume per functional unit	Baltrocchi et al., 2026
Logistics	What is the effect on transport and handling?	Mass, volume, stackability, cube utilisation	Badarudin et al., 2024
Product protection	Does the package protect commodity quality?	Commodity-specific quality and damage indicators	Zhang et al., 2025
Food loss prevention	Does it demonstrably prevent avoidable losses?	Loss, damage, and marketability data	Cervera et al., 2026
Reuse	Can the package safely complete multiple cycles?	Validated reuse cycles and cleaning requirements	Doostdar et al., 2026

Recycling	Can the material actually be recovered?	Collection, sorting, and recycling yield	Wu et al., 2026
End of life	What pathway is realistic?	Scenario-based system assessment	J. S. Lira & E. A. da Silva (2025).
Environmental impact	What are the total life-cycle burdens?	LCA using a defined functional unit	Aguinaga, D. A., & Benites Alfaro, E. G. (2026).
Economic feasibility	Is the system viable at the intended scale?	Cost and techno-economic analysis	Makepa et al., 2023

Evaluation dimension	Key engineering question	Recommended assessment	Reference
Infrastructure	Can the system operate within available facilities?	Collection, processing, and logistics assessment	Aung et al., 2025
Climate resilience	Does performance remain reliable under environmental variability?	Sensitivity to temperature, humidity, and handling conditions	M. N. Aghdam & M. K. Dixit (2026).

DISCUSSION

Engineering performance is system-dependent

Taken together, the reviewed literature makes a fairly strong case that EPS should be evaluated as an engineered packaging system, not as a material whose sustainability or performance can be settled in isolation. Its functional value emerges from the interaction of material properties, package design, commodity characteristics, and operating conditions. The same EPS material can behave quite differently depending on wall thickness, density, geometry, cooling configuration, stack height, and transport environment. (Royuela et al.,2026).

Climate-resilient postharvest application

To achieve climate-resilient postharvest systems, packaging design must adapt to severe logistical realities. Mehtab et al. (2026) argue that tropical distribution networks require packaging to withstand a combination of elevated ambient heat, high humidity, variable transit times, and intermittent power grids. Passive insulated packaging offers a viable buffer, but its efficacy depends entirely on adequate product pre-cooling, strategic refrigerant selection, and disciplined cold chain management. The performance-resource-environment framework introduced in this study addresses this challenge, providing a structured mechanism to balance thermal protection against resource constraints under volatile climate conditions.

Environmental and circularity trade-offs

Dolci et al. (2025) made the point plainly: sustainability can't be settled just by asking whether a package is plastic, bio-based, or biodegradable. A package that fails to protect its contents adequately can end up causing greater product loss, while a technically recyclable material can still have poor real-world recovery rates because collection or

processing infrastructure simply isn't there. The environmental benefit of any packaging system has to be weighed together with its demonstrated effect on product protection and food loss prevention

Implications for Nigeria and agro-industrial growth

In the Nigerian context, EPS and its alternatives need to be assessed against local packaging manufacturing, the state of cold chain expansion, collection and densification infrastructure, cooperatives and aggregators, fish and horticultural value chains, standards and testing facilities, and plain cost and availability(Zego & Husny,2023). Local fabrication of fibre-based and agro-residue packaging, building collection systems for EPS waste, and investing in pilot-scale testing facilities could all support agro-industrial growth while improving postharvest performance at the same time. None of this works in isolation, though; packaging decisions need to be integrated with broader investment in cold chain infrastructure, waste management, and agro-processing (Carnaval et al., 2024).

CONCLUSIONS

Expanded polystyrene remains an important material in postharvest and temperature-controlled food systems, and for good reason. Its low density, thermal resistance, and energy-absorbing structure genuinely deliver thermal buffering and mechanical protection. But that performance can't be assumed from material properties alone. Foam density, wall thickness, package geometry, product loading, cooling configuration, transport duration, and environmental conditions all determine what an EPS package actually achieves in practice. EPS doesn't provide active cooling; its contribution to temperature management only materializes alongside proper pre-cooling, refrigerants, and cold chain discipline. The environmental picture presents a similar systems challenge. Fossilresource dependence, persistent waste, and the practical difficulty of collection and recovery all deserve serious attention, but technical recyclability is not the same thing as practical circularity, and recycling outcomes remain hostage to infrastructure, economics, and operating conditions.

The same caution applies to the alternatives. Bio-based, biodegradable, fibre-based, mycelium-based, and reusable options shouldn't be assumed environmentally superior just because of what they're made from. Comparisons need to rest on functionally equivalent packaging performance under matched commodity and supply-chain conditions. The performance-resource-environment framework proposed here offers one way to make that comparison on engineering terms. Ultimately, sustainable postharvest packaging should be chosen for its ability to deliver the product protection and quality performance required, while minimizing total resource and environmental burden across its full life cycle. Future research would do well to move past simple material substitution and toward integrated, application-specific packaging design, combining experimental performance testing, package engineering, commodity trials, life cycle assessment, techno-economic analysis, and realistic end-of-life evaluation.

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Paper ID 25:
Performance Evaluation of an Improved Traditional Rice Husk-Fired Parboiler

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ABSTRACT

Small-scale processors often rely on traditional paddy rice parboilers that come with issues like low thermal efficiency, a heavy dependence on firewood, and operational constraints that can compromise rice quality. This study set out to create and test a better version of the traditional paddy rice parboiler, using rice husk as the main energy source while using firewood as a control. The upgraded parboiler includes an insulated combustion chamber, a stainless-steel soaking and steaming vessel with a false bottom, dual gate valves for independent drainage of soaking and steaming water, and a specific outlet for paddy discharge. These features are designed to enhance heat utilization, improve safety during operation, and boost overall process efficiency. Performance evaluation was conducted using a Completely Randomized Design with three replications to examine how the energy source (Rice Husk, Firewood), soaking temperature (50, 60, and 70°C), and soaking time (10, 14, and 18 hours) influence milling yield. The variance analysis indicated that energy source, soaking temperature, soaking time, and their interaction effects all had a significant impact ($P < 0.05$) on milling yield. Among the factors studied, soaking temperature was the most influential. The highest average milling yield of 67.1 % was achieved at 60°C, while firewood yielded a slightly better overall mean of 65.1 % compared to rice husk's 64.1 %. Interaction analysis revealed that the top milling yield of 71.0 % came from treatment $E_2T_2S_1$ (firewood, 60°C, 10 hours), whereas the best result for rice husk $E_1T_2S_2$ (Rice Husk, 60°C, 14 hours) was 65.9 kg, indicating that rice husk can match the performance of conventional fuels under the right conditions. These results show that the improved traditional paddy rice parboiler effectively controls the hydrothermal process and allows for the productive use of rice husk as a renewable biomass fuel without a significant drop in milling performance. This technology offers a viable and sustainable alternative for small- and medium-scale rice processors, reducing reliance on conventional firewood as energy source

Key Words: Rice husk**,** improved traditional parboiler; Milling yield; Hydrothermal treatment; Paddy rice;

1. INTRODUCTION

Rice *(Oryza sativa* L.) is a common food for many around the world, acting as a primary source of dietary energy for more than half of the global population (IRRI, 2023). Rice consumption has increased substantially in Nigeria over the past decades, driven by population growth, urbanization, and changing consumption patterns (Mendez del Villar & Lançon, 2015; Nzeka, 2019).. Consequently, improving the quality and efficiency of local rice processing has become a priority for enhancing food security, increasing farmers' incomes, and reducing dependence on imported rice.

Parboiling is a hydrothermal treatment applied to paddy rice before milling, it aimed at enhancing grain quality, minimizing breakage during milling, and improving nutritional retention (Bhattacharya, 2004; Danbaba *et al.*, 2014). The process usually involves soaking the paddy in hot water, steaming it, and then drying it out before milling. During the soaking and steaming stages, starch granules gelatinize, and any cracks in the kernels are partially repaired, resulting in stronger grains that are less prone to breakage during milling (Bhattacharya, 2004; Graham-Acquaah *et al.,* 2015). As a result, proper parboiling is crucial for achieving higher milling yields and better head rice recovery (Ndindeng *et al.*, 2015; Ahmed *et al.,* 2023).

The quality of parboiled rice is significantly affected by the conditions under which it is processed. Some of the most critical factors include the soaking temperature, soaking duration, and the type of thermal energy used during the parboiling process (Soponronnarit *et al.,* 2006; Danbaba *et al.,* 2014). Proper soaking conditions are essential for ensuring that moisture penetrates the grain effectively, while adequate steaming is key for achieving complete starch gelatinization. If the processing is not done correctly whether it is too little or too much it can lead to problems like incomplete gelatinization, excessive cracking of the grains, or poor milling results (Bhattacharya, 2004; Bello *et al.,* 2015).

In Nigeria, many small-scale processors rely on traditional rice parboilers that often suffer from low thermal efficiency, uneven heat distribution, high fuel usage, and significant heat loss to the environment (Danbaba *et al.,* 2014; Ndindeng *et al.,* 2015). These issues frequently result in inconsistent parboiling quality and lower milling recovery rates. Additionally, the heavy dependence on firewood not only drives up production costs but also contributes to depletion of forest resources (Islam, 2003).

Rice husk, an abundant by-product of rice milling, represents a promising alternative energy source for parboiling operations (Islam, 2003). Large quantities of rice husk are generated annually in rice-producing regions, yet much of

it remains underutilized or is disposed of through open burning. Each year, rice-producing regions generate significant amounts of rice husk, yet much of it is either wasted or burned in the open air. By harnessing rice husk as a combustion fuel, waste can be managed in an environmentally friendly way, reduce our reliance on conventional biomass fuels, and cut down on processing costs. The creation of improved traditional parboilers that can efficiently utilize rice husk is therefore a compelling solution for sustainable rice processing, particularly for small- and medium-sized processors.

Previous research has explored how different parboiling conditions impact rice quality (Bhattacharya, 2004; Danbaba *et al.*, 2014; Graham-Acquaah *et al.*, 2015), there is still a gap or limited information is available on the combined effects of energy source, soaking temperature, and soaking time on the milling yield of paddy rice processed using an improved traditional parboiler specifically designed for rice husk combustion. Grasping these connections is crucial for identifying the optimal operating conditions to boost milling performance. To address these limitations, an improved traditional paddy rice parboiler was developed in this study to utilize rice husk as its primary energy source. This machine was intended to improve thermal performance, enhance operational convenience, and promote the efficient utilization of rice husk as a renewable biomass fuel for sustainable paddy rice processing.

2. THEORETICAL ANALYSIS

2.1 Heat Requirement

Thermal energy was estimated from the sensible heat required to raise 350kg of paddy rice and 455kg of soaking water to the desired soaking temperature as;

$Q = M_P C_P \Delta T + M_W C_w \Delta T = 185430$ kJ

Where; Q = Total theoretical energy requirement (kJ); M_p =Mass of paddy rice (kg); C_p =Speccific heat capacity of paddy (1.63kJkg^{-1} ^{0}C^{-1}) Zhang et al, (2024); M_w = Mass of soaking water (kg); C_w = Specific heat capacity of water; (4.200kJkg^{-1}k^{-1}); ΔT= Temperature rise [final – initial temperatures (100-25 ^{0}C)]

$C_p = 1.180 + 3.766 M_{wb}$ Zhang *et al.*, (2024).

At the initial moisture content of **12%**, the calculated specific heat capacity of paddy rice was 1.63 kJ kg^{-1} K^{-1}.

2.2 Paddy Rice Discharging Outlet

The Hagen-Beverloo empirical equation was used to determine the required outlet diameter for gravity flow (Beverloo *et al.*, 1961). The model has been validated in subsequent granular-flow studies (Serano e*t al.*, 2019).

$Q = C\rho_b \sqrt{g}\,(D - kd)^{\frac{5}{2}} [\tan^{-1}\frac{D}{w} - \theta_r] = 0.11m$

$Q_{req} = \frac{M}{t} = 1.167 kg/s$

Where; Q_{req} = Required mass flow rate (kg/sec); M = mass of paddy to emptying (350 kg); t = Targeted emptying time (300 sec)

3. MATERIALS AND METHODS

3.1 Description of The Developed Parboiler

The developed parboiler uses rice husk as the primary energy source, with firewood as the control. The stainless-steel soaking consists of the soaking and steaming chambers separated by a false bottom. Other components attached to the vessel are drainage valves for draining soaking water before parboiling, A paddy rice discharge outlet located on the wall of the vessel but at the level with the false bottom for discharging of parboiled paddy rice. The whole vessel was mounted above an insulated rice husk combustion chamber (Figure 3.1). The chamber has a steel-mesh air intake and feeding ports for rice husk charging. The system has a batch capacity of 350 kg of paddy rice. The constructed improved traditional paddy rice parboiler was as shown in Plate 3.1 below.

3.1 Materials used for the Fabrication

The materials selected for construction of the parboiler and the stoves were selected based on their strength, availability, durability and cost in the local market. Food grade stainless steel sheet and screen was used for the soaking drum and false bottom, Mild steel bars, angle iron and sheets were used for the combustion chamber

3.2 Determination of the Volume of the Soaking Vessel

The volume of the soaking vessel was determined as follows;

Total volume of paddy : $V_{ab} = V_a + V_b = 0.62m^3$

Where $(V_a) = \frac{m}{\rho} = 0.562m^3$ = *volume of paddy rice*; $(V_b) = 10\%\ V_a = 0.05618\ m^3$ = Additional volume for expansion.

Soaking water requirement as 1.3 × paddy mass = 1.3 × 350 = 455 kg (Taleon *et al.*, 2022).

Thus, the volume of soaking water was $V_w = \frac{M_W}{\rho_w}(m^3) = \frac{455}{1000} = 0.455m^3$

Hence the soaking vessel capacity was determined as approximately; $V_{SC} = V_{ab} + V_w = 1.m^3$

3.3 Determination of Paddy discharging outlet

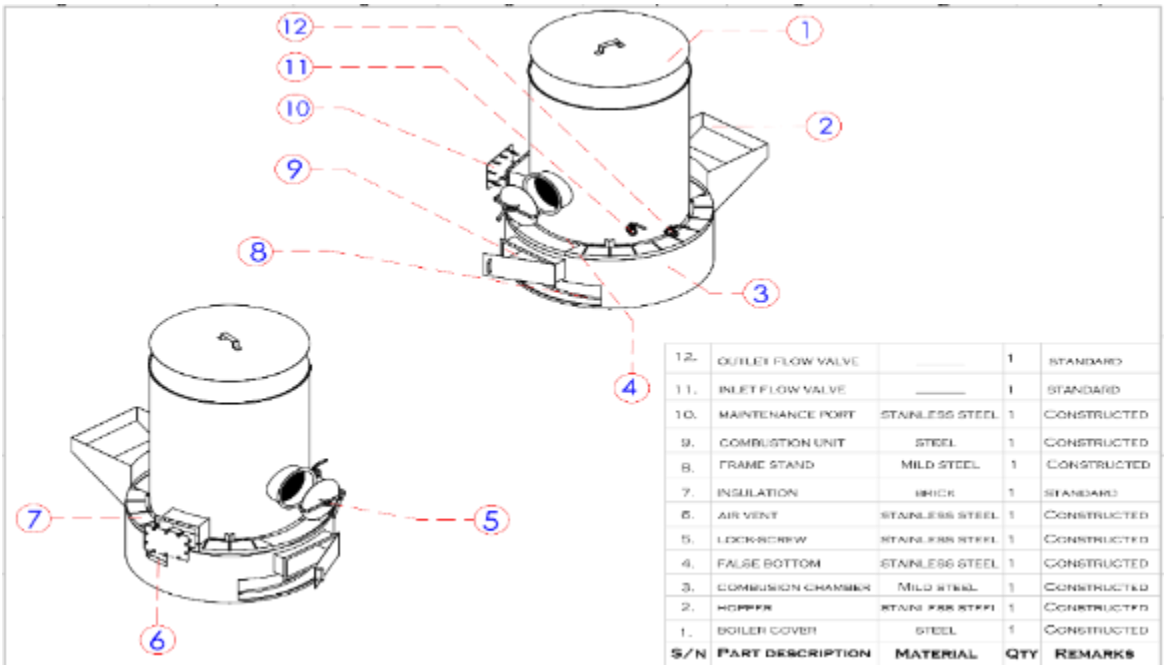
The outlet was sized for a target discharge time of 300 s at a required mass flow rate of 1.17 kg s^{-1}. The theoretical outlet diameter, calculated using the Hagen-Beverloo relationship for a gravity-flow for granular discharge through vertical side walls (Serrano et al, 2019), was taken as the minimum diameter under ideal flow conditions. Considering the higher moisture content and associated inter-particle friction of freshly parboiled paddy, the outlet diameter was increased to 0.21 m to facilitate practical gravity discharge.

3.4 Determination of the Combustion Chamber

$V_S = V_C + V_b = 0.2304m^3$

Where; $V_C = \pi r^2 h_C = 0.1244m^3$ (The cylindrical volume formed by the mud brick wall enclosure)

$V_b = \frac{1}{3}\ h_b(B_1 + B_2 + \sqrt{B_1 B_2}) = 0.106m^3$ (The lower ash collection chamber formed at the base of the chamber.)



S/N	PART DESCRIPTION	MATERIAL	QTY	REMARKS
12.	OUTLET FLOW VALVE	———	1	STANDARD
11.	INLET FLOW VALVE	———	1	STANDARD
10.	MAINTENANCE PORT	STAINLESS STEEL	1	CONSTRUCTED
9.	COMBUSTION UNIT	STEEL	1	CONSTRUCTED
8.	FRAME STAND	MILD STEEL	1	CONSTRUCTED
7.	INSULATION	BRICK	1	STANDARD
6.	AIR VENT	STAINLESS STEEL	1	CONSTRUCTED
5.	LOCK-SCREW	STAINLESS STEEL	1	CONSTRUCTED
4.	FALSE BOTTOM	STAINLESS STEEL	1	CONSTRUCTED
3.	COMBUSION CHAMBER	MILD STEEL	1	CONSTRUCTED
2.	HOPPER	STAINLESS STEEL	1	CONSTRUCTED
1.	BOILER COVER	STEEL	1	CONSTRUCTED

Figure 3.1: Isometric view of the developed parboiler

Plate 3.1: The improved traditional paddy rice parboiler

3.5 Experimental Design

A 3x3x2 factorial experiment in a complete randomized design (CRD) was used to evaluate the effects of the factors on the parboiler performance. Three levels of soaking temperature (T_1 - 50, T_2 - 60 and T_3 - 70 ^oC), three levels of soaking times (10h, 14h and 18h), and two energy sources (E_1 – Firewood and E_2 – Rice husk) were used. The experiment units were repeated three times. The data collected were analysed using Statistical Analysis Software (SAS), and Mean separation was done for the significant factors using Duncan Multiple Range Test (DMRT). The effects of the variation of each of three independent factors and their interactions on the performance of the improved parboiler were verified at 5 % levels of probability using the analysis of variance (ANOVA) Milling yield was used as one of the performance indicators of the parboiler. It was determined by weighing the total mass of milled rice recovered after processing the parboiled paddy. The milling yield was calculated as the ratio of the mass of milled rice recovered to the initial mass of paddy rice processed, expressed as a percentage:

$$Milling\ yield\ (\%) = (M_R / M_P) \times 100)$$

where M_R is the mass of milled rice in kg and M_P is the mass of paddy rice in kg. The total paddy rice parboiled per batch with the parboiler was 350kg

4. RESULTS AND DISCUSSION

4.1 Effect of Energy Source, Soaking Temperature and Soaking Time on Milling Yield

The analysis of variance (Table 4.1) showed that soaking temperature had the strongest significant effect ($P<0.05$) on milling yield, followed by energy source and soaking time. This indicates that the choice of energy source and the conditions used for soaking influenced the amount of milled rice recovered after parboiling. This agrees with Bhattacharya (2004), Danbaba et al. (2014), and Graham-Acquaah et al. (2015), who reported that appropriate soaking and steaming conditions improve moisture absorption, starch gelatinization, and kernel strength, thereby enhancing milling recovery. Thus, the significant effect of soaking temperature and time shows that milling yield responded to changes in soaking temperature, and soaking durations.

The significant interactions among energy source, soaking temperature and soaking time further indicate that the response of milling yield to one factor depended on the levels of the other factors. This indicates that hydrothermal processing variables shouldn't be optimized in isolation. Rather, the effectiveness of each variable is influenced by

the levels of the others This interaction is illustrated in Figure 4.1 where the response varied across the three soaking durations and between the two energy sources.

Table 1: Analysis of variance (ANOVA) for the effects of energy source, soaking temperature and soaking time on milling yield from the improved traditional paddy rice parboiler.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Rep	2	135.3708980	67.6854490	11972.9	<.0001**
Energy	1	13.5300167	13.5300167	2393.33	<.0001**
SoakingTemp	2	199.7707000	99.8853500	17668.8	<.0001**
Soaking Time	2	1.4349000	0.7174500	126.91	<.0001**
Energy*Temp	2	56.6192333	28.3096167	5007.71	<.0001**
Energy*Time	2	2.2482333	1.1241167	198.85	<.0001**
Temp*Time	4	15.3368000	3.8342000	678.23	<.0001**
Energy*Temp*Time	4	31.4086667	7.8521667	1388.97	<.0001**
Error	34	0.1922091	0.0056532		
Corrected Total	53	455.9116571			

**= F-value significant at ($P \leq 0.05$)

4.2 Interaction of Energy Source, Soaking Temperature and Soaking Time on Milling Yield Recorded from the Improved Traditional Paddy Rice Parboiler

Figure 4.1 shows the effect of energy source and soaking temperature on milling yield at varying soaking durations. At 10 h soaking, milling yield from the rice husk treatment increased progressively with soaking temperature, indicating a positive response to increasing temperature within this duration. The firewood treatment, however, showed a marked increase from 50 to 60°C, followed by a decline at 70°C. Thus, at 10 h, the response to temperature was more pronounced with firewood than with rice husk, with 60°C producing a particularly high milling yield under the firewood treatment.

However, at 14 h the response became more moderate for both energy sources. Rice husk again showed an increase in milling yield from 50 to 60°C, followed by a slight decline at 70°C. Firewood followed the same general pattern, with milling yield increasing from 50 to 60°C and subsequently remaining relatively stable at 70°C. Compared with 10 h response, extending the soaking period to 14 h therefore reduced the pronounced response observed for firewood at 60°C, while the rice husk treatment maintained a relatively consistent response across the temperature levels.

Finally, a similar temperature-dependent pattern was observed at 18 h under both energy sources. An increase in milling yield from 50 to 60°C before declining slightly at 70°C, while both energy sources show close responses at 70°C indicate that the difference between energy sources became less pronounced at the higher soaking temperature and longer soaking duration

Generally, the change across soaking durations (a) 10h, (b)14h and (c) 18h. Figure 4.1., demonstrates that milling yield was strongly dependent on the combination of energy source, soaking temperature and soaking duration rather than on any one factor in isolation. The response was particularly pronounced for firewood at 60°C during the shorter soaking period, whereas rice husk produced a more stable milling-yield response across the different soaking conditions. The results therefore indicate that extending soaking time did not necessarily increase milling yield, and that the effect of soaking temperature depended on both the energy source and duration of soaking.

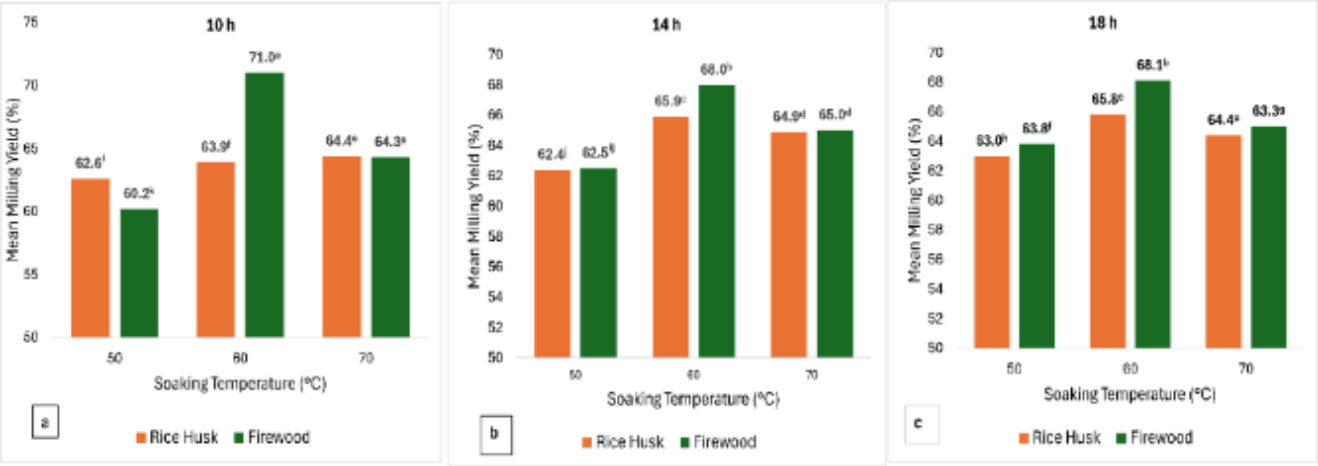


Figure 4.1: Interaction of energy source and soaking temperature at different soaking times on the milling yield of paddy rice: (a) 10 h, (b) 14 h, and (c) 18 h.

5. CONCLUSION

The improved traditional paddy rice parboiler successfully utilized rice husk as its primary energy source. The results showed that energy source, soaking temperature and soaking time significantly affected milling yield ($P<0.05$). Milling yield generally increased with soaking temperature, with the highest yields obtained at 70°C under the conditions tested. The response also varied with soaking duration and energy source, indicating that milling performance depended on the combined processing conditions. Thus, appropriate control of soaking temperature and duration is important for improving milling yield in the parboiling process.

Firewood produced a slightly higher overall milling yield (65.1 %) than rice husk (64.1 %), although the response varied with soaking temperature and duration. The highest milling yield of 71.0 % was obtained with firewood at 60°C and 10 h soaking. These results indicate that rice husk did not outperform firewood with respect to milling yield. Nevertheless, the potential advantage of rice husk should not be interpreted solely in terms of superior product yield. Rather, its relevance lies in its potential as an alternative biomass energy source that can utilize an abundant rice-processing residue and reduce dependence on firewood. The results demonstrate that acceptable milling yields can be achieved using rice husk under appropriate parboiling conditions, although further improvements in combustion and heat-transfer efficiency may be required to achieve performance equivalent to or better than that obtained with firewood.

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Advancing Integration of Smart Technologies in Nigerian Agriculture for Sustainable Development

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ABSTRACT
Agriculture remains a critical sector in Nigeria, contributing significantly to employment, food security, and national economic growth. However, persistent challenges such as low productivity, climate variability, post-harvest losses, and limited access to modern inputs continue to undermine its potential. The emergence of smart agricultural

technologies integrating digital tools, automation, data analytics, and precision farming offers new opportunities for transforming Nigeria agriculture towards sustainability development. This paper examines the role of smart technologies in advancing sustainable agricultural development in Nigeria. It discusses key smart agricultural technologies, applications, benefits, and adoption challenges, while highlighting pathways and recommendations for effective implementation. The study concludes that strategic integration of smart technologies, supported by enabling policies, infrastructure development, and capacity building, can significantly enhance agricultural productivity, resilience, and sustainability in Nigeria.

KEYWORDS: Smart agriculture, Precision farming, Digital agriculture, Sustainable development, Smart Technology

1. INTRODUCTION

The contribution of agriculture to the development of Nigerian economy cannot be over emphasized as it plays a central role in Nigeria's socio-economic development. Over 70% of households in Nigeria are involved in Agriculture directly or indirectly across various value chains. Which includes production, processing or value addition, storage, transportation and marketing of agricultural produce. Creation of jobs for millions of Nigerians, FAO 2023 reported that Nigeria agriculture employs over 36.5 % of the entire labour force and contributing significantly to the national GDP (FAO, 2023). World Bank in 2023 reported 34.14%. Agriculture contributed 21.1% to GDP in the first quarter of 2024. But recent reports only concentrate on forecasting rather than update. Despite its importance, the sector is characterized by low mechanization levels, dependence on rain-fed farming, inefficient resource use, and high post-harvest losses.

(Ozumba *et., al,* 2019) These challenges are further exacerbated by climate change, population growth, and land degradation.

Integration of Smart technologies in Agriculture would address some of these issues. Integration of Smart technologies in agriculture refers to the adoption of digital and automated tools for monitoring, facilitating real-time data collection and decision-making for efficient resource management (World Bank, 2023). These will enable farmers to optimize input utilization, improve crop yield, and mitigate the adverse effects of climate variability, thereby promoting environmental sustainability and economic resilience. In Nigeria, smart agricultural innovations such as sensor-based irrigation systems, GPS-guided tractors and automated processing machines are gradually redefining traditional farming practices (Okonkwo *et al,* 2020).

In Nigeria move to digitize agricultural sector, the National Information Technology Development Agency (NITDA), being supervised by the Federal Ministry of Communications and Digital Economy, has adopted 130 farmers into the National Adopted Village for Smart Agriculture (NAVSA) programme to provide Nigeria farmers with means to showcase their farm produce in the digital market. This project was piloted in Jigawa State in the Northern part of Nigeria. In which farmers were trained and given smart devices, connectivity, and digital skills to adopt new agricultural tools and access broader market (NITDA, 2020).

In recent years, smart agricultural technologies have emerged as viable solutions for improving agricultural efficiency and sustainability. Smart agriculture involves the application of digital and intelligent technologies such as the Internet of Things (IoT), Artificial intelligence (AI), remote sensing, automation, and data-driven decision-making to agricultural production systems. Examples of such in use in Nigeria include Akilimo (Mobile App and paper Tool), Agro mall farmer App, Crop2Cash, Farm Crowdy, Hello Tractor, Livestock 247 etc. This paper examines the role of smart technologies in advancing sustainable agricultural development in Nigeria. It discusses key smart agricultural technologies, applications, benefits, and adoption challenges, while highlighting pathways and recommendations for effective implementation.

2. MATERIALS AND METHODS/METHODOLOGY

A systematic literature review approach was adopted to examine Smart Technologies as related to Agriculture. The research focuses on accessing and analyzing existing studies. This makes it possible to understand different Smart technologies and how they can be applied to agriculture. Reliable academic platforms such as Google Scholar, ScienceDirect, SpringerLink, ResearchGate, and other relevant publishers were sources of information used in this study. These sources are widely recognized for providing credible and up-to-date research in agriculture and engineering. In gathering relevant materials, specific keywords were used during the search process. Boolean

operators such as AND and OR were also applied to refine the search and ensure that only relevant studies were selected. In addition, clear selection criteria were applied. Inclusion criteria include peer-reviewed journal articles, conference papers, and technical reports related to Smart technologies.

Exclusion criteria include non-English publications, articles without full text access, and studies that are not directly related to Smart Technologies as related to agriculture. Relevant information were carefully extracted from the selected studies. Although this study provides useful insights, it is limited to information available in published literature, some recent innovations and unpublished works. Inclusion criteria comprised peer-reviewed journal articles, conference papers, and technical reports directly related to Smart Technologies as related to agriculture. Exclusion criteria included non-English publications, inaccessible full texts, and studies not directly related to Smart technologies in Agriculture.

3. Concept of Smart Technology and Smart Agriculture

The term "SMART" was originally derived from the acronym "Self-monitoring, Analysis and Reporting Technology," but it has since evolved to encompass a broader range of intelligence and advanced functionality. (Matthew *et al.,* 2025). Smart agriculture, which is sometimes referred to as digital or precision agriculture, is an approach that leverages modern technologies to optimize agricultural operations. It involves collection of real-time data from farms, analyzing it, and applying the results to improve productivity, efficiency, and environmental sustainability.

4. Smart Technology Applications in Agriculture

Application of Smart technology in agriculture covers almost all the areas of agricultural practices such as land preparation, planting of crops, weed control, irrigation, harvesting, post-harvest operations, etc.

4.1 Smart Irrigation System.

Smart irrigation technology utilizes the weather data and soil moisture data to determine the irrigation need of plant or a landscape (Sojka *et al.*,2002). Smart irrigation technology makes optimum use of water and soil nutrients, improves irrigation efficiency by reducing water waste, while maintaining quality of crops and plants' health (Drashti et al.,2023). The SMART irrigation system is an emerging innovation that automates irrigation systems and conserves water usage. SMART irrigation adjusts irrigation based on the actual soil and weather conditions, thereby helping the farmers to meet their water demand as well as conserves the water for irrigation process. The use of SMART agriculture by farmers will give the farmers the opportunity to produce yields while using fewer resources, such as fertilizers, water, and seeds. Components of SMART irrigation system includes data acquisition (sensor), irrigation control, wireless communication, data processing and fault detection. Each of these components can be used with Internet of Things (IoT) devices and these will enable the farmers to know the exact status of their field, including soil temperature, amount of water required, weather conditions etc. (Joshua W. *et al.,* 2022).

The Smart irrigation systems use sensor devices to monitor essential parameters such as soil moisture, air temperature, rainfall, and plant water requirements in real-time. Thus, ensuring that watering is done more precisely, according to plants' needs and avoid waste (Patel et al., 2019). Patel et al. (2019) reported that the application of smart irrigation systems in horticulture reduced water use by 50% while it increased crop productivity by 30% while Rau*t et al*. (2020) reported that the technology improved irrigation efficiency in rice and maize crop production.

This technology also has the potential to enhance the environmental sustainability by reducing water wastage and optimizing resources. This is in line with the Sustainable Development Goal (SDG) 6, clean water and sanitation.

4.1.1 Sensors in smart Irrigation system

The use of sensors is pivotal in smart irrigation system, it aids farmers understanding of their crops in a better way, reduces the environmental impacts and conserve resources (Ogunjirin et al.,2020) The technology assist farmers towards their decisions regarding growth and monitoring of the multi-crops in different sections of the field. Some highlighted sensors use in smart irrigation system include; Soil moisture sensor, nutrient sensor, Temperature sensor (soil temperature sensor, air temperature sensor), Rainfall sensor, Water level sensor, etc. A typical Smart irrigation setup through PLC automation is shown in figure 1 below and some highlighted sensors in irrigation system in figure 2.

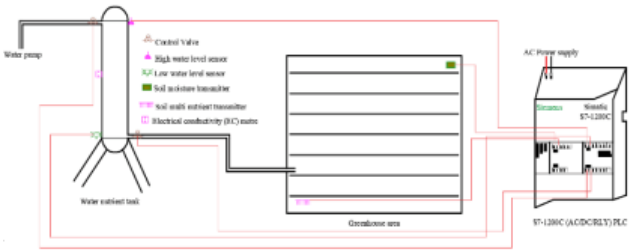

Figure 1: Typical Smart Irrigation set up through PLC Automation

Soil moisture content sensor

A NTC Thermistor temperature sensor

Thermocouple Thermometer

Resistive Temperature Detectors.

Pyrometer

Capacitive Humidity Sensor

Water level

Resistive Humidity Sensor

Thermal Humidity Sensor

Rainfall sensor

Figure 2: Some highlighted sensors in smart irrigation system.

4.2 Smart Agricultural Machinery and Equipment

The application of smart agriculture covers all the processes involved in agricultural production. Which includes land preparation, planting, weed control, harvesting, etc. Some of these are shown in figure 3 below.

Unmanned rice transplanter

Autonomous tractor

Remote Control Power tiller

Real time monitoring system

Figure 3: Application of Smart machinery and equipment

Source: Mehta, 2025.

4.3 Cloud Computing

measured service etc. Cloud computing is a model that enables convenient, on-demand network access to a shared pool of configurable computing resources, examples of which includes: networks, servers, storage, applications, and services that can be rapidly provisioned and released with minimal management effort or service provider interaction (Peter &Timothy,2011) Essential characteristics of cloud computing includes: demand self-service, broad network access.

While models of deploying cloud computing includes: *Private cloud in which the* cloud infrastructure is provisioned for exclusive use by a single organization comprising multiple consumers (e.g., business units) from organizations that have shared concerns: *Public cloud.* In this, the cloud infrastructure is provisioned for open use by the general public. It may be owned, managed, and operated by a business, academic, or government organization, or some combination of them. It exists on the premises of the cloud provider. *Hybrid cloud*. The cloud infrastructure is a composition of two or more distinct cloud infrastructures (private, community, or public). The major advantage, among others, of this new model of computing is the access to different kinds and volume of computing facilities from anywhere and anytime. (Sandeep, 2017).

The use of cloud computing in the agricultural sector involves data gathering and processing. The users of it are able to view the information by connecting to the cloud. The usage of cloud in irrigation is mainly taken in terms of storing the monitored data and then retrieving it when needed. Cloud technology provides both paid and free options to the users for storing, assessing, and displaying the data on varied devices and platforms. The stored data is accessed on various occasions for different applications. This has helped many organizations in the agricultural sector to store, view and retrieve information that assists in improving work efficiency and effectiveness. In smart irrigation system, cloud technology has also been used to generate alerts through developing algorithms which can be used to mitigate various forecasted risks and hazards that could have taken place otherwise. This does not only reduce risks but also improve the outcomes of work in order to attain the set objectives.

4.4 Drones

Drones are widely utilized in many areas of agricultural production including livestock management, optimization of irrigation schedules, real-time monitoring of crop water stress and improving water resource management through technologies such as AI/ML algorithms and multi-spectral imagery. Multi-spectral cameras attached to drones can capture images that can reveal subtle differences in plant health and water stress levels. Drones also help in measuring Real-time data which allows farmers to identify specific land areas of the field that are experiencing water stress and adjust irrigation accordingly. Coupled with the use of AI and ML algorithms, the imagery can be analyzed to identify patterns and predict water needs and by optimizing irrigation schedules which helps precision irrigation delivering water only where and when it's needed. This also improves water saving and reduce the environmental impacts of irrigation. Optimized irrigation can lead to healthier crops and higher yields. With captured data by drones it can provide valuable insights into soil health and detect plant diseases early thereby allowing for timely intervention. Drones also carry out mapping which help in monitoring crop growth, and track the progress of irrigation projects. Drones saves time by covering large areas quickly, providing real-time data and insights that would otherwise be difficult or impossible to obtain. Drones helps farmers achieve greater efficiency and sustainability and it is becoming more affordable. Drones equipped with advanced sensors and imaging systems enable remote sensing and high-resolution data collection in agricultural landscapes. Figure 4 depicts some applications of drones.

Monitoring Field Conditions

Spray Application

Figure 4: Some applications of drones

4.5 Agricultural Internet of Things (AIoT)

Agricultural Internet of Things (AIoT) is an agricultural application technology with the integration of sensors, wireless communication network, and intelligent terminal technologies into the agricultural sector, covering the entire production processes from pre-production to post-harvest. (Ling *et al*, 2025). The computer programmes function as central information hubs for objects, continuously updating and combining data from various sources to carry out different required tasks remotely over the Internet. Figure 5 depicts the Agriculture Smart technology Programmable logic controller flow of operations.

4.6 Mobile and Digital Agricultural Platforms

Mobile-based platforms deliver extension services, market information, weather forecasts, and financial services to farmers, improving access to information and markets.

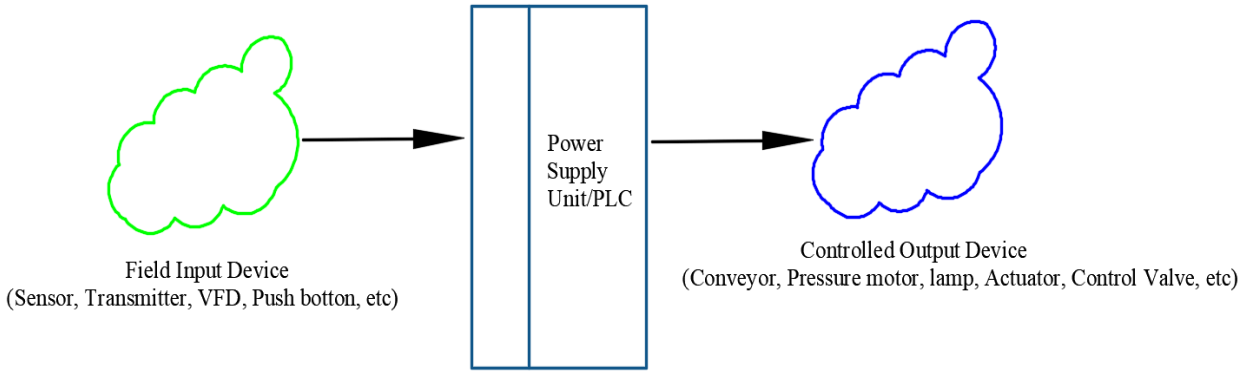

Figure 5: Agriculture Smart technology Programmable logic controller flow of operations.

5.0 Contributions of Smart Technology to Sustainable Development

Some of the contributions of Smart Technology to Sustainable development include**: Economic Sustainability;** Smart technologies increase farm productivity, reduce production costs, and improve farmers' incomes through better market access and reduced losses. **Environmental Sustainability:** Precision input application minimizes excessive fertilizer and pesticide use, reducing soil degradation, water pollution, and greenhouse gas emissions. **Social Sustainability;** Digital platforms empower smallholder farmers by improving access to knowledge, finance, and markets, thereby enhancing rural livelihoods and reducing poverty. **Increased productivity;** With the application of smart technology in Nigeria agriculture which helps to monitor soil moisture content, nutrient levels, and crop health in real time waste, improve crop growth conditions and leading to higher yield. **Efficient Resource Management;** With limited water and financial resources farmers benefit by automating irrigation based on soil moisture, nutrient, temperature, monitoring weather forecast to avoid water loss and reduces energy and input costs.

6. Challenges to Smart Technology Adoption in Nigeria

Despite its potential, adoption of smart agriculture in Nigeria faces several constraints: which include: **Inadequate Infrastructure**; Many rural areas in Africa lack reliable electricity supply, internet connectivity, and adequate communication networks necessary for the seamless functioning of smart technology systems.

High initial investment costs: High upfront costs and investment requirements of smart technology has hindered many from accessing this technology especially the small-scale farm holders. Limited access to financing and the absence of appropriate financial mechanisms further impedes the adoption of smart technologies. **Inadequate technical know-how**: There is a low level of technical skills and knowledge among farmers, extension workers, and other stakeholders which has constituted constraint to the adoption of smart technology. **Smart technology equipment are prone to damage:** especially in harsh environmental conditions. Which presents a considerable constraint in Sub-Saharan Africa. (Aria and Rully, 2024). There is also weak extension services and technical capacity.

7.0 Strategies for Advancing Smart Agriculture in Nigeria

Investment in Digital Infrastructure: Expansion of broadband and mobile network coverage in rural areas. Capacity Building: Training farmers, extension agents, and technicians in smart technology application. Policy Support: There must be a clear development of national strategies for digital and smart agriculture. Public Private Partnership: Collaboration between government, research institutions, and agritech startups is essential. Financial Incentives: Subsidies, grants, and credit facilities to support technology adoption by smallholders.

8.0 Conclusion

Advancing smart technologies in Nigeria agriculture creates a viable pathway for achieving sustainable agricultural development. Through the improvement of crop yield productivity, enhancing climate resilience, and promoting efficient agricultural resources. Smart agriculture addresses Nigeria's agricultural sector's longstanding challenges, such as limited access to modern technology, climate change, poor irrigation infrastructure, low digital literacy, post-harvest losses, etc. However, realizing smart technology potential in Nigeria requires coordinated efforts in the infrastructure development, policy formulation, capacity building, and government, private collaboration investment. Smart agriculture significantly contributes to the United Nation's Sustainable Development Goals (SDG) in Nigeria, which are zero hunger, clean water and sanitation, sustainable cities and communities, and climate action (SDGs 2, 6, 11 and 13 respectively).

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Paper ID 27:
Development and Performance Evaluation of an Improved Chicken Feeder for Small-Scale Farmers

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Abstract
The objective of this study was to develop and evaluate the performance of an improved chicken feeder system utilizing polyvinyl chloride (PVC) pipes in order to minimize feed wastage and enhance efficiency in poultry farming. The feeder's design considered factors such as bird comfort, ease of cleaning, environmental safety and durability. It has a total length of 263 cm with 14 holes that could accommodate 2 birds each. Performance evaluation was conducted for twenty-eight (28) chickens to assess the feeder's effectiveness in reducing waste, feed conversion ratio, and bird growth rate. Results obtained shows that the feeder has a capacity of carrying 170 g of feed per hole. It also has an efficiency of 88.24%. A significant reduction in feed wastage of 11.76% was recorded compared to conventional feeding systems. Additionally, bird growth rates were comparable to those in traditional feeding systems. The PVC pipe feeder proved to be a cost-effective, durability, sustainable, ease of maintenance and efficient solution for poultry farmers, promoting environmentally friendly and profitable production practices. The result suggest that this innovative feeder system is worthy of adoption by poultry farmers. Its estimated cost is about ₦19,000:00

Keywords: Chicken, Cost-Effective, Feeder, Poultry, PVC Pipes

INTRODUCTION

Nigeria's agricultural sector comprises four sub-sectors: crops, livestock, fisheries and forestry. Crops contribute about 85% to agricultural GDP, livestock production about 10%, fisheries and Forestry about 4% and 1%, respectively (Rekwot *et al.*, 2015). Over the years, the contributions of the livestock sub sector to Gross Domestic Product (GDP) have decreased from 5.61% in 1960 to about 2.64% in 2010 (CBN, 2010). Livestock production constitutes an important component of the agricultural economy in developing countries and it is an instrument of socio economic change, improved income and quality of rural life in Nigeria (Ojo, 2003). The traditional indigenous poultry system is inexpensive and low input, with the capacity to handle harsh weather conditions and adapt to adverse environments. They are generally of small-scale, characterized by insufficient hygiene management and receive little or no veterinary inputs, PAN (2017).

Poultry, as an aspect of livestock production outnumbers all other forms of livestock in Nigeria and not surprisingly is found throughout the country (Adeyemo and Onikoyi, 2012). Today, poultry production has developed from backyard business to a commercially oriented industry. The poultry sector is characterized by relative faster growth in consumption and trade volume than many other agricultural livestock sectors. Different species in poultry production include; Chickens (local chickens, broilers, and layers), turkeys, geese, ducks, guinea fowls Quails, Pheasants, Ostriches, Pigeons and Doves.

Poultry is the term used to describe group of birds kept for meat and egg (e.g. chicken) or reared or hunted for a useful purpose. The Poultry industry is an emerging agri-business and has established its position as the fastest growing segment in the agricultural sector in Nigeria. With increased acceptance of chicken, egg and meat, the demand for these products is ever increasing, Sonaya and Swan (2004).

The poultry industry is a key sub-sector of the agricultural industry in Nigeria, contributing significantly to the country's economy and food security. Poultry production in Nigeria is predominantly smallholder-based, with backyard farming accounting for a significant proportion of total production (Bamidele and Amole, 2021; Birhanu et al., 2023). Commercial poultry production is also on the rise, with large-scale farms producing broiler chickens and eggs for both domestic and export markets (Yusuf et al., 2016). The demand for poultry products, including chicken and eggs, is high due to population growth, urbanization, and changing dietary patterns (Ding and Kinnucan, 2011). Poultry farming has created employment opportunities for millions of Nigerians, particularly in rural areas, where job opportunities are limited (Ohajianya et al., 2013). The industry also supports other sectors such as feed production, transportation, and veterinary services (Attia et al., 2022). The rapid growth of the poultry industry in recent years has raised concerns about its environmental and social impacts, including greenhouse gas emissions, water pollution, land degradation, and deforestation (Payandeh et al., 2017). Poultry production requires significant inputs of resources, such as feed, water, and land, and generates large quantities of waste products, such as manure and poultry litter (Gerber et al., 2007). There are concerns about the welfare of the birds, the use of antibiotics and other drugs, and the potential for disease transmission.

Poultry farming is, thus, a prominent sector in the agricultural industry worldwide, providing a vital source of protein and livelihood for numerous communities. Poultry industry plays a crucial role in meeting the increasing global demand for animal protein. For efficient and healthy growth of poultry, it is essential to provide poultry houses with proper nutrition through feed (Gbadamosi, 2016). However, one of the main challenges in poultry farming is the wastage of feed, leading to financial losses for the farmer and environmental pollution (Smith, 2018 and Lacy, 2016). Traditional chicken feeders are often prone to wastage as they allow chickens to scatter and spill feed while eating, resulting in additional costs for the farmer. This also attracts pests and rodents to the poultry houses (Gbadamosi, 2016). Addressing this issue requires innovative and cost-effective solutions to reduce feed wastage while ensuring effective delivery of feeds to the chickens.

However, the demand for poultry products in Nigeria is growing rapidly due to population growth, urbanization, and changing dietary habits. This presents an excellent opportunity for farmers to increase their production and generate income (Heise et al., 2015). Commercial poultry production is also on the rise, with large-scale farms producing broiler chickens and eggs for both domestic and export markets (Yusuf et al., 2016; Kassali et al., 2022). Poultry production in Nigeria has a promising future due to several factors, including the high demand for poultry products, the availability of local and international markets, and the potential for job creation and economic growth. However, the industry also faces several challenges that could hinder its growth and sustainability.

There is a ready market for poultry products both locally and internationally. Nigeria has a large domestic market, and there is increasing demand for Nigerian poultry products in other African countries, Europe, and Asia (Heise et al., 2015). With a large population and a growing middle class, Nigeria provides a ready market for poultry products within its borders. The demand for poultry products such as chicken, eggs, and turkey remain consistently high due to their affordability and versatility in various culinary traditions.

However, there are several factors that contribute to sustainable poultry production among farmers in Nigeria including access to high-quality feed and water, proper housing, disease prevention and control, proper waste management, access to market and financial support, among others (Ja'afar-Furo and Gabdo, 2010). The sustainability of poultry production in Nigeria is evaluated based on its economic, environmental, and social impacts.

Poultry equipment is made up of instruments or tools used for a particular job or activity in poultry production management. Poultry houses cannot function satisfactorily unless they are properly equipped and supplied with appliances. These are the basic requirements for the successful management of birds. Poultry equipment vary from the simple to the complex and from the most elementary to the most advanced electronic devices. The equipment can

be broadly grouped into those for general applications and those for specific applications. Those for general applications are used at all post-natal stages of growth; these consist mainly of feeders, drinkers and crates. Those for specific stages of growth include brooders for chicks-brooding and nests for layers, Ganiyu (2005). The use of improved production technologies and management practices can enhance the efficiency and productivity of poultry farming in Nigeria (Olaniyi et al., 2008). These include modern housing systems, improved breeds, disease prevention measures, data-driven management, efficient waste management, and advanced feeding techniques among others.

The development of the poultry industry has been described as the fastest means of bridging the protein deficiency gap prevailing in most of the developing countries. The poultry industry, if properly harness can also serve as a source of foreign earnings complementing crude oil which at present constitutes the main source of foreign earnings in Nigeria. In poultry production small scale poultry production represents one of the few opportunities for saving, investment and security against risks. It accounts for approximately 90% of total poultry production (Branckaert, 1999 and FAO (1998).

In response to this, the development of innovative feeding solutions, such as zero-wash chicken feeders, has become a focus of research and development in the poultry industry (Barenett*et al*., 2019). In particular, the utilization of PVC pipes for constructing chicken feeders has emerged as a sustainable and efficient solution to minimize food wastage and enhance poultry farming practices (Odum and Chukwuji, 2022). This would allow the poultry farmers to minimize cost of production through reduced wastage, improve feed efficiency, and enhance the overall health and productivity of their poultry flocks. The aim of this study is, therefore, to develop and evaluate the performance of a chicken feeder that would minimize feed wastage thereby reducing the cost of production. This will also help to keep the feed clean and dry, reducing the risk of contamination thus keeping the birth healthier. In addition, the study will also promote a healthier environment for a sustainable poultry farming practices as observed by Olutumise et al. (2023).

MATERIALS AND METHOD

Materials

This section gives details discussion of the materials and method used in the development and performance evaluation of the developed chicken feeder using the PVC pipes. The selection of the material used is very crucial thereby, choosing the blue pipe over ash colour because of its durability and resilience in terms of usability as recommended by Smith *et al*. (2018). The components or parts of the feeder include a PVC pipe diameter of 10cm, Caps, a galvanized steel wire for handle use for suspension and a hopper. The details of the materials are presented in Table 1 below:

Table 1: Material requirement and the estimated cost for the construction of the feeder

S/N	Materials	Specifications	Quantity	Unit price (₦)	Cost (₦)
1	PVC (polyvinyl chloride) pipe	10.16cm x 263cm	1	5,000	5,000
2	Steel rod for handle use for suspension	100×0.3×0.0785cm		300	300
3	Sand paper		½ yard	800	400
4	Adhesive gum		1 tube	1,500	1,500
5	Hopper	24x12x10 cm	1	2,000	2,000
6	Caps	10.16cm	4	600	2400
7	A pair of compasses	17×6×3×10×1 cm	1	1,500	1,500
8	Knife.	13×10×3 cm	1	1,500	1,500
9	Steel Rule	3 m	1	1,200	1,200
10	Saw blade		1	1,500	1,500
Contingencies (10% Sub-Total)					1,750
Total					**19,030**

Methods

Description of the construction feeder

PVC pipes forms the main structure of the feeder (Figure 1). It has a total length of 263 cm and a diameter of 10 cm. The PVC pipes are lightweight and easy to work with, making them ideal for constructing a feeder that can be easily installed and maintained as suggested by Gbotosho and Burt, 2013). The plastic feeder are also resistant to rust and corrosion. The smooth surface of PVC pipes also facilitates the flow of feed, ensuring that chickens can access the feed without any obstructions, enhancing the efficiency of the feeding process as recommended Ewemoje *et al*., (2011). There are fittings or caps that serves as connectors used to connect the pipes to form the feeder of desired length. An adhesive gum (that act like cement) is also used to secure the fittings between the pipes and ensure a sturdy construction. A saw or pipe cutter is used for cutting the pipes to the desired lengths. Cutting saw and knife is then used in creating holes in the pipes to allow chickens to access the feed. Screws or fasteners are used to secure the mesh or netting to the feeder. The PVC pipes has 14 holes each of diameter 14 cm, spaced 3 cm apart were drilled. A hopper is also constructed for ease of loading in order to minimize wastage of feed (Figure 2).

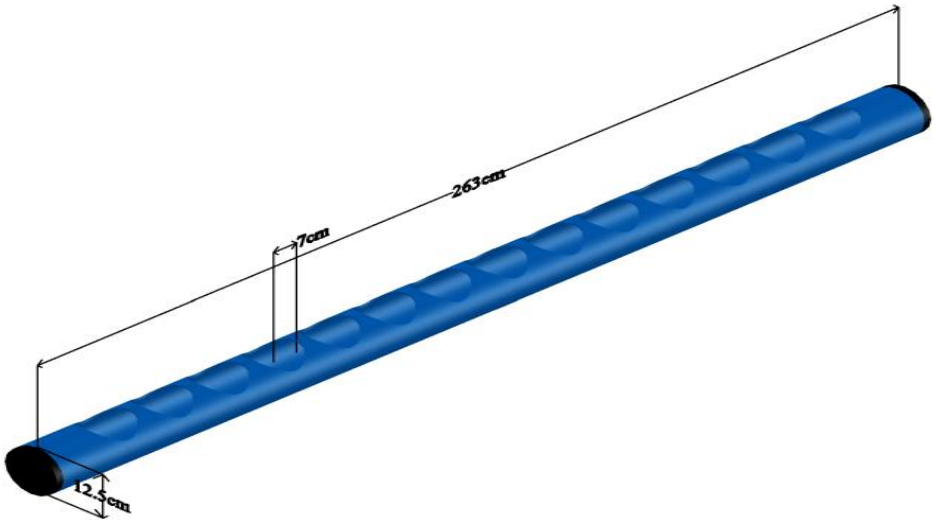

Figure 1: The Developed Chicken Feeder

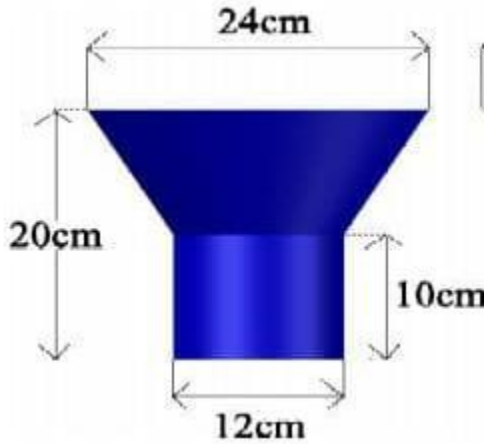

Figure 2: Feed Hopper

How to use the Feeder:

The feeder is placed on a flat surface, while feed is pour through the openings. The height of the feeder is adjusted so that the birds can easily reach the feed. The openings are closed at a stage to monitor the feeder in order to make sure that the birds are eating freely and that the feeder is not running out of feed. The feeder should be checked regularly

to make sure that it is not running out of feed. Cleaning the feeder at intervals with hot water and soap would prevent the growth of bacteria. It is are easy to clean and maintain, reducing the risk of contamination and disease spread However, the greatest disadvantage of the developed feeder is that the birds cannot completely empty the feed since a little percentage of the feed will be retained at the base of the feeder.

Design Calculations and Assumptions

Design Specifications and assumptions:

i. Pipe length (L) = 263 cm
ii. Circular holes = 14 holes
iii. Diameter (D) = 10 cm
iv. Radius (R) = 5 cm
v. Distance between holes (d) = 3 cm
vi. Feed carrying capacity = 2.38 kg
vii. Number of chickens (N) = 28
viii. Uniform feed distribution
ix. Constant feed density
x. No feed contamination

Calculations:

i. **Total Number of Holes** (n) is given by Gbotosho and Burt, 2013):

$$n = \frac{L}{D + d} \quad (1)$$

$$\therefore n = \frac{263}{10 + 3} = 14.22\ cm\ \approx 14\ holes$$

ii. Feed Capacity per Hole

Feed capacity per hole is given by Gbotosho and Burt, 2013):

$$F_c = \frac{TFc}{Nh} \quad (2)$$

Where: TFc = Total feed capacity; Nh = Number of holes

$$TF_c = \frac{238}{14} = 0.17\frac{kg}{hole} = 170g/hole$$

iii. Volume of Feed (Ganiyu, 2005)**:**

$$\boldsymbol{V_f = \frac{M_f}{D_f}} \quad (\mathbf{3})$$

Where: Vf = Volume of feed; Mf = Mass of feed / Density of feed

Assuming feed density (ρ) = 0.6 g/cm³ (Ganiyu, 2005);

$$\therefore\ \boldsymbol{V_f = \frac{2.38}{0.6} = 3966.67}\ \text{cm}^3$$

iv. Feeder Efficiency (Ganiyu, 2005)**:**

$$\boldsymbol{F_e = \frac{F_c}{F_o}\ x\ 100} \quad (\mathbf{4})$$

Where: Fe = Feeder Efficiency (%); Fc = Feed consumed; Fo = Feed offered

From table: 4.1, day three. Reason; The maximum value of the efficiencies was used

i.e Feed offered – feed waste

Feed offered=2.38kg

Feed waste=0.28kg

Feed consumed=2.38-0.28=2.10kg

$$\therefore\ \boldsymbol{F_e = \frac{2.10}{2.38}\ x\ 100\ = 88.24}\ \%$$

v. Feed Wastage Rate (Ganiyu, 2005)**:**

$$F_r = \frac{F_w}{F_o} \, x \, 100 \qquad (5)$$

Where: Fr = Feed wastage rate (%)

$$\therefore F_r = \frac{0.28}{2.38} \, x \, 100 \; = 11.76 \, \%$$

RESULTS AND DISCUSSION

This section presents the results of the performance evaluation of the developed chicken feeder using PVC pipes. The primary objective of this study was to assess the efficacy of the designed feeder in reducing feed wastage and improving feeding efficiency in poultry farming as well as compare it with the traditional feeding method.

Table 2 shows the results obtained using traditional chicken feeding system while Table 3 show the results obtained using an improved chicken feeder. While the traditional feeder has an average feed efficiency of 63.73%, the improved feeder has an average efficiency of 88.24%. The lower efficiency associated with the traditional feeder was observed due to the behavior of the chicken by scratching and billing out the feed onto the ground. Besides wasting the feed, it also leads to attracting mice, rats and wild birds. The spilled feed also causes environmental hazards if the feed is not removed from the ground. The traditional feeder is thus labour intensive since a lot of human time is needed to clean the feeder and its surroundings. Cost of maintenance in traditional feeding system, therefore, makes it to be

Table 2: Evaluation of Traditional (Trough) chicken Feeder

S/N	Time of Observation (min)	Feed Applied (kg)	Feed Wastage (kg)	Feed Consumed (kg)	Feed efficiency (%)
1	60	2.38	0.87	1.51	63.45
2	60	2.38	0.92	1.38	57.98
3	60	2.38	0.80	1.58	66.39
4	60	2.38	0.79	1.59	66.81
5	60	2.38	0.84	1.54	64.71
6	60	2.38	0.88	1.50	63.03
Average					**63.73**

Table 3: Evaluation of the Developed Feeder

S/N	Time of Observation (min)	Feed Applied (kg)	Feed Wastage (kg)	Feed Consumed (kg)	Feed efficiency (%)
1	60	2.38	0.25	2.13	89.49
2	60	2.38	0.31	2.07	86.97
3	60	2.38	0.28	2.10	88.24
4	60	2.38	0.25	2.13	89.49
5	60	2.38	0.32	2.06	86.55
6	60	2.38	0.30	2.08	87.39
Average					**88.24**

uneconomical. Conversely, the improved developed feeder was designed with an anti-scratch materials and enclosed ports that only permits the chicken to pick feed directly from the feeder. The chicken pecks the feed right from the opening but cannot scratch or waste it. The holes/openings feature a small lip to block the chickens/birds from raking feed out with their beaks. The improved feeder thus reduce cost of labour as well as feed wastage, thereby making it more economical to use. The improved feeding system, therefore, strive for faster growth of chickens with higher meat and/or egg production due to its optimal feed conservation. There is the possibility of minimizing feed contamination. This helps to keep the birds healthy and prevents the spread of diseases. On the other hand, the traditional feeding system only meet the family basic needs as well as mitigating risks. They ensure livestock survival and adapting local conditions with products primarily intended for self-sufficiency or local market.

The scenario of adaptation also plays a crucial role when selecting feeder for poultry. Traditional systems are often used in smaller operations where budget constraints as significant. However, in commercial settings such as small scale broiler or layer farms, improved system of feeding is necessary.

Another advantage of using the improved feeder is the issue of standardization. The body shape, meat quality and flavor of chickens raised through this system are relatively uniform, and meets the requirement of modern distribution since every chicken has equal chance of feeding. Although flavor of traditional system of feeding may be unique, but individual differences are much and the quality is very unstable.

Conclusion

The developed chicken feeder presents a viable solution for poultry farmers seeking to optimize feeding efficiency, reduce waste, and promote sustainability. Results obtained shows that the feeder has a capacity of carrying 170 g of feed per hole. It also has an efficiency of 88.24%. A significant reduction in feed wastage of 11.76% was recorded compared to conventional feeding systems. The study's findings contribute to the development of sustainable and efficient poultry feeding systems, addressing economic, environmental, and animal welfare concerns. Additionally, the simplicity of the design and ease of fabrication make the PVC pipe feeders an attractive option for poultry farmers looking to enhance their feed management practices. Conversely, the improved systems such as this developed feeder, offer superior efficiency, reduced labour costs, and overall sustainability for small and medium scale poultry operations.

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Determination of Some Heavy Metals in Processed Powdered Pepper Sold in Makurdi

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ABSTRACT
Processed powdered pepper is widely consumed in Nigeria, yet contamination with potentially toxic metals can occur during production, drying, grinding, handling and marketing. This study determined the concentrations of cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb) and nickel (Ni) in processed powdered pepper sold in three major markets in Makurdi, Benue State, Nigeria. Samples were collected from Wurukum, Modern and North Bank markets, while a laboratory-prepared sample served as a control. Three replicate samples were 18 analysed for each group. Approximately 0.5 g of each sample was digested with nitric acid and hydrogen 19 peroxide and analysed by atomic absorption spectrophotometry. Results were expressed as mean ± standard 20 deviation and compared using one-way analysis of variance (ANOVA), followed by Duncan's multiple range 21 test at $p < 0.05$. The recalculated overall mean concentrations were 0.0242 mg/kg for Cd, 0.2992 mg/kg for Cr, 22 0.3308 mg/kg for Co, 0.1167 mg/kg for Pb and 0.2208 mg/kg for Ni. Cadmium did not differ significantly 23 among sampling groups ($F = 1.923$, $p = 0.204$), whereas Cr ($F = 263.153$, $p < 0.001$), Co ($F = 445.284$, $p < 24$ 0.001), Pb ($F = 9.000$, $p = 0.006$) and Ni ($F = 365.497$, $p < 0.001$) differed significantly. Modern Market recorded the highest Cr and Co concentrations, Wurukum Market the highest Pb concentration, and North Bank Market the highest Ni concentration. The findings demonstrate localized variation in metal concentrations and support continued food-safety surveillance of powdered pepper in Makurdi. However, the study measured concentrations only and did not estimate dietary exposure; therefore, it should not be described as a formal human-health risk assessment.

KEYWORDS: heavy metals; powdered pepper; food safety; atomic absorption spectrophotometry

1. INTRODUCTION

Pepper (Capsicum spp.) is among the most widely cultivated and consumed spice crops in the world, valued for 33 its pungency, colour, aroma, and rich content of bioactive compounds such as capsaicin, vitamins A and C, and 34 various antioxidants (Batiha et al., 2020, Omale et al., 2026). In Nigeria, and particularly within tropical West 35 Africa, pepper occupies a central place in the culinary, nutritional, and economic life of both rural and urban 36 populations, serving as an almost indispensable ingredient in local dishes. It is marketed in several processed 37 forms, including dried whole pods, pastes, and powders, of which dried and ground pepper remains the most 38 common form sold in open markets.

In Makurdi, the capital of Benue State, powdered pepper is a staple commodity traded extensively across major markets such as Wurukum, Modern Market, and North Bank (Omale et al., 2026). Processing in these markets is largely traditional, relying on sun-drying and manual or mechanical grinding, often without formal adherence to food safety or quality control standards. This informality in processing and handling exposes the product to a range of contamination risks, among which heavy metal contamination is of particular concern.

Heavy metal contamination of food crops in Nigeria has been linked to industrialisation, agricultural chemical use, vehicular emissions, and poor postharvest handling practices (Orisakwe et al., 2012). Metals such as lead (Pb), cadmium (Cd), chromium (Cr), cobalt (Co), and nickel (Ni) (Okwelle and Mac-Pepple, 2020)may enter the pepper value chain through contaminated irrigation water, agrochemical residues, atmospheric deposition, or contact with metallic processing equipment during drying, grinding, and packaging. Unlike many organic contaminants, heavy metals are not biodegradable and possess long biological half-lives, allowing them to bioaccumulate in plant tissues and, subsequently, in human organs following consumption (Radwan and Salama, 2006; Zheljazkov et al., 2006).

The public health implications of chronic dietary exposure to heavy metals are well documented. Depletion of essential body minerals, renal dysfunction, neuro-behavioural and developmental abnormalities, hypertension, and carcinogenic effects have all been associated with sustained heavy metal intake (Arora et al., 2008; Galanis et al., 2009). Because pepper is consumed almost daily and in relatively large quantities across Nigerian households, even low-level but persistent contamination could translate into significant cumulative exposure over time.

Despite this risk, there is limited empirical data on the concentration of heavy metals in powdered pepper sold within Makurdi markets, and routine monitoring or regulatory quality control of this product is largely absent. This gap in surveillance leaves both consumers and regulators without the information needed to assess whether pepper sold in these markets complies with permissible limits established by bodies such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO).

This study was therefore designed to determine the concentrations of selected heavy metals — cadmium, chromium, cobalt, lead, and nickel — in powdered pepper samples obtained from three major markets in Makurdi metropolis (Modern Market, North Bank Market, and Wurukum Market), alongside a freshly prepared control sample. Specifically, the study sought to: (i) collect powdered pepper samples from the selected markets and prepare a control sample; (ii) determine the concentrations of the selected heavy metals in the market and control samples; (iii) evaluate the potential health risks associated with consumption of pepper containing heavy metals above recommended safe limits; and (iv) statistically analyse the resulting data using Analysis of Variance (ANOVA) to determine whether contamination levels differ significantly across markets.

The findings of this study are expected to provide baseline data on heavy metal contamination in a widely consumed spice, contribute to consumer and vendor awareness of potential health risks, and inform regulatory efforts toward safer food handling and processing practices in Makurdi and comparable urban markets across Nigeria.

2. MATERIALS AND METHODS

2.1 Materials

The materials used for the determination of heavy metals comprised dried pepper samples obtained from three local markets in Makurdi, Benue State, Nigeria — Wurukum, Modern, and North Bank markets — together with a control sample prepared by the researcher.

2.2 Methodology

2.2.1 Sample Collection

Powdered pepper (Capsicum spp.) samples were collected from three selected markets within Makurdi metropolis, Benue State, Nigeria: Wurukum, Modern, and North Bank markets. A control sample was prepared by the researcher from fresh, unprocessed pepper obtained independently of the market supply chain, to provide a baseline unaffected by market handling and processing conditions.

2.2.2 Sample Preparation

The pepper obtained for the control was subjected to standardised preparation procedures to ensure uniformity and consistency of results across all samples.

Grinding: The dried pepper was ground into fine powder using a mortar and pestle. Grinding was carried out uniformly across samples to minimise variation in particle size, which could otherwise affect the outcome of the heavy metal analysis.

Storage: The prepared powdered pepper samples were stored in airtight, moisture-proof containers and kept in a desiccator to preserve their physical and chemical integrity throughout the experimental period.

2.3 Procedure for Determination of Heavy Metals (Cd, Cr, Co, Pb, and Ni) in Processed Pepper

Pepper samples were obtained from the three markets and the control, with three replicates collected per source, giving a total of twelve samples. Each sample was placed in a clean, labelled container and transported to the laboratory for analysis.

In the laboratory, approximately 0.5 g of each pepper sample was weighed into a digestion vessel. Concentrated nitric acid (HNO_3, 5 mL) and hydrogen peroxide (H_2O_2, 2 mL) were added to each sample, and the mixture was digested in a microwave digester at 180 °C for 15 minutes, until a clear solution was obtained. After cooling, the digests were filtered through Whatman No. 42 filter paper and made up to 50 ml with deionised water in a volumetric flask. A reagent blank, a spiked sample, and a certified standard reference material were digested alongside the test samples for quality assurance and quality control.

Concentrations of cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), and nickel (Ni) were determined using 105 an Atomic Absorption Spectrophotometer (AAS). Flame AAS (FAAS) was used for analytes present at higher concentrations, while graphite furnace AAS (GF-AAS) was used for trace-level determinations requiring lower method detection limits. The analytical wavelengths used were 228.8 nm for Cd, 283.3 nm for Pb, 357.9 nm for 108 Cr, 240.7 nm for Co, and 232.0 nm for Ni. Calibration standards ranging from 0 to 5 mg/L were prepared from 109 certified stock solutions of each metal, and all samples, blanks, and standards were analysed in triplicate.
The concentration of each metal in the samples was calculated using the formula:

$$Metal\ (mg/kg) = (C \times V) / W$$

where C is the metal concentration in the digest (mg/L), V is the volume of the digest (L), and W is the weight 113 of the sample (kg).

2.4 Statistical Analysis

Data obtained were analysed using the Statistical Package for the Social Sciences (SPSS) to conduct a one-way Analysis of Variance (ANOVA). All results were expressed as mean ± standard deviation (SD) for each parameter, calculated from the replicate samples. Means were compared using ANOVA to determine whether statistically significant differences ($p < 0.05$) existed among the sample sources. Where significant differences were detected, Duncan's Multiple Range Test (DMRT) was applied as a post hoc test to separate the means and identify the specific sources of variation.

3. RESULTS AND DISCUSSION

3.1 Results

The raw values and mean concentrations of the heavy metals determined in the powdered pepper samples are presented in Tables 1 to 4.

Table 1: Raw Experimental Results for Heavy Metals in Processed Pepper from the Selected Markets in Makurdi

Sample	Replication	Cd (mg/kg)		Cr (mg/kg)		Co (mg/kg)	Pb (mg/kg) Ni (mg/kg)
	1	0.02	0.25	0.42	0.30	0.04	
WM	2	0.01	0.24	0.44	0.30	0.04	
	3	0.01	0.25	0.44	0.20	0.04	
	1	0.02	0.51	0.76	0.00	0.07	

MM	2	0.02	0.49	0.75	0.10	0.07				
	3	0.04	0.49	0.74	0.10	0.09	**NM**	1	0.05	0.26	0.03
		0.10	0.73							

Sample	Replication	Cd (mg/kg)	Cr (mg/kg)	Co (mg/kg)	Pb (mg/kg)	Ni (mg/kg)
	2	0.03	0.24	0.10	0.10	0.81
	3	0.02	0.22	0.13	0.00	0.69
	1	0.03	0.23	0.06	0.00	0.03
CTR	2	0.02	0.21	0.05	0.10	0.01
	3	0.02	0.20	0.05	0.10	0.03

Key: WM = Wurukum Market, MM = Modern Market, NM = North Bank Market, CTR = Control; Cd = Cadmium, Cr = Chromium, Co = Cobalt, Pb = Lead, Ni = Nickel.

Table 2: Mean Heavy Metal Concentration per Market

Market	Cd (mg/kg)	Cr (mg/kg)	Co (mg/kg)	Pb (mg/kg)	Ni (mg/kg)
WM	0.013	0.247	0.433	0.267	0.040
MM	0.027	0.497	0.750	0.067	0.077
NM	0.033	0.240	0.087	0.067	0.743
CTR	0.023	0.213	0.053	0.067	0.023

Table 3: Descriptive Statistics of Heavy Metal Concentrations by Market

Parameter	Market	N	Mean (mg/kg)	SD	Min	Max
Cd	WM	3	0.0133	0.00577	0.01	0.02
	MM	3	0.0267	0.01155	0.02	0.04
	NM	3	0.0333	0.01528	0.02	0.05
	CTR	3	0.0233	0.00577	0.02	0.03
	Total	12	0.0242	0.01165	0.01	0.05
Cr	WM	3	0.2467	0.00577	0.24	0.25
	MM	3	0.4967	0.01155	0.49	0.51
	NM	3	0.2400	0.02000	0.22	0.26
	CTR	3	0.2133	0.01528	0.20	0.23

	Total	12	0.2992	0.12041	0.20	0.51
Co	WM	3	0.4333	0.01155	0.42	0.44
	MM	3	0.7500	0.01000	0.74	0.76
	NM	3	0.0867	0.05132	0.03	0.13
	CTR	3	0.0533	0.00577	0.05	0.06
	Total	12	0.3308	0.29761	0.03	0.76
Pb	WM	3	0.2667	0.05774	0.20	0.30
	MM	3	0.0667	0.05774	0.00	0.10
	NM	3	0.0667	0.05774	0.00	0.10
	CTR	3	0.0667	0.05774	0.00	0.10
	Total	12	0.1167	0.10299	0.00	0.30
Ni	WM	3	0.0400	0.00000	0.04	0.04
	MM	3	0.0767	0.01155	0.07	0.09
	NM	3	0.7433	0.06110	0.69	0.81
	CTR	3	0.0233	0.01155	0.01	0.03
	Total	12	0.2208	0.31687	0.01	0.81

Table 4: One-Way ANOVA of Heavy Metal Concentrations Across Markets

Parameter	Source	df	Sum of Squares	Mean Square	F	Sig.
Cd	Between Groups	3	0.001	0.000	1.923	0.204
	Within Groups	8	0.001	0.000		
	Total	11	0.001			
Cr	Between Groups	3	0.158	0.053	263.153	<0.001
	Within Groups	8	0.002	0.000		
	Total	11	0.159			
Co	Between Groups	3	0.968	0.323	445.284	<0.001
	Within Groups	8	0.006	0.001		
	Total	11	0.974			
Pb	Between Groups	3	0.090	0.030	9.000	0.006
	Within Groups	8	0.027	0.003		
	Total	11	0.117			
Ni	Between Groups	3	1.096	0.365	365.497	<0.001
	Within Groups	8	0.008	0.001		
	Total	11	1.104			

3.2 Discussion

The results of the heavy metals determined in the powdered pepper and control samples are discussed below.

3.2.1 Cadmium (Cd)

Cadmium concentration in the processed pepper samples ranged from 0.0133 mg/kg in Wurukum Market (WM) to 0.0333 mg/kg in North Bank Market (NM), with an overall mean of 0.0242 mg/kg. One-way ANOVA indicated that the variation among markets was not statistically significant ($F = 1.923$, $p = 0.204$), implying a relatively uniform distribution of Cd across all sampling sites. Duncan's Multiple Range Test (DMRT) confirmed this observation, with all market means falling within the same homogeneous subset and showing no significant pairwise differences.

The uniform and low Cd levels suggest that the processing and marketing environments had minimal influence on Cd contamination in the pepper samples. The recorded concentrations are well below the permissible limit of 0.2 mg/kg established by the FAO/WHO Codex Alimentarius Commission (2024) for spices, indicating that the peppers pose no immediate health risk from cadmium exposure.

These results broadly agree with the findings of Asomugha et al. (2016), who reported comparably low cadmium concentrations in natural Nigerian spices, including Capsicum frutescens. Similarly, Onakpa et al. (2018) found Cd levels in Nigerian vegetables to be within safe limits, attributing the low accumulation to limited industrial activity in the production zones and low Cd mobility in the soil. The trace-level presence of cadmium may be attributable to natural soil composition or minor contamination during grinding and packaging. Since Cd is a cumulative toxicant

affecting the kidneys and bones (ATSDR, n.d.), continuous monitoring is still recommended even though current levels are within safe limits.

Prolonged consumption of cadmium-contaminated food has been associated with: • Kidney damage, Bone demineralisation, Liver and lung toxicity, Carcinogenic effects, Cadmium has no known beneficial role in the human body.

3.2.2 Chromium (Cr)

Chromium concentration varied significantly across the markets, ranging from 0.2133 mg/kg in the control (CTR) to 0.4967 mg/kg in Modern Market (MM), with an overall mean of 0.2992 mg/kg. The ANOVA result showed a highly significant difference ($F = 263.153$, $p < 0.001$), indicating that market location substantially influenced Cr content in the pepper samples. Duncan's test identified MM as the group with a significantly higher mean value than the other sources, implying that pepper sold in MM was more contaminated with Cr than that from WM, NM, and the control. The elevated Cr level in MM could be linked to contamination from metallic grinding machines or environmental emissions, as MM is a major urban market with heavy commercial activity and vehicular traffic. Chromium contamination in spices has been reported in several Nigerian studies: Asomugha et al. (2016) similarly reported measurable chromium concentrations in natural Nigerian spices, including pepper, sold in local markets.

Although no universally defined Codex limit exists for Cr in spices, the concentrations observed in this study are lower than the 1.0 mg/kg level suggested by WHO (2019) as tolerable for foodstuffs. However, the high F value and Duncan grouping indicate localised contamination that should not be overlooked. Prolonged ingestion of chromium, particularly the hexavalent form (Cr^{6+}), can cause skin irritation, liver dysfunction, and carcinogenic effects (ATSDR, n.d.). Controlling environmental sources and maintaining equipment hygiene during grinding and packaging are therefore essential preventive measures.

Short-term (acute) exposure may cause nausea, vomiting, and diarrhoea, abdominal pain and ulceration of the mouth and digestive tract.

Long-term (chronic) exposure may cause kidney and liver damage, allergic reactions such as skin rashes and dermatitis, respiratory irritation when inhaled in powder form, and carcinogenic effects, particularly from hexavalent chromium (Cr(VI)), which is associated with lung and stomach cancers.

3.2.3 Cobalt (Co)

Cobalt concentration ranged from 0.0533 mg/kg in the control to 0.7500 mg/kg in MM, with an overall mean of 0.3308 mg/kg. ANOVA revealed a highly significant difference among the markets ($F = 445.284$, $p < 0.001$). Duncan's post hoc grouping showed that MM and WM recorded significantly higher Co levels than NM and the control, indicating that contamination was site-specific.

The higher cobalt concentration in MM and WM could be attributed to contamination from metallic grinding equipment or storage containers. Cobalt, though an essential trace element in small amounts, becomes toxic at higher levels, leading to cardiovascular and thyroid complications (Leyssens et al., 2017).

The mean cobalt (Co) concentration recorded in this study (0.3308 mg/kg) was within the range reported by Asomugha et al. (2016) and Aigberua et al. (2018) in Nigerian spices and culinary condiments, but lower than the 11.117 mg/kg reported by Gaya and Ikechukwu (2016) in ginger, suggesting that cobalt concentrations vary with spice type, source, and potentially environmental and processing conditions.

While international regulatory limits for cobalt in spices are not well defined, the mean values obtained here fall within the range typically observed in foodstuffs (< 1 mg/kg). Nevertheless, the significant statistical differences highlight the need for routine surveillance to minimise unnecessary exposure.

Short-term (acute) effects such as: nausea and vomiting from gastrointestinal irritation, diarrhoea and abdominal pain from mucosal irritation, a metallic taste in the mouth, and skin rashes or dermatitis resulting from cobalt sensitivity or allergy.

Long-term (chronic) effects such as prolonged ingestion or exposure to cobalt may cause haematological, cardiovascular, and neurological effects.

3.2.4 Lead (Pb)

Lead concentration ranged from 0.0667 mg/kg in MM, NM, and the control to 0.2667 mg/kg in WM. ANOVA indicated a significant difference ($F = 9.000$, $p = 0.006$) among the markets, and Duncan's test showed that WM had a significantly higher Pb mean than all other markets, which did not differ significantly among themselves.

This result suggests that pepper sold in WM was more contaminated with Pb, possibly due to environmental pollution, as the market is located close to major roadways with high vehicular traffic. Vehicular exhaust, tyre wear, and lead-containing dust are known contributors to Pb contamination in food, and markets located near busy highways have generally been associated with higher Pb concentrations in food produce than those farther from traffic.

The Pb concentrations recorded in this study (0.0667–0.2667 mg/kg) are below the FAO/WHO (2019) and Codex Alimentarius (2024) permissible limits of 1–3 mg/kg for spices, indicating that although significant differences exist among markets, all values remain within safe consumption limits. Comparable studies, such as Onakpa et al. (2018), also reported Pb levels below 0.3 mg/kg in market-sourced pepper, closely aligning with the present results.
Nonetheless, the relatively higher Pb level in WM raises environmental concerns, as lead is a cumulative toxic metal with neurotoxic, nephrotoxic, and haematological effects, particularly in children and pregnant women (ATSDR, n.d.). Continuous dietary exposure can lead to gradual accumulation; measures such as relocating processing activities away from traffic zones and using lead-free grinders are therefore recommended. Associated health risks include: neurological effects, renal (kidney) damage, cardiovascular effects, reproductive and developmental toxicity, hematological effects.

3.2.5 Nickel (Ni)

Nickel concentration exhibited the widest variation among the metals studied, ranging from 0.0233 mg/kg in the control to 0.7433 mg/kg in NM, with an overall mean of 0.2208 mg/kg. ANOVA showed a highly significant difference ($F = 365.497$, $p < 0.001$), and Duncan's test revealed that NM had a significantly higher mean Ni level than all other markets, indicating that Ni contamination was strongly localised to NM.

The high Ni content in NM samples may be linked to soil contamination, as nickel is a naturally occurring metal in agricultural soils, and its uptake by crops can be influenced by soil pH and organic matter content. Ni contamination could also originate from processing tools or water used during washing or grinding.

The Ni values recorded in this study fall within the range reported for nickel in natural Nigerian spices by Asomugha et al. (2016). Although Codex and FAO/WHO have not established explicit limits for Ni in spices, concentrations above 0.5 mg/kg are generally considered elevated for routine consumption. The Ni concentration recorded in NM (0.7433 mg/kg) therefore warrants further investigation and possible mitigation. Nickel exposure poses risks such as dermatitis, asthma, and gastrointestinal disorders. Continuous monitoring is essential to ensure that levels remain within safe ranges. The high F-value obtained for Ni in this study underscores the influence of local environmental factors and supports the need for improved hygiene and controlled processing conditions.

Acute effects (short-term exposure) may be generally mild, but at higher doses exposure may cause gastrointestinal distress such as nausea, vomiting, and diarrhoea, a metallic taste, and headache or dizziness in sensitive individuals.

Chronic effects (long-term exposure) may lead to hypersensitivity or allergy, kidney and liver dysfunction, respiratory issues if inhaled during grinding or handling, and possible carcinogenic effects.

Overall, the ANOVA results demonstrate that market of origin significantly influenced the concentrations of most heavy metals, with the exception of cadmium. Duncan's post hoc analysis effectively identified the specific markets responsible for elevated metal levels — MM for Cr and Co, WM for Pb, and NM for Ni. These differences may reflect variations in environmental exposure, processing methods, and equipment used during grinding and packaging.

All measured metal concentrations were below the FAO/WHO (2019) and Codex Alimentarius (2024) permissible limits, suggesting that the pepper samples analysed are generally safe for consumption. However, the statistically significant differences observed across markets highlight localised contamination that warrants preventive measures, such as equipment maintenance, the use of stainless-steel grinders, and storage away from polluted environments.

These findings are consistent with previous reports indicating that heavy metal levels in Nigerian spices are highly dependent on market and handling practices (Onakpa et al., 2018; Asomugha et al., 2016). Continuous surveillance, public sensitisation, and enforcement of good agricultural and manufacturing practices remain vital to maintaining safe heavy metal levels in food products.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

The objectives of this study were successfully achieved through the collection of processed powdered pepper samples from Wurukum Market (WM), Modern Market (MM), and North Bank Market (NM), together with a prepared control (CTR). The collected samples were prepared and analysed under the same laboratory conditions, providing a reliable basis for determining and comparing heavy metal concentrations among the sampling locations.

The analysis confirmed the presence of all five selected heavy metals — cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), and nickel (Ni) — in all pepper samples. Cadmium had the lowest overall mean concentration, at 0.0242 mg/kg, while chromium, cobalt, lead, and nickel recorded overall mean concentrations of 0.2992mg/kg, 0.3308 mg/kg, 0.1167 mg/kg, and 0.2208 mg/kg, respectively. Although concentrations varied among markets, all measured values fell within the permissible limits recommended by FAO/WHO and the Codex Alimentarius Commission, indicating that the processed pepper sold in Makurdi is generally safe for consumption.

The detected heavy metal concentrations do not currently pose an immediate health risk, as all values were below the recommended safety limits. However, chromium, cobalt, lead, and nickel showed localised increases in specific markets, suggesting possible contamination from environmental pollution, processing equipment, and handling practices. Because continuous consumption of contaminated food may result in bioaccumulation over time, regular monitoring remains necessary to protect public health and maintain food safety.

The ANOVA results showed that cadmium concentration did not differ significantly among the markets ($F = 275$ 1.923, $p = 0.204$), indicating a relatively uniform distribution. In contrast, chromium ($F = 263.153$, $p < 0.001$), cobalt ($F = 445.284$, $p < 0.001$), lead ($F = 9.000$, $p = 0.006$), and nickel ($F = 365.497$, $p < 0.001$) exhibited statistically significant differences among the sampled markets. Duncan's Multiple Range Test further identified Modern Market as having significantly higher chromium and cobalt concentrations, Wurukum Market as having the highest lead concentration, and North Bank Market as having the highest nickel concentration. These findings demonstrate that market location significantly influenced the concentrations of most heavy metals, with the exception of cadmium.

4.2 Recommendations

Based on the findings of this study, the following recommendations are made:

1. Government agencies such as the National Agency for Food and Drug Administration and Control (NAFDAC) and the Standards Organisation of Nigeria (SON) should routinely monitor heavy metal concentrations in spices and other food products sold in Nigerian markets.

2. Processors should be encouraged to use stainless-steel or food-grade plastic grinders instead of rust-prone metallic equipment that can leach metals into pepper powder. Pepper processing and packaging should be carried out away from high-traffic and industrial areas to minimise exposure to vehicular and airborne contaminants.

4. Awareness campaigns should be organised for traders and consumers on the dangers of heavy metalcontamination and best hygienic practices during drying, grinding, and storage by adopting standardised methods.

Further studies should assess the typical dietary exposure to the selected heavy metals through powdered pepper consumption to estimate the potential health risks to consumers and determine whether the levels pose significant health concerns.

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Hydrogen Fuel Cell Technology for Sustainable Agricultural Machinery: A Review of Opportunities, Challenges and Future Prospects.

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ABSTRACT
Hydrogen fuel cells are emerging as a promising clean energy source for farm machinery, offering a sustainable alternative to traditional diesel-powered engines that contribute significantly to greenhouse gas emissions in the agricultural sector. Despite growing global interest in hydrogen fuel cell (HFC) technology, most applications remain in experimental or early commercial stages. The main objective of this work is to explore the hydrogen fuel cell as an emerging clean energy source for farm machinery. Data were generated from documents and other academic materials from major Data base and analyzed. The analysis revealed that adoption of hydrogen fuel cell across the world is largely at the prototype level. The current application of hydrogen fuel cell on farm machinery is low. Recommendations to overcome these challenges include investments in green hydrogen production, Research and Development in fuel cell technology. By addressing these barriers, hydrogen fuel cells have the potential to reduce the carbon footprint of farming operations, lower fuel costs, and contribute to a more resilient and sustainable agriculture.

Key Words: Hydrogen, Fuel-cell, Agricultural machinery, Energy, sustainable mechanisation; Nigeria.

INTRODUCTION

1.1 Background of the Study

Globally, mechanisation is central to farm productivity and income (Daum, 2023; Liu et al., 2025), yet most field power still comes from diesel. In the United States and European Union, diesel machinery accounts for about 75% of field engines, and land preparation and harvesting alone can exceed 60% of a farm's energy use (Katumwesigye et al.,2025). Tractors, combine harvesters, tillage implements, irrigation pumps, grain processors, and various other machines are essential components of contemporary agricultural mechanization. These machines have traditionally relied heavily on diesel and petrol engines, which are associated with carbon emissions, noise pollution, and increasing fuel costs. Moreover, the agricultural sector, especially in developing countries like Nigeria, is particularly vulnerable to fluctuating fuel prices and supply chain disruptions (Reddy, 2022). Hydrogen fuel cell as an alternative energy source is an electrochemical device that converts the chemical energy of hydrogen directly into electricity, with water and heat as the only by-products. This process eliminates the need for combustion, thereby offering a near-zero emission solution for various energy applications (Sazali *et al.,* 2020).

Despite its potential, the adoption of hydrogen fuel cells in farm machinery faces several challenges. These include the high initial cost of fuel cell systems, the lack of infrastructure for hydrogen production, storage, and distribution, and limited awareness or technical expertise among farmers and equipment operators (Hassan *et al*., 2022).

This work seeks to explore the technical, economic, environmental, and practical implications of hydrogen fuel cells as an emerging clean energy source for farm machinery. It aims to provide a comprehensive understanding of the underlying principles of fuel cell operation, current trends in technology development, potential applications in the agricultural sector, and the challenges that must be addressed to facilitate large-scale adoption.

1.2 Statement of the Problem

Agricultural mechanization in Nigeria and sub-Saharan Africa is predominantly dependent on fossil fuels; namely diesel and petrol; which power most agricultural machinery including tractors, irrigation pumps, and harvesters (Liu *et al.*, 2025; Adepoju *et al.*, 2022). This dependency presents several interlinked challenges that threaten the long-term sustainability and affordability of mechanized farming systems due to the volatility of fossil fuel prices; driven by global market shifts, local subsidy removals, and supply constraints which creates financial unpredictability for farmers and mechanization service providers. (Daum, 2023).

Additionally, the widespread use of diesel engines contributes significantly to environmental degradation, emitting greenhouse gases and air pollutants that exacerbate climate change and degrade rural air quality. These limitations underscore the need for a clean, sustainable, and adaptable energy alternative capable of powering farm operations off-grid.

Hydrogen fuel cells, despite their potential as zero-emission, high-efficiency power sources, remain largely unadopted and under-researched in the agricultural sector of developing economies like Nigeria. There is a critical knowledge and infrastructure gap: stakeholders lack awareness, policy direction is missing, and the technological ecosystem to support hydrogen energy; from production to application, is underdeveloped (Khadem *et al.*, 2017; Ituze, 2017; Behling *et al.*, 2015).

Thus, this seeks to address the persistent problem of unsustainable fossil fuel reliance in agricultural mechanization by examining hydrogen fuel cells as a viable, clean energy alternative, with emphasis on their relevance to Africa's energy and food security agenda.

1.3 Aim and Objectives

1.3.1 General Objective

The general objective of this seminar is to explore the hydrogen fuel cell as an energy source for sustainable agricultural machinery

1.3.2 Specific Objectives

The specific objectives of the seminar are to:

1. Examine the principles and working mechanisms of hydrogen fuel cell technology in relation to energy conversion and power generation.
2. Identify the current applications of hydrogen fuel cells in agricultural machinery and related sectors.
3. Assess the environmental, economic, and operational advantages and propose recommendations for hydrogen fuel cell-powered farm machinery over conventional internal combustion engine (ICE) systems.
4. Evaluate the technological readiness, infrastructure needs, and investment requirements for deploying hydrogen fuel cells in agriculture.
5. Analyze the challenges and barriers limiting the adoption of hydrogen fuel cell technology in the agricultural sector, especially in developing countries like Nigeria.

1.4 Justification of the Study

Traditional fossil fuel-based systems are no longer tenable in the face of climate change, escalating fuel costs, and the need for carbon-neutral farming operations.

Hydrogen fuel cells emit no greenhouse gases or air pollutants during operation; only water and heat as by-products. This makes them an ideal alternative for driving the next generation of clean farm machinery.

Given the current gaps in literature, infrastructure, and policy concerning hydrogen fuel use in agricultural mechanization, particularly in developing economies; this work provides a timely and critical contribution to ongoing discourse on sustainable farm power systems.

1.5 Scope and Limitations

The scope includes a critical review of existing global applications, performance data, environmental benefits, and economic implications of hydrogen-powered agricultural equipment such as tractors, irrigation pumps, and postharvest machinery. This work does not include laboratory experiments, field testing, or first-hand data collection.

2. THEORETICAL ANALYSIS

2.1 Principles of Operation of Hydrogen Fuel Cell

A fuel cell consists of two electrodes – a negative electrode (or anode) and a positive electrode (or cathode) – sandwiched around an electrolyte. Hydrogen is fed to the anode, and oxygen is fed to the cathode. At the heart of the fuel cell lies a simple principle: hydrogen molecules (H_2) are split into protons (H^+) and electrons (e^-) at the anode. The electrons travel through an external circuit, generating electric current to power equipment or machinery, while the protons pass through an electrolyte to the cathode, where they recombine with electrons and oxygen to form water; the only by-product. The process can be summarized by the following reactions (Akyüz *et al.*, 2024):

Anode Reaction: $H_2 \rightarrow 2H^+ + 2e^-$, Cathode Reaction: $½O_2 + 2H^+ + 2e^- \rightarrow H_2O$, Overall Reaction:$H_2 + ½O_2 \rightarrow H_2O$ + Electrical Energy + Heat

Fuel cells are modular and can be stacked to produce different power outputs, ranging from a few watts (for small devices) to several megawatts (for power stations). In agriculture, fuel cells can be scaled to drive mobile machines like tractors or stationary systems like irrigation pumps (Akyüz et al., 2024).

3. METHODOLOGY

3.1 Information Sources and Search Strategy

The study draws insights primarily from secondary data sources for 10 years (2014-2025), including peer-reviewed literature, technical reports, and documented case studies. Scopus, Web of Science and Google Scholar were searched using four concept groups: hydrogen technology (e.g., "hydrogen fuel cell", "PEM fuel cell"); agricultural application (e.g., "agricultural machinery", "tractor"); sustainability framing (e.g., "decarbonization", "low-carbon"); and systems context (e.g., "refueling", "total cost of ownership", "life cycle assessment"). Figures 1–5 are used to support analysis data sets.

3.2 Data Collection and Items

This section contains reports of fuel-cell applications reported from 2014–2025, each with region, machine type, fuel-cell type, efficiency (%), hydrogen consumption (kg h^{-1}), power (kW), emissions (g CO_2 kWh^{-1}), refuelling time (min), adoption status (prototype, under research, commercial use) and source. Records were classified as *mobile field machinery* (tractors, drone), *stationary farm power* (generators, irrigation and water pumps, greenhouse heating) or *non-agricultural* (forklifts, trucks, transport vehicles, barges) and analyzed. Also, Technology application and reported performance or economic metrics were extracted and coded into four themes: technical performance, deployment, economics and infrastructure, and challenges and prospects.

4. RESULTS AND DISCUSSION

4.1RESULTS

(a) ***Adoption of Hydrogen Fuel Cell***

Despite these efforts, Figure1. Shows that many systems remain at the prototype or research stage; highlighting the need for expanded policy support.

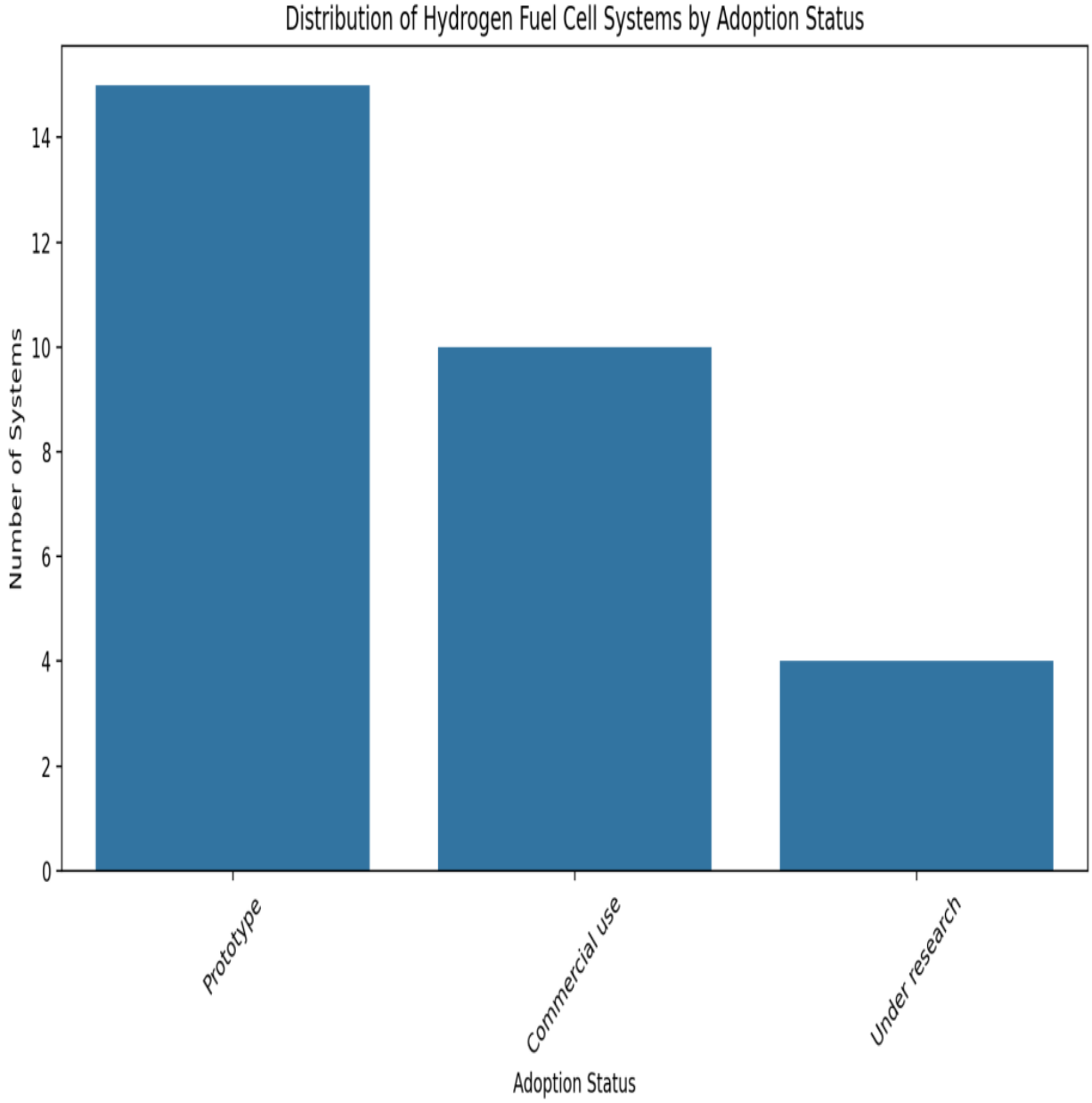

Figure 1: Adoption of hydrogen fuel cell across the world

(b) Composition of the Compiled Dataset

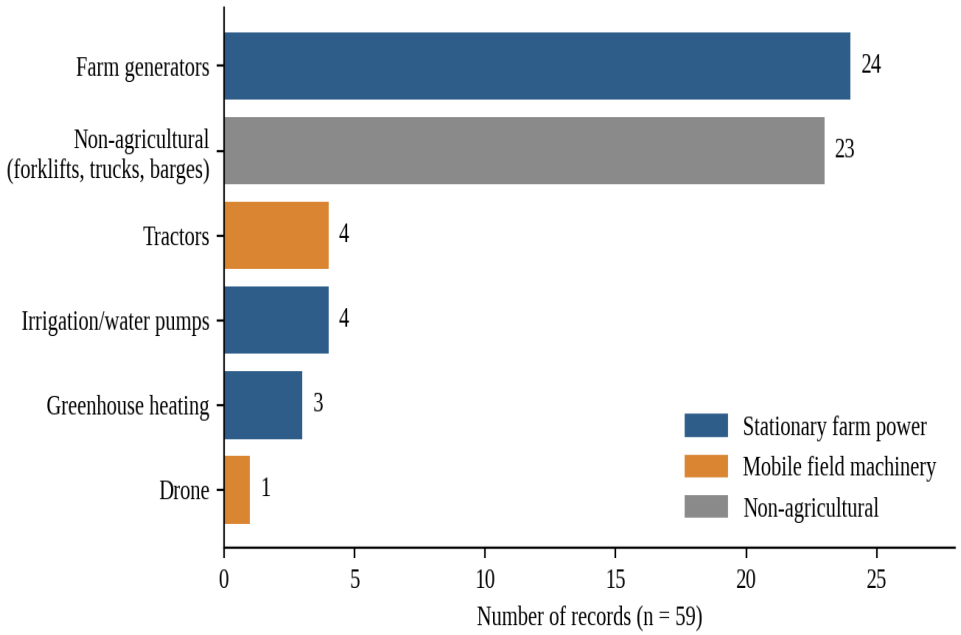

Figure 2: *Composition of the Compiled Dataset by Application (n = 59)*

(C) Technical Performance

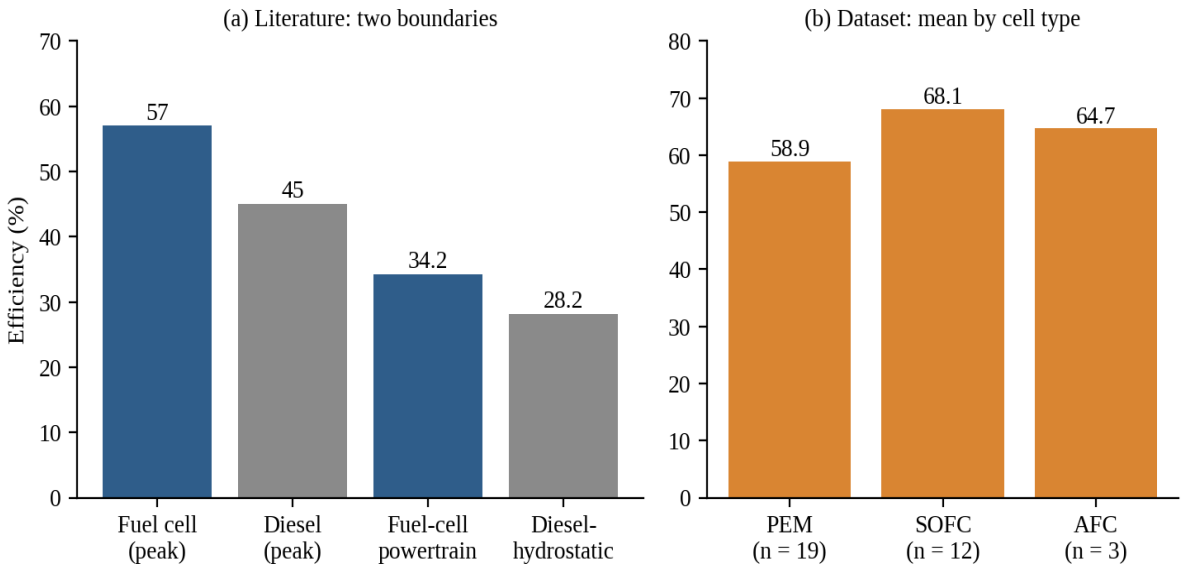

Figure 3: *Efficiency Reported in the Literature and in the Compiled Dataset*

(d) Hydrogen fuel cell consumption

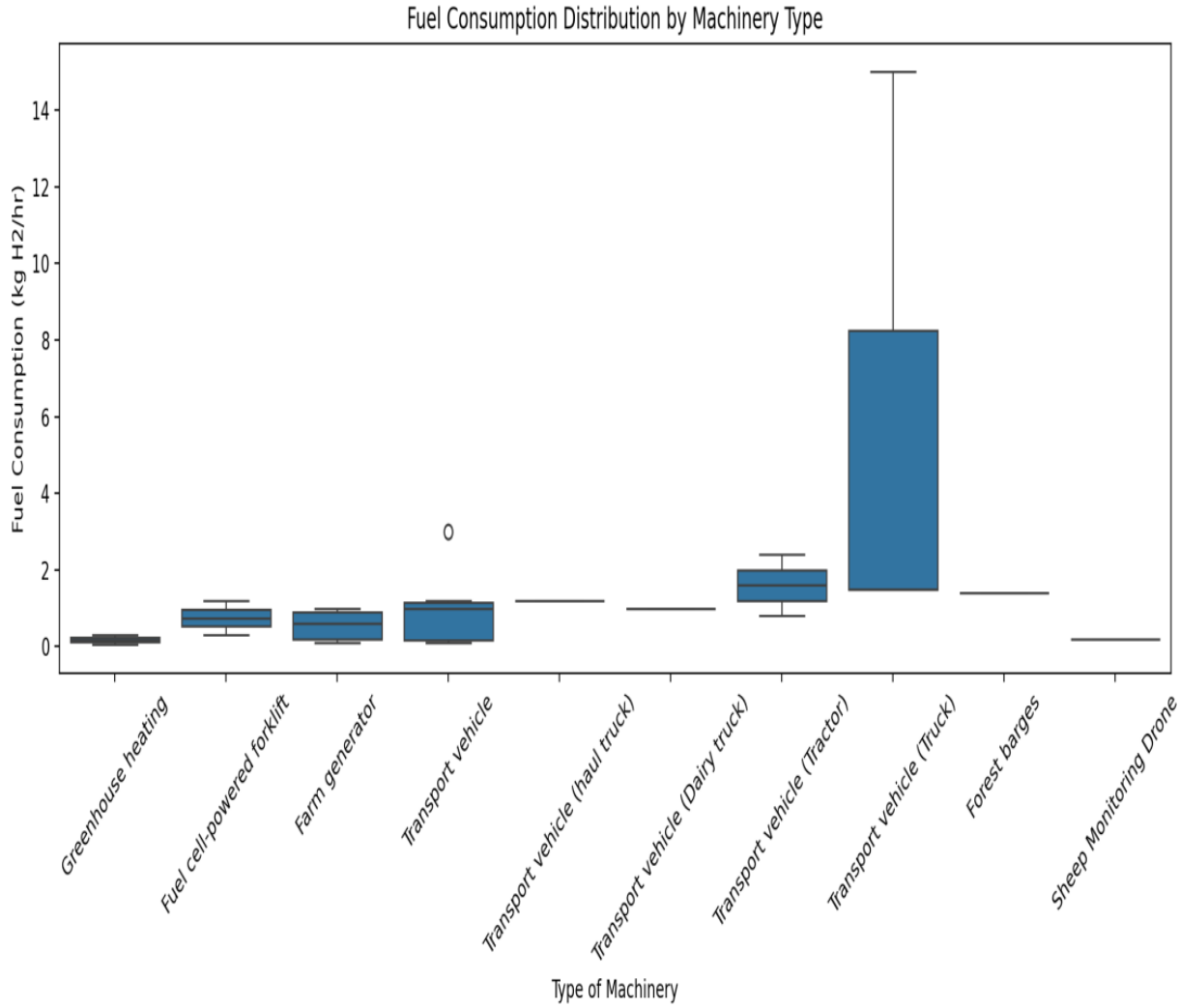

Figure 4: Hydrogen fuel cell consumption for various farm machinery

(e) Carbon emission

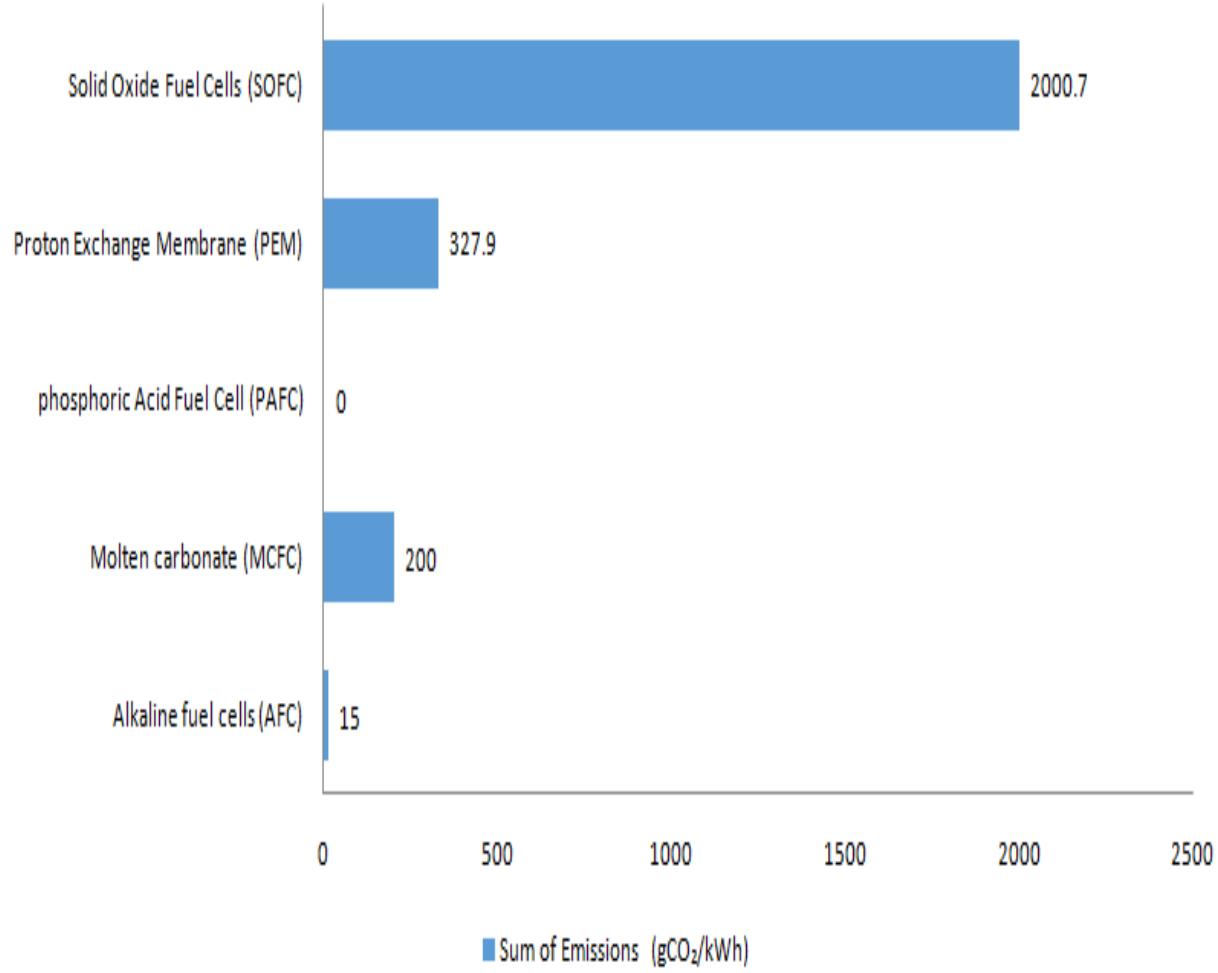

Figure 5: Carbon emission of types of hydrogen fuel cell for farm machinery.

4.2. DISCUSSION

Adoption of Hydrogen Fuel Cell: Figure 1 shows that many systems remain at the prototype or research stage; highlighting the need for expanded policy support. This confirms that while commercial use is growing, further incentives are needed to accelerate adoption, especially in low- and middle-income countries.

Hydrogen fuel cell consumption for various farm machinery Hydrogen-fueled tractors offer longer runtime and faster refueling than battery-electric alternatives, making them more viable for large-scale farming. Figure 4 further demonstrates the energy consumption patterns across different machinery, validating their suitability for energy-intensive fieldwork.

Technical Performance and Fuel Efficiency The data presented reveal that HFCs, especially Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC); offer consistently high efficiency. PEMFC systems commonly operate at 60% efficiency, as observed in hydrogen-powered tractors in Japan and the USA (Behling *et al.*, 2015; Dawnbreaker, 2016), irrigation pumps in Bangladesh (Khadem *et al.*, 2017), and farm

generators in Senegal and New Zealand (Jansen *et al.,* 2018; White *et al.,* 2018). This efficiency outperforms diesel engines, which typically range between 25–35%. As shown in Figure 3, SOFCs lead in thermal efficiency, followed closely by PEMFCs and AFCs. Figure 3 further illustrates that while hydrogen fuel consumption varies, higher efficiencies are maintained across diverse machinery applications, validating the suitability of HFCs for energy-intensive agricultural tasks.

Cost of Production and Operation Operational cost is one of the strongest arguments for adopting hydrogen systems in agriculture. Despite higher capital costs, HFC-powered machines show significant savings in fuel and maintenance. The operating costs are considerably lower than diesel-powered systems, which average $0.5–$1.5/hr depending on location and fuel availability. Additionally, maintenance requirements are consistently reported as "less" or "moderate," suggesting long-term cost reductions.

Emissions and Environmental Benefits: As shown in Figure 5, these applications significantly reduce carbon output compared to diesel-powered systems. As shown in Figure 5, HFC-powered machines produce 0–0.4 gCO_2/kWh, compared to diesel machines that emit over 270 gCO_2/kWh on average. The overall lifecycle emissions of agricultural operations can approach zero, aligning with climate-smart agriculture goals.

4.3 Opportunities, Challenges and Future Prospects

(a) Opportunities

Integration with Smart and Autonomous Agricultural Mechanization

One of the most exciting prospects for hydrogen fuel cells is their synergy with smart and autonomous farming technologies. The demand for clean, lightweight, and long-duration power aligns perfectly with the operational needs of autonomous systems such as: The hydrogen-powered sheep monitoring drone in Australia (PEMFC, 50 W output, 0.2 kg H_2/hr), indicating the feasibility of lightweight applications for precision livestock farming (Spagnuolo *et al.,* 2025).

Hydrogen-fueled irrigation pumps, like those in Bangladesh and the USA, can be automated and controlled remotely using IoT platforms, reducing labor dependency and water use inefficiency (Khadem *et al.,* 2017; Maganza *et al.,* 2023).

Role in Climate-Smart Agriculture and Sustainability

Perhaps the most compelling case for hydrogen in agriculture lies in its role within climate-smart agriculture (CSA); an approach that seeks to improve productivity, resilience, and environmental sustainability.

Maine CSA contributions of hydrogen fuel cells include: Emission reductions: As demonstrated in Figure 3, HFC-powered farm machinery emits 0–0.3 gCO_2/kWh, a stark contrast to the 200–270 gCO_2/kWh typical of

These advancements are gradually reducing the performance-cost gap that once limited hydrogen use in farming. As shown in Figure 1, fuel cell systems are becoming more efficient and applicable to a broader range of agricultural mechanization operations.

(b) Challenges of Hydrogen Fuel Cells

Despite the promise of hydrogen fuel cells, their adoption in farm machinery remains limited due to a range of challenges which include; Hydrogen Production and Storage, Infrastructure and Distribution and Technical and Operational Challenges.

Hydrogen Production and Storage: Hydrogen is a highly efficient and clean-burning fuel, but highly flammable and must be stored and transported with care. This can be a particular concern in agricultural settings, where the potential for accidents is heightened by the use of heavy machinery and the presence of flammable materials. Additionally, the need for specialized equipment and infrastructure to handle hydrogen fuel can also be a challenge (Li *et al*., 2021).

Infrastructure and Distribution: The deployment of hydrogen fuel cells on farms also depends on the availability of hydrogen refueling infrastructure and reliable distribution logistics. Currently, most agricultural

regions, especially in the Global South and Africa; lack even basic hydrogen infrastructure, but with the current interest in hydrogen cell technology, and regulatory frameworks the development of infrastructure may help to address some of the safety and regulatory concerns associated with hydrogen fuel cells, making them more widely accepted and adopted (Ahmed *et al*., 2023).

Fueling Stations: Hydrogen fueling stations are sparse globally and are predominantly located in urban centers to serve automotive applications (Jeon *et al.*, 2024). Table 1 shows that most HFC-powered farm equipment exists in prototype or research phases due to limited access to hydrogen supply chains.

Technical and Operational Challenges: While hydrogen fuel cell (HFC) systems show significant promise for agricultural mechanization, their deployment is often hindered by technical and operational issues; particularly under the harsh conditions commonly encountered in farm environments. These challenges concern the durability of fuel cells, especially in mobile applications, and the complexity of maintenance and servicing, which can affect long-term performance and reliability.

Economic and Policy Barriers: In addition to technical limitations, the widespread adoption of hydrogen fuel cell technology in farm machinery is restricted by several economic and policy barriers. These include the high initial costs of fuel cell systems and the lack of local manufacturing capacity, especially in developing economies.

High Initial Capital Costs: Hydrogen fuel cell systems, especially PEMFC and SOFC; remain capital-intensive technologies, particularly for developing countries and smallholder farmers. The components responsible for high costs include: Platinum-based catalysts, high-pressure or cryogenic hydrogen storage tanks, power conditioning electronics and advanced control systems (Ikumapayi *et al.*, 2024).

Hydrogen fuel cell technology faces several technical, operational, economic, and policy-related challenges that must be overcome to support its broader use in agriculture. While fuel cells offer high efficiency and low emissions, their durability under field conditions, need for specialized servicing, high capital cost, and import dependence limit their appeal; especially for smallholder farmers in emerging economies.

(c) Prospects and Implications for Nigeria

The application of hydrogen fuel cells particularly Proton Exchange Membrane Fuel Cells (PEMFC), has shown promising results. These developments, shown in Figure 1, confirm that hydrogen-fueled tractors are moving from concept to practical application.

Another major advantage of hydrogen fuel cells is their scalability in terms of power output. Table 1 shows a wide range of applications; from small irrigation pumps (2–5 kW) to large-scale farm generators (up to 2000 kW):

These values indicate superior reliability over diesel generators, which typically require more frequent maintenance and overhauls.

For Nigeria, a staged pathway is the more defensible near-term option: first, stationary applications (pumps, generators, greenhouse power) supplied by on-farm or cooperative renewable electrolysis; then pilot hybrid mobile machinery once field durability is demonstrated. The reasoning is that stationary records are the most mature, one on-farm hydrogen source serves both stages, and mobile durability is unvalidated. Neither Nigeria-attributed record cites a source that, by title, reports a field deployment (Ampah et al., 2022; Ikumapayi et al., 2024), so local evidence is effectively absent. Institutional measures proposed in the source material (a national agricultural hydrogen roadmap involving NASENI and FMARD, local-assembly incentives, technician training and curriculum modules) are consistent with these findings but were not tested here.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This seminar has critically examined the role of hydrogen fuel cell technology as a clean, emerging energy source for farm machinery, drawing on documented use cases and performance evaluations from Nigeria, Senegal, South Korea, and beyond. Across various applications; including tractors, irrigation systems, post-harvest processing units, and autonomous agricultural equipment; hydrogen fuel cells have shown remarkable promise. They offer high energy conversion efficiency, particularly Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid

Oxide Fuel Cells (SOFCs), often exceeding 60%, alongside benefits such as low environmental impact, quick refueling times, and zero carbon emissions during operation. For example, South Korea's hydrogen-powered agricultural drones and Senegal's pilot irrigation pumps powered by green hydrogen underscore the global momentum building around this technology.

In Nigeria, however, there remains a gap in hydrogen fuel cell policy and implementation, especially within the agricultural sector. While the National Agency for Science and Engineering Infrastructure (NASENI) and the Federal Ministry of Agriculture and Rural Development (FMARD) have shown interest in renewable technologies, a dedicated transition framework for hydrogen-powered mechanization is yet to be articulated. This represents both a challenge and an opportunity for Nigeria to lead in climate-smart agriculture across Africa. The main barriers identified include; High cost and limited local production of green hydrogen, Storage and distribution challenges, particularly in rural areas, Safety concerns, and lack of rural infrastructure and skilled technical personnel in many developing countries. Technical durability under harsh farm conditions and the need for specialized maintenance also remain challenges, especially in regions with limited engineering expertise. Despite these barriers, the growing body of international research, field trials, and policy support suggests a promising trajectory for HFC integration in agricultural systems.

In conclusion, to unlock the full potential of hydrogen in Nigeria's agriculture, stakeholders must act collectively and urgently. From building rural hydrogen hubs to investing in engineering education, the time to act is now..

6.2 Recommendations

1. Develop a National Hydrogen Transition Plan for Agriculture: Nigeria should create a roadmap that integrates hydrogen fuel cell deployment into the agricultural sector. This should be led by NASENI in collaboration with FMARD and supported by the Ministry of Power and Ministry of Science and Technology.
2. Incentivize Local Production and Deployment: Introduce tax incentives, grants, and subsidies to support local manufacturing and importation of hydrogen fuel cell components for agricultural use.
3. Foster Public–Private Partnerships (PPPs): Encourage collaboration between government bodies, universities, start-ups, and international partners to pilot hydrogen-based farm machinery in selected regions.
4. Invest in Technical Training and Infrastructure: Establish hydrogen training hubs in agricultural colleges and equip rural technicians through capacity-building programs.

5Leverage Regional Models: Learn from Senegal's decentralized hydrogen micro grid for irrigation and South Korea's hydrogen-powered agricultural technology to inform Nigeria's adaptation strategies.

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Paper ID 32:
Integrated Climate-Resilient and Smart Agricultural Engineering Framework for Sustainable Food Security in the Niger Delta: A Case Study of Bayelsa State, Nigeria

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ABSTRACT
The Niger Delta of Nigeria possesses substantial agricultural, fisheries, forestry, and aquatic resources; yet its contribution to sustainable food security is increasingly threatened by flooding, climate variability, soil degradation, oil pollution, salinity intrusion, inadequate agricultural infrastructure, post-harvest losses, and limited access to modern technologies. Bayelsa State represents one of the most environmentally vulnerable parts of the Niger Delta because of its extensive network of rivers, creeks, wetlands, mangrove ecosystems, and low-lying agricultural landscapes. The state's riverine geography creates both opportunities and constraints for agricultural development. Recent studies have reported that farmers and fishermen in Bayelsa are experiencing declining crop yields, reduced fish resources, changing rainfall patterns, increasing temperatures, and recurrent flooding. This paper proposes an Integrated Climate-Resilient and Smart Agricultural Engineering Framework (ICRSAEF) for Bayelsa State. The framework combines climate-smart agriculture, geospatial technology, artificial intelligence, precision agriculture, water-resource engineering, sustainable soil and land management, renewable-energy systems, resilient agricultural structures, mechanisation, aquaculture, and post-harvest technologies. Geographic Information Systems (GIS), remote sensing, Internet of Things (IoT) sensors, and artificial intelligence can be integrated to identify flood-prone agricultural areas, monitor soil and water conditions, guide crop selection, and improve early-warning systems. Engineering interventions such as raised-bed and floating agriculture, controlled drainage, solar-powered irrigation, rainwater harvesting, elevated processing facilities, cold-chain systems, and renewable-energy-powered agro-processing are proposed. The paper argues that agricultural engineering interventions in Bayelsa should not simply attempt to reproduce conventional upland farming systems. Instead, agricultural development should be designed around the state's wetland, riverine, and coastal environment. A coordinated approach involving government, communities, universities, engineers, farmers, private investors, and environmental regulators is therefore recommended. The proposed framework can contribute to increased food production, reduced climate vulnerability, improved livelihoods, environmental restoration, and sustainable agro-industrial development in the Niger Delta.

Keywords: Climate-smart agriculture, Bayelsa State, Niger Delta, agricultural engineering, GIS, artificial intelligence, flooding, soil management, renewable energy, sustainable food security, aquaculture.

1. Introduction

Agriculture remains a fundamental component of food security, employment, and rural livelihoods in Nigeria. However, climate change and environmental degradation are rapidly changing the operational conditions under which agricultural production occurs across the country. The Nigerian National Climate Change Policy explicitly identifies agriculture as highly vulnerable to climate shifts and calls for more resilient, highly productive, and climate-smart agricultural systems that optimize the management of land, water, soil nutrients, and genetic resources.

The Niger Delta presents a particularly complex agricultural environment. The region consists of extensive wetlands, river systems, creeks, floodplains, mangrove forests, freshwater swamps, and delicate coastal ecosystems. Bayelsa State is situated at the geographic core of this environment, possessing a predominantly riverine and estuarine landscape. According to the Bayelsa State Government, the state covers approximately 10,773 km² and comprises eight Local Government Areas (LGAs): Ekeremor, Kolokuma/Opokuma, Yenagoa, Nembe, Ogbia, Sagbama, Brass, and Southern Ijaw.

This unique geography provides significant comparative advantages for rice cultivation, cassava, plantain, vegetable production, aquaculture, and capture fisheries. However, severe climate variability, seasonal overflow from the River Niger and River Benue systems, coastal storm surges, and environmental pollution from hydrocarbon exploration present major existential threats to farming communities. Conventional upland agricultural engineering models have proven largely ineffective in this unique hydrologic regime. Consequently, there is an urgent need for an integrated engineering framework tailored to wetland and aquatic ecosystems.

2. Problem Statement & Baseline Vulnerabilities in Bayelsa State

Agricultural development in Bayelsa State faces multi-dimensional challenges stemming from natural hydrological conditions, anthropogenic disruptions, and infrastructural deficits:

- **Recurrent Flooding & Inundation:** Seasonal flood waves submerge thousands of hectares of farmland across Yenagoa, Sagbama, Kolokuma/Opokuma, and Southern Ijaw LGAs, destroying staple crops prior to harvest and sweeping away aquaculture stock.
- **Soil Degradation & Salinity Intrusion:** Intense rainfall causes severe nutrient leaching in freshwater swamps, while sea-level rise and tidal surges drive salt water into coastal agricultural lands in Brass, Ekeremor, and Nembe, rendering topsoil unproductive.
- **Oil Spill Contamination:** Decades of crude oil spillage have severely polluted terrestrial soils and aquatic bodies, destroying soil bio-flora, reducing crop germination rates, and contaminating aquatic habitats.
- **Infrastructure Deficits & Post-Harvest Losses:** The lack of climate-resilient storage, elevated processing units, and cold-chain logistics in riverine communities leads to post-harvest crop and fish losses exceeding 40-50%.

2.1 Agro-Ecological Vulnerability Mapping Across Bayelsa LGAs

LGA Zone	Primary Agro-Ecological Feature	Key Engineering & Climate Threats
Sagbama, Kolokuma/Opokuma, Yenagoa	Freshwater Alluvial Floodplains	Severe seasonal river flooding, siltation, bank erosion, crop submersion.
Southern Ijaw, Ekeremor	Freshwater Swamps & Lowland Creeks	Prolonged waterlogging, crude oil pollution, transport constraints.
Brass, Nembe	Coastal Mangrove & Brackish Water Zone	Salinity intrusion, storm surges, coastal erosion, tidal inundation.
Ogbia	Mixed Freshwater / Brackish Transition	Seasonal flooding, topsoil acidity, post-harvest fish/crop spoilage.

Table 1: Agro-ecological distribution and predominant climate hazards in Bayelsa State.

3. The Integrated Climate-Resilient & Smart Agricultural Engineering Framework (ICRSAEF)

To address these persistent environmental and structural vulnerabilities, this paper proposes the ICRSAEF model. Rather than forcing terrestrial farming norms onto a wetland terrain, ICRSAEF adapts engineering designs to harmonize with the hydrologic reality of Bayelsa State.

3.1 Key Engineering Pillars of the Framework

1. Precision Agriculture & Smart Geospatial Monitoring: Deployment of GIS, multi-spectral satellite remote sensing, and IoT sensors for real-time monitoring of soil moisture, salinity levels, water pH, and early-warning flood modeling.

2. Wetland-Adapted Agricultural Structures & Water Engineering: Design of raised-bed farming systems, floating agricultural rafts, controlled dykes, solar-powered irrigation, and polder systems to enable year-round production despite flood cycles.

3. Renewable-Energy-Powered Processing & Cold-Chain Logistics: Integration of solar photovoltaic systems and mini-grids to power elevated processing facilities, solar fish dryers, and ice-making plants in off-grid riverine communities.

4. Climate-Resilient Aquaculture & Integrated Farming: Constructing elevated fish ponds, floating cages, and recirculating aquaculture systems (RAS) integrated with crop production (aquaponics) to safeguard aquatic stock from floods.

5. Sustainable Soil Remediation & Land Management: Implementation of bio-remediation techniques, organic soil amendments, and controlled lime application to manage oil-polluted soils and acidic sulphate wetlands.

4. Implementation Strategy & Policy Recommendations

Successful operationalization of the ICRSAEF requires a synchronized multi-stakeholder governance structure involving institutional, financial, and community actors:

- **Establishment of Agricultural Engineering Innovation Hubs:** Set up specialized state-backed engineering technology transfer centers in Bayelsa to fabricate low-cost, locally adapted equipment such as solar dryers, floating rafts, and small-scale threshers.
- **Inter-Agency Collaborative Governance:** Form a multi-disciplinary taskforce comprising the Bayelsa State Ministry of Agriculture, Ministry of Environment, Niger Delta Development Commission (NDDC), engineering bodies (NSE/NIAE), and local community leaders.
- **Private Sector & Diaspora Investment Incentives:** Develop public-private partnership (PPP) frameworks and green finance windows to attract investment in solar-powered cold storage and riverine agro-logistics.
- **Community Capacity Building & Digital Literacy:** Train rural farmers, youth, and women cooperative groups on IoT tool usage, climate-smart agronomy, and simple equipment maintenance.

5. Conclusion

The Niger Delta, and Bayelsa State in particular, stands at a critical juncture where conventional agricultural approaches are no longer viable in the face of severe climate change impacts and hydrologic hazards. The proposed Integrated Climate-Resilient and Smart Agricultural Engineering Framework (ICRSAEF) offers a transformative roadmap that embraces the riverine ecosystem rather than combating it. By synergizing artificial intelligence, geospatial intelligence, renewable energy, and resilient water resource engineering, Bayelsa State can mitigate flood risks, eliminate post-harvest losses, ensure sustainable food security, and serve as a benchmark for wetland agricultural engineering across Sub-Saharan Africa.

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Paper ID 33:
Post-Harvest Engineering and Value Addition Technologies: A Case Study of Bayelsa State, Nigeria

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ABSTRACT

Bayelsa State occupies a strategic position in Nigeria's Niger Delta agricultural economy, with substantial potential for cassava, plantain, rice, cocoyam, vegetables, oil palm, and fisheries. However, the benefits of agricultural production are substantially constrained by post-harvest losses, inadequate storage and processing facilities, poor rural logistics, flooding, high humidity, limited access to electricity, weak market linkages, and low adoption of appropriate technologies. These challenges are particularly important in Bayelsa because a large proportion of its communities are riverine and depend on waterways for movement of agricultural commodities. This paper examines post-harvest engineering and value addition technologies applicable to Bayelsa State and develops a climate-resilient value-chain framework for reducing losses and increasing the economic value of agricultural products. The study adopts a qualitative case-study approach based on a review of published studies, government information, and technical literature on post-harvest management, agricultural value chains, and Bayelsa's agricultural environment. Particular attention is given to cassava, plantain, rice, and fish value chains. Evidence from Bayelsa indicates that flooding can substantially reduce farm profitability and contribute to crop spoilage and forced early harvesting. Recent research on plantain production in Southern Ijaw, for example, found considerably lower net farm income during flooded years than during non-flooded years. The paper proposes integrated interventions including solar-powered cold rooms, improved fish smoking kilns, solar and hybrid dryers, hermetic storage, modular cassava processing units, improved rice milling, moisture monitoring, digital traceability, improved packaging, aggregation centres, waterway-based agro-logistics, and decentralized renewable-energy systems. The paper argues that post-harvest engineering should not be treated as a single storage intervention but as an integrated system linking harvesting, handling, transportation, drying, processing, packaging, storage, marketing, waste utilization, and digital information. Such an approach can reduce food losses, create rural employment, improve food safety, and strengthen Bayelsa's transition from primary agricultural production to agro-industrial development.

Keywords: Post-harvest engineering; value addition; Bayelsa State; agricultural value chains; cold chain; solar drying; cassava; plantain; rice; fisheries; climate resilience.

1. Introduction

Agriculture remains central to Nigeria's food security, employment, and rural economy. FAO reports that agriculture contributed approximately 28% of Nigeria's GDP between 2021 and 2024 and employed about 40% of the labour force during the period. However, inadequate technology, weak market access, climate change, poor infrastructure, and post-harvest losses continue to constrain the sector.

The challenge is not only how much food Nigeria produces, but how much of that production reaches consumers in good condition and at an economically viable price. Post-harvest losses occur during harvesting, handling, transportation, drying, threshing, processing, and storage. Moisture, heat, pests, microbial deterioration, mechanical damage, and poor storage conditions can cause both quantitative and qualitative losses.

Bayelsa State presents a particularly important case for post-harvest engineering. The state's riverine geography, extensive waterways, high rainfall, humid tropical climate, and recurrent flooding create both opportunities and constraints for agriculture. Southern Ijaw and other riverine areas contain communities where farming and fishing are closely integrated with water-based transportation and local markets. Research on Southern Ijaw describes agriculture, fishing, palm-oil processing, and trading among the major livelihood activities.

The agricultural potential is considerable. Recent work on Bayelsa identifies cassava, plantain, cocoyam, vegetables, and swamp rice among crops suited to the state's ecological conditions, while fisheries are supported by the extensive aquatic environment.

The central challenge, therefore, is to move from a production-oriented agricultural system to a production-plus-preservation-plus-processing-plus-market system. Post-harvest engineering provides an important pathway for achieving this transition.

2. Problem Statement

Bayelsa's agricultural commodities experience losses and declining quality because production is frequently disconnected from appropriate post-harvest infrastructure. The major problems include:

- Inadequate farm-level storage facilities;
- Insufficient drying infrastructure;
- Poor handling of highly perishable commodities;
- Inadequate cold-chain facilities for fish and fresh produce;
- Limited access to reliable electricity;
- Difficult movement of agricultural products from riverine communities;
- Poor road and waterway logistics;
- Flooding of farms, storage facilities, and processing areas;
- Limited access to modern processing machinery;
- Inadequate packaging and grading systems;
- Weak aggregation and market information systems;
- Limited access to finance for smallholder farmers and processors; and
- Low adoption of modern post-harvest technologies.

Evidence from Bayelsa demonstrates that flooding is already an important economic constraint. A 2024 study of plantain farmers in Southern Ijaw reported net farm income of approximately ₦74,617/ha during a flooded year compared with ₦231,575/ha during a non-flooded year. Farmers reported coping through early harvesting, movement to alternative crops, fishing, and other measures.

A recent 2026 study of cassava farmers in Bayelsa similarly identified spoilage, low production, and loss of farm assets among problems associated with flooding, while early planting, early-maturing varieties, and storage facilities were among farmers' coping strategies. These findings demonstrate that post-harvest management in Bayelsa must be designed as part of a broader climate-resilience strategy.

3. Aim and Objectives

3.1 Aim

The aim of this paper is to examine post-harvest engineering and value addition technologies capable of reducing agricultural losses and improving agro-industrial development in Bayelsa State.

3.2 Specific Objectives

1. Examine the major post-harvest challenges affecting agricultural value chains in Bayelsa State;
2. Identify appropriate engineering technologies for reducing post-harvest losses;
3. Examine value-addition opportunities for major Bayelsa commodities;
4. Develop a climate-resilient post-harvest value-chain framework for the state;
5. Assess opportunities for renewable-energy-powered post-harvest systems; and
6. Recommend engineering, institutional, and policy interventions for sustainable agro-industrial development.

4. Methodology

This study adopts a qualitative case-study and literature-review approach. Information was synthesized from:

- Published studies on agriculture and post-harvest losses in Bayelsa State;
- Studies on flooding and agricultural production in the state;
- Government information on agricultural programmes;
- FAO technical literature on post-harvest management;
- World Bank literature on food loss and agricultural value chains; and
- Engineering principles relating to drying, storage, processing, cold-chain management, renewable energy, and logistics.

The analysis focuses on four representative commodity groups: cassava, plantain, rice, and fish. These commodities were selected because they represent important food, livelihood, and value-addition opportunities in Bayelsa and illustrate different post-harvest engineering requirements. The study does not present new primary survey data. Instead, it develops an engineering framework from existing evidence and proposes technologies that can be tested and scaled through pilot projects.

5. Agricultural and Post-Harvest Context of Bayelsa State

Bayelsa is characterized by extensive waterways, wetlands, floodplains, and riverine settlements. More than three-quarters of the state's area has been reported as water-covered, creating significant implications for agricultural transportation, infrastructure, and market access.

The same environment provides opportunities for rice cultivation, cassava, plantain, fisheries, and other agricultural activities. The state government's recent agricultural programmes have placed emphasis on rice, cassava, and plantain production, while also supporting farmer training in areas such as irrigation and post-harvest management.

However, increasing production without simultaneous investment in post-harvest infrastructure may simply increase the quantity of produce exposed to losses. The engineering priority should therefore be:

Produce → Harvest → Handle → Transport → Dry/Cool → Process → Package → Store → Aggregate → Market → Recycle Waste

6. Major Post-Harvest Challenges

6.1 High Humidity and Rainfall

High atmospheric humidity makes drying difficult and increases the risk of mould development and deterioration. Traditional open-air drying exposes products to rain, dust, insects, rodents, animals, microbial contamination, and prolonged drying periods. FAO identifies drying, storage moisture, and poor environmental conditions as important contributors to post-harvest deterioration.

6.2 Flooding

Flooding is one of the most significant environmental constraints to agricultural production and post-harvest operations in Bayelsa. Flooding can destroy standing crops, prevent timely harvesting, submerge stored commodities, damage processing equipment, cut off road access, increase transportation costs, force premature harvesting, interrupt market access, and increase spoilage.

A 2024 study of plantain production in Southern Ijaw identified prolonged rainfall, overflowing rivers, poor drainage, and blocked natural water channels among factors contributing to flooding. Consequently, post-harvest facilities in Bayelsa should be designed with flood-resilient foundations, elevated platforms, drainage systems, and water-access logistics.

7. Commodity-Specific Post-Harvest Engineering Solutions

7.1 Cassava Value Chain

Fresh cassava roots deteriorate rapidly after harvesting. The engineering strategy should therefore reduce the time between harvesting and processing.

Recommended technologies include modular cassava processing centres that integrate mechanical peeling, washing, grating, pressing, sieving, fermentation, drying, milling, and packaging. Potential value-added products include gari, high-quality cassava flour (HQCF), starch, cassava chips, animal feed, industrial flour, and ethanol feedstock.

7.2 Plantain Value Chain

Plantain is highly susceptible to physical damage and accelerated ripening. Research in Yenagoa has previously examined the relationship between post-harvest losses and profitability among plantain farmers, demonstrating the economic importance of post-harvest management.

Recommended technologies include ventilated plastic crates, padded harvesting systems, low-cost ripening chambers, solar dryers, and processing equipment for plantain flour and chips. Value-added products include plantain flour, chips, dried plantain, snacks, and baby-food ingredients.

8. Rice Post-Harvest Engineering

Rice production has considerable potential in Bayelsa, particularly in suitable floodplain and swamp environments. The major engineering challenge is achieving effective: harvesting → threshing → drying → milling → grading → packaging → storage.

8.1 Mechanical Harvesting: Small and medium-scale rice farmers can benefit from mini combine harvesters, reapers, threshers, and mechanical winnowers.

8.2 Mechanical or Solar-Assisted Drying: Recommended technologies include batch dryers, continuous-flow dryers, solar-assisted dryers, biomass-assisted dryers, and hybrid solar-electric dryers.

8.3 Improved Rice Mills: Modern rice mills can improve milling recovery, grain appearance, cleanliness, grading, packaging quality, and market value.

9. Fisheries and Fish Value Chain

Fisheries represent a particularly important post-harvest opportunity in Bayelsa because many communities are located along rivers and creeks. Fish is highly perishable and requires rapid preservation after capture.

9.1 Improved Smoking Kilns: Traditional systems expose processors to smoke and excessive heat. Improved kilns provide controlled airflow, uniform heat distribution, reduced fuel consumption, and safety.

9.2 Solar Fish Dryers: Solar dryers reduce dependence on firewood and protect fish from rain and contamination.

9.3 Solar-Powered Cold Rooms: Small modular cold rooms located at fishing hubs (Solar PV → Charge Controller → Battery → Refrigeration Unit → Cold Room) provide essential cold storage in off-grid riverine communities.

10. Solar and Renewable Energy for Post-Harvest Systems

Energy availability is a major constraint to agricultural processing. A decentralized renewable-energy architecture (Solar PV + Battery Storage + Efficient Motors + Thermal Storage + Smart Controls) is proposed to power cassava graters, rice mills, dryers, cold rooms, freezers, and packaging machines.

11. Storage Technologies

11.1 Hermetic Storage: Reduces oxygen/moisture movement, controlling storage insects and mould in dry crops such as rice and maize.

11.2 Elevated Flood-Resilient Stores: Storage structures in Bayelsa should be raised above known flood levels, fitted with moisture sensors, built with durable materials, and accessible by both road and water.

12. Smart Post-Harvest Technologies

Post-harvest engineering should incorporate digital technologies including IoT-based sensors for real-time monitoring of temperature/humidity, digital traceability via QR codes for food safety, and AI tools for demand forecasting, spoilage prediction, and route optimization.

13. Water-Based Agro-Logistics

Because of Bayelsa's extensive waterway network, agricultural logistics must integrate water transport. A water-based agro-logistics model includes motorized agricultural boats, floating aggregation platforms, insulated fish containers, and solar-powered cold boxes.

14. Integrated Bayelsa Post-Harvest Value-Chain Model

The framework transforms post-harvest management from an isolated farm task into a regional agro-industrial system:

PRODUCTION (Cassava / Plantain / Rice / Fish)
↓
TIMELY HARVESTING & PRIMARY HANDLING (Cleaning, Sorting, Grading)
↓
CLIMATE-RESILIENT LOGISTICS (Road + Water Transport)
↓
PRESERVATION (Solar Drying, Cold Storage, Improved Kilns, Hermetic Bags)
↓
PROCESSING & PACKAGING (Flour, Gari, Chips, Packaged Rice, Smoked Fish)
↓
DIGITAL MARKET LINKAGES & BY-PRODUCT UTILIZATION (Feed, Compost, Bioenergy)

15. Proposed Engineering Intervention Matrix

Commodity	Major Loss Point	Recommended Technology	Value-Added Product
Cassava	Delayed processing	Modular processing centre	Gari, flour, starch, chips
Plantain	Bruising / rapid ripening	Improved crates, drying & processing	Flour, chips, dried plantain
Rice	Drying & inefficient milling	Mechanical dryer & modern rice mill	Graded packaged rice

Fish	Rapid spoilage	Solar cold room & improved kiln	Chilled, smoked & dried fish
Vegetables	High perishability	Solar dryer / solar cold storage	Dried vegetables, fresh produce
Oil palm	High processing losses	Improved small-scale mills	Palm oil, kernel products
Mixed crops	Poor rural logistics	Aggregation centres & water transport	Bulk marketable produce

Table 1: Matrix of commodity loss points, recommended engineering technologies, and targeted value-added outputs.

16. Proposed Pilot Projects for Bayelsa State

- **Pilot 1: Solar-Powered Riverine Agro-Processing Hub -** Integration of solar PV, cassava processing, rice milling, solar dryers, cold storage, and digital market access in key riverine locations.
- **Pilot 2: Community Fish Cold Chain -** Establishing solar cold boxes and cold rooms across fishing points to eliminate fish spoilage.
- **Pilot 3: Flood-Resilient Agricultural Storage -** Elevated warehouses equipped with moisture sensors, hermetic storage, and flood warning integrations.
- **Pilot 4: Mobile Processing Units -** Deploying mobile cassava graters, rice threshers, and fish kilns to remote communities.

17. Circular Economy Opportunities

Post-harvest engineering addresses waste by converting cassava peels into livestock feed/biogas, rice husk into biomass briquettes, plantain residues into compost/fibre, and fish offal into fishmeal or organic fertilizer.

18. Gender and Youth Dimensions

Programs should explicitly involve women and youth in equipment operation, digital logistics, processing enterprises, equipment maintenance, and cold-chain management.

19. Financing and Business Models

A 'Processing-as-a-Service' pay-per-use model is recommended to make machinery affordable to smallholder farmers through cooperatives and public-private partnerships.

20. Environmental and Climate Considerations

Interventions emphasize renewable energy, flood-resilient civil engineering, natural ventilation, and reduced biomass combustion to maintain climate-smart standards.

21. Institutional Framework

Effective execution relies on collaboration between the Bayelsa State Government (policy/standards), Universities/NDU (technology adaptation/training), Private Investors (operating cold facilities/processing units), and Farmer Cooperatives (aggregation/user base).

22. Policy Recommendations

- Establish the Bayelsa State Post-Harvest Engineering Programme;
- Develop commodity-specific processing clusters for cassava, rice, plantain, and fish;

- Establish solar-powered cold-chain hubs in riverine communities;
- Promote community solar drying centers;
- Construct elevated flood-resilient storage infrastructure;
- Promote water-based agro-logistics with motorized agricultural boats;
- Establish equipment leasing schemes for smallholder cooperatives;
- Strengthen agricultural extension in post-harvest engineering;
- Create digital agricultural market platforms; and
- Target technical and financial support to youth and women-owned agro-enterprises.

23. Conclusion

Bayelsa State possesses significant agricultural and fisheries potential, but the economic benefits of production are constrained by post-harvest losses, inadequate infrastructure, flooding, poor logistics, limited processing capacity, and unreliable energy supply. The solution is not simply to increase production. Bayelsa requires an integrated post-harvest engineering and value-addition ecosystem that preserves agricultural products, transforms raw materials into higher-value commodities, and connects rural producers with markets.

"Produce more, lose less, process better and earn more."

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MECHANIZATION OF PALM OIL PROCESSING IN SOUTHERN NIGERIA: STATUS, CHALLENGES, PROSPECTS AND OPPORTUNITIES – A REVIEW

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Abstract

Palm oil is one of Nigeria's most important agricultural commodities, and Southern Nigeria, where the oil palm (Elaeis guineensis) is indigenous and widely cultivated, is the centre of production. National output of about 1.4–1.5 million tonnes (Mt) falls short of demand, estimated at about 1.9 to over 2.5 Mt depending on the source, and the Federal Government puts annual palm oil import spending at USD 500–600 million. This narrative review examines the status of palm oil processing mechanization in Southern Nigeria, its constraints and its prospects, using peer-reviewed literature and government, institutional and industry reports published between 2014 and 2026. Mechanization is concentrated in digestion and oil extraction; harvesting, fruit bunch evacuation, packaging and waste handling remain largely manual. The sector has two tiers: industrial estates with imported, automated lines, and smallholders, who are the majority of producers, using locally fabricated or semi-mechanized equipment with lower extraction efficiency, variable oil quality and higher maintenance needs. The main constraints are capital cost and limited credit, unreliable power and poor rural roads, a shortage of skilled technicians, ageing plantations that limit fruit supply, weak research–industry linkages, inconsistent fabrication quality, and unmanaged mill waste. Prospects include the demand gap, public–private estate programmes, improving indigenous fabrication, biomass and biogas use of mill residues, and low-cost process monitoring. Progress depends on fabrication standards and testing, finance and leasing models for smallholders, rural infrastructure and technical training.

Keywords: palm oil processing; mechanization; Southern Nigeria; digester; screw press; review

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) is a leading source of edible oil, industrial raw material and bioenergy feedstock, and supports food security, employment and rural incomes in tropical countries (Murphy *et al.*, 2021). Indonesia and Malaysia produce about 82% of projected 2026/27 world output (United States Department of Agriculture [USDA], 2026), whereas Nigeria, though Africa's largest producer, supplies under 2%. Nigeria led world production and export until the mid-1960s, when it supplied more than 40% of world output (Federal Ministry of Agriculture and Food Security [FMAFS], 2026). Output then lagged because of several factors, including policy and investment shifts during the oil boom, disruption of the eastern oil palm belt during the civil war, ageing plantations, and sustained investment in Southeast Asia (Shehu & Salleh, 2020). Nigeria now produces about 1.4 Mt against demand above 2.5 Mt and spends USD 500–600 million a year on imports (FMAFS, 2026); other estimates of demand are lower, so the deficit is best read as a range (Section 4.1).

Southern Nigeria is the country's principal oil palm belt because of its rain-forest climate and soils, and oil palm clusters form where suitable climatic and soil conditions prevail (Partnership Initiatives in the Niger Delta [PIND]

Foundation, n.d.-b). In the nine Niger Delta states of Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo and Rivers, some 690 oil palm clusters have been mapped (PIND Foundation, n.d.-b), and processing mills and studies are also reported in the South-East and in Ogun and Osun states in the South-West (Owolarafe *et al.*, 2024; Agbogo *et al.*, 2026). The industry supports many households through cultivation, processing, transport and trade, and smallholders produce about 80% of national output (PIND Foundation, n.d.-a; Bankole *et al.*, 2018). Most production remains with smallholders and artisanal processors who rely on traditional or semi-mechanized methods characterized by low efficiency, high labour demand and poor oil quality (PIND Foundation, n.d.-a; Anyaoha & Zhang, 2023).

Mechanization is widely regarded as essential for reviving the industry (Afrinvest, 2025; Agbogo *et al.*, 2026). Modern equipment, including sterilizers, threshers, digesters, screw presses, clarifiers, nut crackers, fibre separators and automated controls, can improve extraction efficiency, reduce post-harvest losses and raise profitability. Locally fabricated equipment and smart processing technologies may make mechanization more affordable for small and medium processors (Kiggundu & Jjagwe, 2021; Owolarafe *et al.*, 2024; Golden Agri-Resources, 2025). Against this, adoption faces limited credit, weak rural infrastructure, unreliable electricity, high equipment cost, weak research–industry linkages, a shortage of skilled personnel, ageing plantations and inadequate extension services (PIND Foundation, n.d.-a; Afrinvest, 2025; Owolarafe *et al.*, 2023, 2024). Oil extraction is also well below that of leading producers: the PIND brief, drawing on fieldwork in 2013, reports that improved mechanized mills in the Niger Delta recovered 13–18% of fresh fruit bunches (FFB) as oil and semi-mechanized mills 8–10% from improved-variety fruit (PIND Foundation, n.d.-a), against a Malaysian national average of 19.67% in 2024 (Malaysian Palm Oil Board [MPOB], 2025), although the bases differ.

Demand growth, policy attention, private investment and engineering innovation present openings, including integrated digester–screw press units, renewable-energy-powered mills and digital monitoring. This review examines the status of palm oil processing mechanization in Southern Nigeria, evaluates the technological, economic, institutional and environmental constraints, and discusses prospects. It closes with recommendations for policy, investment, research and technology development.

Scope. This review covers mechanization of palm oil processing, from fruit bunch reception to crude oil, kernel recovery and mill waste handling. Harvesting and fruit bunch evacuation are discussed only as the upstream interface that governs mill throughput and oil quality. Plantation establishment and management are outside the scope. “Southern Nigeria” means the South-South, South-East and South-West geopolitical zones (South-South: Akwa Ibom, Bayelsa, Cross River, Delta, Edo and Rivers; South-East: Abia, Anambra, Ebonyi, Enugu and Imo; South-West: Ekiti, Lagos, Ogun, Ondo, Osun and Oyo).

1.1 Review approach

This is a narrative review. Sources were identified in October 2026 through targeted web searches of scholarly, institutional and news sources and through the record pages of publishers and indexing services (Directory of Open Access Journals, African Journals Online, the International System for Agricultural Science and Technology, IDEAS/Research Papers in Economics, Springer, Elsevier and DergiPark), using combinations of palm oil, oil palm, processing, mechanization, digester, screw press, extraction efficiency, fabrication, Nigeria and the names of the Southern states. Records were included if they addressed palm oil processing equipment, practices, economics or policy in Nigeria, or gave a comparison from another producing country, and were published in English between 2014 and 2026; two undated institutional reports (PIND Foundation, n.d.-a, n.d.-b) were included for their data on the Niger Delta. Opinion pieces and press items were used only for dated events, official announcements and stakeholder positions, not for engineering performance claims. Because the review is narrative, no formal screening counts were kept; each source in the reference list was opened and checked against the statement it supports, and 42 sources are cited. The status levels in Table 1 are the authors’ synthesis of the sources in its Basis column, using the criterion stated under the table.

2. Status of mechanized palm oil processing in Southern Nigeria

Southern Nigeria is the centre of Nigeria's oil palm industry. The region comprises the South-South, South-East and South-West geopolitical zones, where oil palm has long been a major livelihood. Although Nigeria is Africa's largest palm oil producer, its mechanization level is considerably lower than that of Indonesia and Malaysia, and domestic output does not meet demand (Afrinvest, 2025; Shehu & Salleh, 2020). In this review, *mechanization level* describes the share of an operation's throughput handled by powered equipment: low means mainly manual or simple tools; moderate means powered equipment handles roughly one-third to two-thirds of throughput; high means it handles most of the throughput for most processors. These thresholds are the authors' working criterion, not a published framework, so Table 1 is a qualitative synthesis. Table 1 summarizes the resulting picture.

Processing mechanization has improved gradually over the past two decades, particularly among medium- and large-scale processors (PIND Foundation, n.d.-a; Owolarafe *et al.*, 2024). Digestion, oil extraction, clarification and kernel recovery increasingly use sterilizers, threshers, digesters, screw and hydraulic presses, clarifiers, nut crackers, fibre separators and kernel dryers. Mechanization remains uneven, however. Most smallholder processors mechanize only digestion and oil extraction, while harvesting, fruit bunch transport, sterilization, stripping, clarification and waste handling are largely manual (PIND Foundation, n.d.-a; Agbogo *et al.*, 2026). Mechanical harvesters have been introduced through training of farmers (PIND Foundation & Nigerian Institute for Oil Palm Research [NIFOR], 2017), but measured adoption is not documented: at the training, NIFOR's acting executive director noted that many farmers had yet to adopt modern techniques (PIND Foundation & NIFOR, 2017). This partial mechanization limits efficiency and contributes to post-harvest losses.

The industry has a dual structure. Large estates and integrated companies, such as Okomu Oil Palm Plc (a 45 t/h mill), operate largely automated plants using imported technology, with mechanical sterilizers and strippers, digester–screw presses and centrifugal clarification (Owolarafe *et al.*, 2024). In contrast, smallholders, who produce about 80% of national output (PIND Foundation, n.d.-a; Anyaoha & Zhang, 2023), process fruit with locally fabricated or semi-mechanized digesters, screw presses, hydraulic presses or manual equipment made by indigenous workshops. These machines have reduced labour and increased capacity but generally give lower extraction efficiency, less consistent oil quality and higher maintenance needs than industrial plants (Anyaoha & Zhang, 2023; PIND Foundation, n.d.-a).

Indigenous engineering has widened the supply of affordable equipment for small and medium enterprises. Research institutions, universities and private firms have developed locally fabricated digesters, screw presses, sterilizers and integrated units that reduce dependence on imports and investment cost (Owolarafe *et al.*, 2024; PIND Foundation, n.d.-a). Combining digestion and expression in one unit is among the most important recent developments, improving operating efficiency and reducing processing time and energy use. NIFOR and the Raw Materials Research and Development Council (RMRDC), with universities and private firms, have designed low-cost digesters, presses, nut crackers, sterilizers and small plants suited to local conditions (RMRDC, 2024, 2025).

Automation and digital control are also emerging. Modern mills elsewhere use programmable logic controllers, sensors and automated feeding, and Internet of Things, machine learning and predictive maintenance are expected to improve efficiency (Golden Agri-Resources, 2025). In Nigeria, the only surveyed mill reporting complete automation of FFB-to-special-palm-oil processing was Okomu, while the public mills at NIFOR and Okitipupa had stopped production and the smaller private mills retained manual steps (Owolarafe *et al.*, 2024). Even so, overall mechanization in Southern Nigeria remains low to moderate. It is concentrated in processing, while mechanized harvesting, material handling, transport, grading and post-processing are poorly developed. Finance, technical capacity, infrastructure and technology transfer constrain wider adoption.

The status of palm oil processing is therefore best described as transitional. Local fabrication and medium-scale technologies have progressed, but mechanization has not reached most rural processors. Future progress depends

on equipment design as well as institutional support, financing, training, infrastructure and commercialization.

Table 1. Mechanization status of palm oil processing and upstream operations in Southern Nigeria

Operation	Smallholder / small mill	Industrial mill	Level	Basis
Harvesting (upstream)	Manual cutting	Mostly manual	Low	PIND Foundation & NIFOR (2017); adoption not documented
FFB evacuation (upstream)	Manual, tricycle, truck	Truck	Low	Afrinvest (2025); authors' judgement
Sterilization	Drums or pots	Mechanical sterilizers	Low	PIND Foundation (n.d.-a); Owolarafe *et al.* (2024)
Threshing	Mostly manual	Mechanical strippers	Low	PIND Foundation (n.d.-a); Owolarafe *et al.* (2024)
Digestion	Mechanical digesters	Mechanical	High	PIND Foundation (n.d.-a); Agbogo *et al.* (2026)
Oil extraction	Screw or hydraulic press	High-capacity presses	High	PIND Foundation (n.d.-a); Agbogo *et al.* (2026)
Clarification	Mostly manual	Mechanical clarifiers and centrifuges	Low	Owolarafe *et al.* (2024); authors' judgement
Nut and fibre separation	Mostly manual	Mechanical	Low	Owolarafe *et al.* (2024); PIND Foundation (n.d.-a)
Kernel cracking and drying	Mostly manual	Crackers and dryers	Low	Owolarafe *et al.* (2024); authors' judgement
Storage and packaging	Mostly manual	Semi-automated	Low	Authors' judgement; no measured data found
Waste management (empty fruit bunches [EFB], fibre, shell, palm oil mill effluent [POME])	Largely manual, often unmanaged	Partly managed	Low	Section 2; Abogunrin-Olafisoye *et al.* (2024); Obada *et al.* (2023)

Levels (for smallholders and small mills): Low = mainly manual or simple tools; Moderate = powered equipment handles roughly one-third to two-thirds of throughput; High = powered equipment handles most throughput for most processors. Table 1 is the authors' qualitative synthesis of the sources in the Basis column; it is not a measured survey of mechanization levels.

3. Challenges of mechanized palm oil processing in Southern Nigeria

Adoption of mechanization in Southern Nigeria is constrained by interrelated technological, financial, institutional, infrastructural, environmental and socio-economic challenges (Afrinvest, 2025; Akinrinde *et al.*, 2026). These constraints keep the sector below the productivity of Indonesia and Malaysia (Afrinvest, 2025; Anyaoha & Zhang, 2023). Addressing them needs coordinated action by government, research institutions, investors, financial organizations and local engineering industries (FMAFS, 2026; RMRDC, 2025). Table 2 consolidates the challenges, their effects and their implications for mechanization.

3.1 Technological constraints

Efficient processing technology is limited in availability and uptake. Although locally fabricated digesters, presses, sterilizers, threshers and clarifiers are increasingly available, many facilities use obsolete or poorly designed equipment with low extraction efficiency (RMRDC, 2025). Such machines often suffer from inadequate design, poor fabrication quality, frequent mechanical failure and limited automation (Owolarafe *et al.*, 2023, 2024). The efficiency penalty of staying with traditional methods is measurable: in Cross River State, mean technical efficiency was 81% for improved processing technologies against 62% for traditional ones (Abdulsalam *et al.*, 2014).

Most small and medium processors mechanize only digestion and oil extraction, while harvesting, bunch transport, sterilization, clarification and waste management remain largely manual (PIND Foundation, n.d.-a; Agbogo *et al.*, 2026). Substantial recoverable oil is consequently lost, reducing extraction efficiency and profitability (PIND Foundation, n.d.-a; Anyaoha & Zhang, 2023).

Dependence on imported industrial machinery is a further constraint. Large mills rely on imported equipment, spares and specialist services, and breakdowns cause long downtime because replacement parts are costly and hard to obtain locally (Owolarafe *et al.*, 2024). This raises maintenance cost and discourages investment.

Commercialization of research outputs also remains inadequate (PIND Foundation, n.d.-a; Owolarafe *et al.*, 2024; RMRDC, 2025). NIFOR and universities have developed several processing technologies, but weak collaboration among researchers, fabricators, manufacturers, extension agencies and processors limits adoption.

3.2 Financial constraints

Capital cost is among the greatest barriers. A mechanized facility needs substantial investment in equipment, power, buildings, transport and maintenance (Afrinvest, 2025; Akinrinde *et al.*, 2026), which is beyond most rural processors. Access to affordable credit is limited (Afrinvest, 2025; FMAFS, 2026). A household-survey study of Nigerian smallholders likewise identifies collateral requirements and the cost of borrowing among the factors behind credit rationing (Balana *et al.*, 2020). Commercial bank lending is described as unfavourable to small agro-processors because of short loan terms and mandatory collateral that many lack, and because processors keep no enterprise records on which creditworthiness can be assessed (PIND Foundation, n.d.-a). Government financing exists, and the Central Bank of Nigeria reportedly disbursed about ₦30 billion to oil palm farmers, but producer associations rejected its 9% rate as unsustainable and asked for 2% (The Guardian, 2019); processors surveyed in Osun State rated inadequate funds and weak government support and policy among their most severe constraints (Adeniyi *et al.*, 2019). Without sustainable finance, processors cannot replace obsolete equipment or expand, and many continue with inefficient traditional methods despite rising demand. A recent study of 464 processors in Southeast Nigeria found higher allocative efficiency among mechanized processors (86.6%) than manual ones (74.4%); mechanized processors ranked the high cost of improved equipment as their leading constraint, and the authors recommended subsidized acquisition and technology leasing (Agbogo *et al.*, 2026).

Equipment cost evidence is limited and dated. Fieldwork reported in the PIND brief (2013) put the set-up cost of a semi-mechanized mill (digester with a hand-operated press) at about ₦0.52 million, an improved mill with a digester–screw press at ₦1.2–1.5 million, and a full improved line at ₦1.8–2.7 million; NIFOR priced a full line including sterilizer, stripper and clarifier at about ₦2.7 million with reported delivery in 6–12 months, against 4–6 weeks and lower component prices from trained local fabricators (PIND Foundation, n.d.-a). The brief estimated that the cost of an improved mill could be recouped within a year, which is the programme's own estimate rather than a measured outcome. These are nominal 2013 prices and are not comparable with current costs, which were not found in the sources reviewed.

3.3 Inadequate infrastructure

Poor infrastructure undermines processing throughout Southern Nigeria (Afrinvest, 2025; Akinrinde *et al.*, 2026). Producing communities are mostly rural, with weak roads, unstable electricity, limited water and poor communications. Bad roads delay evacuation of FFB; because fruit deteriorates quickly after harvest, delay raises free fatty acid (FFA) content, reduces quality and lowers value. Unreliable electricity forces many processors onto diesel generators, which raises operating cost, and rising fuel prices have worsened this. Limited clean water affects sterilization, clarification and sanitation, compromising quality and food safety (Anyaoha & Zhang, 2023).

3.4 Human capacity and technical skills gap

Mechanized processing needs skilled operators able to run, maintain and repair equipment. Evidence points to a shortage of trained personnel in mechanization, maintenance and fabrication. Most of 98 surveyed equipment fabricators learned informally from another person and lacked functional bending, rolling and lathe equipment (Owolarafe *et al.*, 2023), and small-scale processors surveyed in Osun State identified training needs in digestion, stripping and clarification (Adeniyi *et al.*, 2019). Poor maintenance was the main reason the public mills at NIFOR and Okitipupa stopped production (Owolarafe *et al.*, 2024), which shows how neglected maintenance leads to failures, shorter machine life and higher cost. Rural-urban youth migration reduces the supply of competent labour. Technical education, vocational training and extension are therefore essential (FMAFS, 2026).

3.5 Ageing plantations and limited raw material supply

The productivity of a mill depends on a steady supply of good fresh fruit bunches (Owolarafe *et al.*, 2024). Many plantations in Southern Nigeria consist of ageing, low-yielding trees, and the decline in national output has been attributed partly to plantation age and the small area of new planting (Owolarafe *et al.*, 2024). Replanting with improved hybrid (tenera) seedlings is limited because it is capital-intensive and certified nurseries are scarce (Onyiuke, 2026). Little or no fertilizer is applied on smallholder plantations, and national average yields are about 15% of the world average (Impens *et al.*, 2017). Some mills therefore operate at a smaller scale than planned when fruit supply is short (Owolarafe *et al.*, 2024); the same survey found that public mills performed far below installed capacity mainly because of poor maintenance and lack of imported spare parts, which is a separate problem (Section 3.1). For the large estates, 2012 estimates put milling utilization at about 42% at Presco and 66% at Okomu, attributed to low FFB yields, ageing plantations and inconsistent smallholder supply (PIND Foundation, n.d.-a). Under-utilization raises unit cost and lowers returns, so mechanization investments are only as good as the fruit supply behind them.

3.6 Weak research–industry linkages

Although universities and institutes have developed many processing innovations, commercialization is weak. Findings rarely progress beyond prototypes because of inadequate funding, limited industrial partnership and poor extension. Fabricators often lack updated designs, and processors are unaware of new technologies. Closer collaboration among researchers, engineering firms, manufacturers, extension agencies and processors is needed to speed technology transfer (PIND Foundation, n.d.-a; Owolarafe *et al.*, 2024; RMRDC, 2025).

3.7 Environmental challenges

Conventional processing generates solid waste, wastewater, fibre, empty fruit bunches, shells and palm oil mill effluent (Abogunrin-Olafisoye *et al.*, 2024; Anyaoha & Zhang, 2023). In many rural centres these wastes are disposed of without treatment, causing pollution. Traditional processing also depends on firewood for sterilization and boiling, which contributes to deforestation, greenhouse gas emissions and biodiversity loss. Mechanized systems powered by biomass boilers, biogas digesters, solar energy or gasification offer alternatives but remain underused because of high initial cost.

3.8 Policy and institutional challenges

Policy inconsistency has historically constrained investment. Frequent changes in priorities, weak implementation of agricultural programmes and poor coordination reduce the effectiveness of agricultural policy (Adekunle & Aregbeshola, 2025), and the prolonged lack of maintenance at the Okitipupa mill was linked to inconsistent government policy (Owolarafe *et al.*, 2024). The oil boom of the 1970s also shifted government attention away from agriculture (Shehu & Salleh, 2020). Extension services remain inadequate, limiting farmers' access to improved seedlings, technologies, training and market information. Fragmented land tenure discourages large-scale mechanized plantations and reduces economies of scale (Akinrinde *et al.*, 2026). Small-scale processing often yields oil that does not meet industrial requirements (PIND Foundation, n.d.-a), and a food-safety researcher has called for stronger surveillance and enforcement by the National Agency for Food and Drug Administration and Control on palm oil sold in markets (News Agency of Nigeria, 2026b), which points to weak regulatory enforcement and inconsistent product quality.

3.9 Socio-economic challenges

Mechanization can have unintended social effects if not inclusive. Rural women are a significant share of palm oil processors, but their position is uneven: about 95% of small-scale mills in Akwa Ibom were reported to be managed by women, whereas in other states mechanization shifted processing towards men (PIND Foundation, n.d.-a). Gender-targeted credit and support for improved mechanized mills have been proposed to raise women processors' extraction efficiency (Uduji *et al.*, 2026), and plantation land acquisition in Cross River State has weakened women's land rights and incomes (Ojo *et al.*, 2017). Land acquisition for commercial plantations can also cause conflict between investors and host communities, and poor engagement may displace smallholders and threaten livelihoods (Ojo *et al.*, 2017; Olam Agri, 2025). Inclusive policies that prioritize community participation, gender equity, cooperatives and local employment are therefore essential.

3.10 Innovation deficit and limited digital transformation

Modern palm oil industries elsewhere increasingly use artificial intelligence, Internet of Things, machine vision, robotics, digital twins and predictive maintenance. In contrast, most facilities in Southern Nigeria operate manually or with limited automation. Digital monitoring of temperature, pressure, screw speed, sterilization time and moisture is uncommon, which limits process optimization, quality control and reliability (Golden Agri-Resources, 2025; Owolarafe *et al.*, 2024). Research on smart processing systems is therefore an important opportunity.

3.11 Critical discussion

The challenges are highly interconnected (Afrinvest, 2025; Akinrinde *et al.*, 2026). Financial constraints limit investment in equipment; poor infrastructure raises costs; weak institutional support restricts technology transfer; and a skills shortage reduces equipment efficiency. These factors reinforce one another in a cycle of low productivity, limited profitability and slow adoption. Breaking the cycle requires coordinated action on financing, infrastructure, research commercialization, human capacity and policy implementation. Without it, Nigeria is unlikely to realize the potential of mechanized processing or compete with leading producers. Fruit supply (Section 3.5) is a binding limit: mechanization alone does not raise FFB volumes.

Table 2. Major challenges to mechanized palm oil processing, their effects and implications

Sec.	Challenge	Major effect	Implication for mechanization
3.1	Dependence on imported machinery	High maintenance cost, downtime	Spare-part supply and local servicing are needed before adoption scales

Sec.	Challenge	Major effect	Implication for mechanization
3.1	Weak design and fabrication quality	Frequent breakdowns	Standards and testing must precede subsidies
3.2	High equipment cost; limited finance	Low adoption, poor mill investment	Leasing, shared mills and credit guarantees suit smallholders
3.3	Poor rural roads	More post-harvest loss, higher FFA	Mills must sit near fruit supply, or evacuation must be improved first
3.3	Unreliable electricity	High operating cost	Favour biomass or solar-assisted and low-power designs
3.4	Shortage of skilled technicians	Frequent machine breakdowns	Training and maintenance services are a condition of adoption
3.5	Ageing plantations	Low FFB supply, idle capacity	Capacity should be matched to fruit supply, not installed ahead of it
3.6	Weak research commercialization	Low uptake of indigenous designs	Pilot, test and certify before scale-up
3.7	Mill waste and fuelwood use	Pollution, sustainability concerns	Waste-to-energy should be designed into new mills
3.8	Policy inconsistency; weak extension	Discourages long-term investment; slow adoption	Stable multi-year programmes are needed
3.9	Exclusion of women and smallholders	Uneven benefits	Equipment-sharing and cooperative models
3.10	Limited digital automation	Reduced process efficiency	Start with low-cost sensing, not full automation

4. Prospects and opportunities for mechanized palm oil processing in Southern Nigeria

Despite the challenges, the sector has considerable growth potential (FMAFS, 2026; Nairametrics, 2025a). Rising domestic demand, favourable agro-ecology, government interventions, private investment, indigenous engineering and digital technologies together provide a foundation for change. If these are harnessed, mechanization can improve productivity, add value, strengthen food security and generate employment (FMAFS, 2026; News Agency of Nigeria, 2026a). Table 3 summarizes the opportunities and the mechanism through which each is expected to work.

Table 3. Major opportunities for mechanized palm oil processing

Opportunity	Mechanism	Expected outcome
Rising domestic demand	More throughput per mill improves the capital case	Local output expansion
Indigenous fabrication	Lower purchase price, local spares and servicing	Reduced machinery cost and import dependence
Government programmes	Estates, finance and policy support	Higher adoption
Renewable energy from residues	Biomass, biogas and solar replace diesel and firewood	Lower operating cost and emissions
Digital monitoring	Sensing of temperature, pressure and uptime	Better process control, fewer breakdowns

Opportunity	Mechanism	Expected outcome
Value addition	Sale of kernel, cake, compost and biogas	Higher margin, less waste
Public–private partnerships	Shared capital and offtake	Investment and infrastructure
Research and innovation	Local design and testing capacity	Better-adapted equipment
Export expansion	Compliance with quality standards	Foreign exchange earnings
Employment	Fabrication, operation and servicing jobs	Rural industrialization

4.1 Growing domestic and international market demand

Demand is a strong driver of mechanization. Palm oil is used in food, cosmetics, pharmaceuticals, soap, oleochemicals and biodiesel. Nigeria's demand exceeds domestic production, and the gap is filled by imports (FMAFS, 2026). The Federal Government reports production of about 1.4 Mt against demand above 2.5 Mt, a shortfall above 1 Mt, and annual import spending of USD 500–600 million (FMAFS, 2026). Other estimates differ: Afrinvest puts 2024 output at 1.5 Mt and consumption at 2.0 Mt, a gap of about 0.45 Mt (Afrinvest, 2025), and USDA's October 2026 projection for 2026/27 gives 1.50 Mt of output against 1.915 Mt of consumption (USDA, 2026), so the deficit is best read as a range. Imports of Malaysian palm oil alone rose 15.1% to 285,825 tonnes in 2025 (BusinessDay, 2026). The argument for mechanization follows a chain: higher demand means greater throughput per mill, a stronger business case for capital equipment and better investment prospects, provided FFB supply and finance are secured. By improving processing efficiency and reducing post-harvest losses, mechanized systems can raise domestic output, reduce import dependence and conserve foreign exchange. Growing regional demand also offers export opportunities: sub-Saharan Africa's imports of Malaysian palm oil rose 11.9% to 4.12 Mt in 2025 (BusinessDay, 2026).

4.2 Government policies and institutional support

Government interest in revitalizing the industry has renewed. Federal and state governments have identified oil palm as a strategic commodity for diversification and rural industrialization (FMAFS, 2026; RMRDC, 2024). The Federal Government has unveiled a coordinated plan to cut import bills by up to USD 500 million a year through a public–private investment model built on large estates and downstream processing (FMAFS, 2026; News Agency of Nigeria, 2026a). Under this plan, phase one establishes seven integrated oil palm estates of 10,000 ha each, with milling, refining, storage and logistics, and housing for over 2,000 families per site. Phase two focuses on downstream processing and palm-based manufacturing for value addition and export.

Agencies and partners have introduced programmes on improved harvesting and processing technology, training and finance: NIFOR and the PIND Foundation have trained farmers on motorized harvesters (PIND Foundation & NIFOR, 2017), and the Central Bank of Nigeria reportedly disbursed about ₦30 billion to oil palm farmers (The Guardian, 2019). RMRDC has partnered with the National Palm Producers Association of Nigeria to revamp the sub-sector, and the association notes that by-products such as biomass could supply furniture materials, electricity, fertilizer and other products (RMRDC, 2024). If these programmes are implemented consistently, with effective monitoring and evaluation, they could accelerate mechanization.

4.3 Indigenous engineering and local equipment fabrication

Section 3.1 identified poor fabrication quality and frequent breakdowns as constraints; local fabrication is also the most direct route to affordable equipment. These positions are consistent: the benefit is conditional on engineering practice. Evidence of capability exists. Assetrise Limited, with the Nigerian Society of Engineers (NSE),

commissioned a locally fabricated 3-tonne-per-hour mill in Ibadan, which the Society described as evidence that Nigerian engineers can build the machinery the country needs (Nairametrics, 2025b). A palm kernel oil expeller with an adjustable choke was reported to reach 87.10% extraction efficiency at a capacity of 100 kg/h, although the abstract does not state how efficiency was defined (Adegbola *et al.*, 2025). A survey of five mills in four states found that NIFOR's integrated small-scale processing equipment, built in three capacity classes from 0.1 to 1.0 t FFB/h, did not reach commercial status for lack of funding and maintenance (Owolarafe *et al.*, 2024). Elsewhere, a motorised extractor designed for smallholders gave higher efficiency and better oil quality than a manual vertical press, with oil extraction efficiency of 77.1% against 64.4% (Kiggundu & Jjagwe, 2021). The Nigerian reports give little sustained performance data for palm oil extraction. The available figures are 2013 extraction rates of 13–18% for improved mechanized mills against 8–10% for semi-mechanized mills (PIND Foundation, n.d.-a) and technical efficiency of 81% against 62% for improved and traditional processing in Cross River State (Abdulsalam *et al.*, 2014); uptime, energy use and cost per tonne of FFB were not reported in the sources reviewed, and the equipment-cost figures available (Section 3.2) date from 2013.

For local fabrication to become a reliable opportunity, the following need attention: (i) standard designs with documented capacities; (ii) material selection, especially for screw shafts, press cages and contact surfaces; (iii) fabrication tolerances for screw–cage clearance and shaft alignment; (iv) independent testing against a common protocol; (v) performance certification; (vi) quality assurance in workshops; (vii) after-sales service; (viii) spare-part availability; and (ix) operator and maintenance training. Where these are absent, local machines show the lower efficiency and higher maintenance burden described in Section 3.1. Where they are present, as in the cases above, they support the lower cost and better local fit claimed for indigenous equipment. In the same survey, the public mills at NIFOR and Okitipupa had stopped production because of poor maintenance and the lack of imported spare parts, and the authors recommended training for local fabricators and closer links between mills and research institutes (Owolarafe *et al.*, 2024). Strengthening partnerships among universities, institutes, firms and manufacturers will further improve quality and commercialization.

4.4 Advances in smart processing technologies

The shift to digital agriculture offers opportunities to modernize processing. Programmable logic controllers, Internet of Things devices, artificial intelligence, machine learning, cloud computing and digital twins can improve process control and efficiency (Golden Agri-Resources, 2025; The Sun Malaysia, 2025). Smart systems already show measurable benefits: a Malaysian mill using AI-integrated systems is reported to have cut manual labour needs by 45% (The Sun Malaysia, 2025). This is a reported result from one mill and should not be read as an expected gain in Nigeria.

Smart systems monitor sterilization temperature, digestion time, press pressure, shaft speed, oil moisture and vibration, supporting predictive maintenance, lower downtime, better quality and energy savings (Golden Agri-Resources, 2025). For small and medium processors, affordable sensor-based monitoring can bridge the gap between traditional processing and fully automated mills.

4.5 Renewable energy integration

Energy is a significant share of processing cost, so renewable energy offers economic and environmental gains (Abogunrin-Olafisoye *et al.*, 2024; Obada *et al.*, 2023). Fibre, kernel shells and EFB can fuel boilers, gasifiers or combined heat-and-power systems. EFB is largely dumped to rot in Nigeria, causing greenhouse gas emissions, so its use for energy is a significant opportunity (Abogunrin-Olafisoye *et al.*, 2024; Obada *et al.*, 2023). POME can be converted to biogas for electricity (Abogunrin-Olafisoye *et al.*, 2024). Solar photovoltaic systems can supplement power for lighting, instrumentation and controls where grid supply is unreliable. RMRDC has recommended that palm oil companies move to biomass or solar power (RMRDC, 2025). Renewable energy can reduce diesel use, emissions and cost.

4.6 Value addition and by-product utilization

Mechanization enables use of by-products beyond crude palm oil. Palm kernel yields kernel oil and cake for livestock feed; fibre and shells serve as fuel; EFB can be composted into fertilizer; and POME can be treated to give biogas and soil amendments. Nigeria's route to a sustainable industry may include converting waste to value through integrated oil palm residue biorefineries (Abogunrin-Olafisoye *et al.*, 2024). These products diversify revenue, reduce waste and improve profitability. The Assetrise–NSE mill reportedly processes EFB into organic fertilizer as part of a zero-waste model (Nairametrics, 2025b).

4.7 Employment generation and rural industrial development

Contrary to concern that mechanization reduces employment, appropriate mechanization can stimulate rural development by creating jobs in fabrication, operation, maintenance, transport, quality assurance, marketing and logistics. Employment effects depend on context: mechanizing one task can raise demand for labour in tasks that stay manual, and job losses are most likely where mechanization is pushed through large subsidies in areas without labour shortages or alternative jobs (Daum, 2023). Growth of mechanized processing also supports workshops, spare-parts manufacture, renewable energy services, installation, training and extension. Mechanization can thus contribute to productivity, poverty reduction, youth employment and inclusive rural development (FMAFS, 2026; Nairametrics, 2025a).

4.8 Private sector investment and public–private partnerships

Private investment indicates growing confidence in the industry. Large companies continue to expand their mills and plantations: Presco Plc announced in December 2025 the acquisition of 10,000 ha in Cross River State to widen the raw material base for its mills and refineries (ThisDay, 2025). FMAFS has stated that Nigeria has over three million hectares suitable for oil palm, much of it underused, while existing plantations are hampered by ageing trees and limited inputs. Financial projections for the integrated estates show internal rates of return of 18–25% and payback of five to seven years, driven by domestic demand and regional markets (FMAFS, 2026). These are projections, not outcomes.

Public–private partnerships can mobilize finance, promote technology transfer, improve infrastructure and integrate smallholders into commercial chains (FMAFS, 2026; News Agency of Nigeria, 2026a). Contract farming, cooperative processing centres, equipment leasing and shared mechanization services can let resource-poor farmers benefit without bearing the full cost of ownership. Equipment rental has likewise been proposed to close mechanization gaps in Colombian oil palm (Zapata-Hernández *et al.*, 2024), where the authors recommend collective renting to raise the use of machinery that is otherwise used for only a small share of the year.

4.9 Research, innovation and human capacity development

Universities, institutes and engineering organizations are central to technological advance (RMRDC, 2024, 2025). Future research should prioritize high-efficiency integrated digester–screw press systems, low-cost automation for small processors, energy-efficient sterilization, renewable-energy-powered plants, AI-assisted optimization and digital quality monitoring, machine learning models for predicting extraction efficiency, and climate-resilient processing. Postgraduate research, industry collaboration, engineering incubators and vocational training will strengthen local capacity.

4.10 Regional and global competitiveness

Nigeria has comparative advantages for a stronger position in the palm oil industry: favourable climate, extensive suitable land, a large domestic market, abundant labour, growing engineering capacity and policy attention. With over three million hectares of suitable land and a global market valued above USD 70 billion a year (Moss, 2026),

stakeholders have affirmed that Nigeria can reduce imports and regain market share (FMAFS, 2026). Improved mechanization can help meet international quality standards by reducing FFA, limiting contamination, improving traceability and standardizing operations. Compliance with sustainability certification will improve access to premium markets (BusinessDay, 2026; FMAFS, 2026).

4.11 Critical discussion

Opportunities extend beyond more crude palm oil. Mechanization can catalyse wider transformation through technology, industrial development, renewable energy, value addition, employment and exports. Realizing them requires coordinated investment in infrastructure, finance, research commercialization, local manufacturing, digital technology and human capital, and policy that gives smallholders and rural processors equitable access (Abogunrin-Olafisoye *et al.*, 2024; BusinessDay, 2026; FMAFS, 2026).

5. Conclusions

Mechanization is an important pathway for improving the productivity, processing efficiency and competitiveness of Nigeria's palm oil industry. This review finds that mechanization of palm oil processing in Southern Nigeria is uneven. Digestion and oil extraction are widely mechanized, largely through locally fabricated equipment, while bunch evacuation, packaging and waste management remain largely manual. A two-tier structure persists between industrial mills and smallholder processors.

The main constraints are capital cost and limited credit, unreliable power and roads, a shortage of skilled technicians, ageing plantations, inconsistent fabrication quality, weak research–industry linkages and unmanaged mill waste. These are interlinked: finance, infrastructure, fruit supply and skills each limit the return on equipment. Prospects lie in the demand gap, public–private programmes, better-tested indigenous equipment, use of residues for energy and value addition, and low-cost process monitoring. Realizing them requires coordinated action by government, research institutions, manufacturers, financial institutions, extension services and processors. Evidence on equipment cost, capacity utilization and extraction performance remains thin and dated and is the main gap for future work.

6. Recommendations

1. Support indigenous equipment makers with testing, certification and incubation.
2. Develop credit, guarantee and leasing schemes suited to smallholder processors.
3. Extend mechanization to bunch evacuation, sterilization, clarification, packaging and waste handling.
4. Strengthen research–industry collaboration and commercialization of tested designs.
5. Expand technical training, maintenance and extension services.
6. Replant ageing plantations with improved varieties to secure fruit supply.
7. Improve rural roads, electricity and water supply in oil palm areas.
8. Promote biomass, biogas and solar use in processing.
9. Introduce low-cost digital monitoring before full automation.
10. Maintain stable, long-term policies and enforce quality standards.
11. Include women, youth, cooperatives and smallholders in mechanization programmes.

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Paper ID 38:
Mechanical Properties of Heat-Sealable Starch–Polyvinyl Alcohol Biopolymer Films Incorporated with Palm Kernel Oil for Sustainable Food Packaging

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Abstract
The increasing environmental burden associated with petroleum-based food packaging has stimulated interest in renewable polymer-based alternatives with adequate mechanical and barrier performance. This study developed heat-sealable starch–polyvinyl alcohol (PVA) biopolymer films incorporating palm kernel oil and evaluated the effects of formulation composition and oil concentration on their functional properties. Films were prepared by solution casting using three starch concentrations (0.50, 0.75 and 1.00 g) and three palm kernel oil levels (0, 1 and 3 drops). Film thickness, tensile strength, Young's modulus, elongation at break, permeability, opacity and sealing temperature were determined, and the data were analysed using analysis of variance and Duncan's Multiple Range Test at $p < 0.05$. Increasing starch–PVA formulation from 0.50 to 1.00 g increased tensile strength from 23.32 to 27.18 MPa, Young's modulus from 98.49 to 123.92 N/m² and elongation at break from 132.88 to 147.66%, while permeability decreased from 1.3956 to 0.7633. Palm kernel oil produced a contrasting mechanical response: tensile strength decreased from 34.25 MPa in the oil-free film to 19.17 MPa at the highest oil level, whereas elongation at break increased from 102.89 to 179.02%. Oil incorporation also increased film thickness and opacity while reducing the measured permeability. The results demonstrate that starch–PVA composition and palm kernel oil concentration can be used to tailor the balance between strength, stiffness, flexibility and barrier performance. The developed films therefore show potential as renewable packaging materials for food applications, although further validation under actual food-storage conditions is required.

Keywords: Heat-sealable films; Cassava starch; Polyvinyl alcohol; Palm kernel oil; Tensile strength; Young's modulus.

1. Introduction

Packaging plays a critical role in preserving the quality, safety, and marketability of fresh fruits and vegetables throughout storage, transportation, distribution, and retail. Appropriate packaging can protect highly perishable produce from mechanical damage, contamination, and adverse environmental conditions while helping to maintain product quality and extend shelf life (Siracusa et al., 2022). However, the food-packaging sub-sector remains heavily dependent on conventional petroleum-based plastics because of their favourable mechanical strength, low cost, durability, processability, and barrier properties. Materials such as polyethylene, polypropylene, and polystyrene are therefore extensively used in food-packaging applications. Despite these advantages, their persistence in the environment and inadequate end-of-life management have resulted in substantial accumulation of plastic waste in terrestrial and aquatic ecosystems (Ncube et al., 2021). The fragmentation of persistent plastic materials into micro- and nanoplastics has further intensified concerns regarding environmental pollution, ecosystem integrity, and potential human exposure (Shah et al., 2024).

Fruits and vegetables constitute important components of a healthy diet because they provide essential vitamins, minerals, dietary fibre, and a wide range of biologically active compounds (Vasco et al., 2008; Liberty et al., 2013). Nevertheless, their high moisture content and metabolic activity make them particularly susceptible to deterioration after harvest. Maintaining their quality during storage and distribution therefore requires appropriate postharvest handling and packaging systems (Espitia and Otoni, 2018; Sani et al., 2021). Although conventional petroleum-derived plastics have traditionally fulfilled many of these packaging requirements, increasing concerns regarding plastic pollution and resource depletion have stimulated interest in sustainable alternatives. Consequently, the development of packaging materials derived wholly or partly from renewable resources has

become an important research priority within the context of sustainable food systems and circular material economies.

Biodegradable polymer films derived from renewable biological resources represent a promising alternative to conventional petroleum-based packaging. These materials can be designed to undergo degradation through biological processes under appropriate environmental conditions, thereby potentially reducing their long-term persistence after disposal. Common feedstocks for biodegradable packaging include starch, cellulose, chitosan, gelatin, and other polysaccharides and proteins (Tabassum et al., 2024). Among these materials, starch has received considerable attention because of its abundance, low cost, renewability, biodegradability, and favourable film-forming properties (Avérous and Halley, 2009; Mali et al., 2010).

Cassava starch is particularly attractive for biodegradable packaging development, especially in tropical and cassava-producing regions where the crop is widely available. Cassava is an important starch source, and its relatively high starch content makes it suitable for thermoplastic processing and film production (Charles et al., 2005; FAO, 2023). During thermoplastic processing, starch undergoes gelatinization and molecular reorganization in the presence of heat, moisture, and plasticizers, resulting in a continuous polymer matrix capable of forming biodegradable films (Tharanathan, 2003; Pelissari et al., 2017). However, films produced from starch alone generally exhibit limitations, including relatively low mechanical strength, brittleness, high moisture sensitivity, and poor resistance to water vapour. These deficiencies are primarily associated with the hydrophilic nature of starch and the extensive intermolecular hydrogen bonding within the starch polymer network (Sothornvit and Krochta, 2005; Müller et al., 2008). Such limitations restrict the performance of unmodified starch films and necessitate formulation strategies capable of improving their structural and functional properties.

One widely investigated approach involves blending starch with complementary polymers. Polyvinyl alcohol (PVA) has attracted considerable interest because of its good film-forming ability, mechanical performance, flexibility, and compatibility with hydroxyl-containing biopolymers. The hydroxyl groups in PVA can interact with those of starch through intermolecular hydrogen bonding, potentially improving polymer compatibility and the integrity of the resulting film matrix (Chiellini et al., 2003; Cyras et al., 2008). Previous studies have shown that starch–PVA blends can exhibit improved mechanical properties and reduced brittleness compared with films prepared from starch alone (Müller et al., 2008; Tang and Alavi, 2011). Consequently, starch–PVA blending represents a useful strategy for developing polymer films with enhanced physicochemical and mechanical characteristics for potential packaging applications (Sanyang et al., 2016; Mendes et al., 2016).

In addition to adequate mechanical performance, heat sealability is an important functional requirement for many flexible food-packaging materials. Heat sealing involves the application of controlled heat and pressure to join polymer surfaces and produce a closed package. Effective seals are essential for maintaining package integrity and limiting the entry of contaminants or uncontrolled exchange of moisture and gases, depending on the intended packaging application (Han, 2014; Robertson, 2016). The performance of a heat-sealed package is influenced not only by the sealing conditions but also by the mechanical behaviour and structural characteristics of the film. Films with inadequate strength may fail during processing or handling, whereas excessively rigid materials may crack or fracture during folding and transportation (Marsh and Bugusu, 2007; Robertson, 2016). Therefore, achieving an appropriate balance between strength, stiffness, and flexibility is essential for the development of biodegradable films intended for heat-sealable packaging applications.

The mechanical performance of polymeric packaging films is commonly evaluated using tensile strength, Young's modulus, and elongation at break (ASTM International, 2022). Tensile strength indicates the maximum stress a material can withstand before failure and provides information on its ability to resist mechanical loads during handling and use. Young's modulus describes material stiffness and resistance to elastic deformation, whereas elongation at break reflects the extent to which a material can deform before rupture and is therefore an important indicator of flexibility and ductility (Callister and Rethwisch, 2020). Considered together, these parameters provide a comprehensive assessment of the mechanical suitability of biodegradable films for practical packaging applications (Siracusa et al., 2008; Robertson, 2016).

The incorporation of hydrophobic compounds into starch-based polymer systems may further influence the structural organization and mechanical behaviour of the resulting films. Palm kernel oil, which contains a substantial proportion of saturated fatty acids, may modify intermolecular interactions within starch–PVA matrices and potentially alter film flexibility, stiffness, and resistance to mechanical deformation. However, oil incorporation may also disrupt polymer continuity when phase compatibility is inadequate. Consequently, evaluating the influence of palm kernel oil concentration on the mechanical properties of starch–PVA films is important for identifying formulations with balanced performance for packaging applications.

Therefore, the present study aimed to develop heat-sealable cassava starch–poly(vinyl alcohol) biopolymer films incorporating different concentrations of palm kernel oil and to evaluate their mechanical properties. Specifically, the study investigated the effects of formulation composition and palm kernel oil incorporation on tensile strength, Young's modulus, and elongation at break. The findings are expected to improve understanding of the structure–property relationships in starch–PVA–oil film systems and provide a basis for optimizing renewable polymer films for potential use in sustainable and heat-sealable food-packaging applications. Such materials could contribute to reducing dependence on persistent conventional plastics while promoting the development of value-added packaging materials from renewable resources.

2. Materials and Methods

2.1 Materials

2.2 Extraction of Cassava Starch

Cassava starch was extracted using the conventional wet extraction technique. Fresh cassava roots were peeled, washed thoroughly, grated, and mixed with distilled water to release the starch granules. The slurry was filtered through muslin cloth to separate the starch suspension from fibrous materials. The filtrate was allowed to sediment under gravity, after which the supernatant was carefully decanted. Distilled water was used throughout the experimental procedures. Petri dishes (10 cm diameter) and plastic trays were used for film casting and drying. The starch sediment was spread on stainless-steel trays and dried at ambient temperature for 48 h before being milled and stored in airtight containers until use.

Figure 1: Cassava starch extraction

2.3 Film Preparation

The thermoplastic films were prepared using the method of Todhanakasem *et al.,* (2022) with modifications. Film preparation was done by experimenting combinations of the composition PVA and starch and PVA only were used in the experiment.

50g of PVA was measured and was added to 50ml of distilled water. The mixture was gently heated and stirred until it totally dissolved as shown in fig 2. 0.5g, 0.75g and 1g of starch with 50ml distilled water was prepared. The PVA solution was added to make up the 100ml. The mixture was heated to 90℃ and stirred for 5 minutes after which was allowed to cool , 0, 1 and 3 pelm karnel oil were added respectively.

The resulting mixtures were cooled to room temperature and cast on Petri dishes (10 cm diameter) and allowed to dry for 48 hr at room temperature. After drying, the films were peeled and stored for further use. A total of 18 runs were obtained for both mixtures respectively (PVA and Starch, PVA only).

Fig 2: Films preparation

Fig 3: Casted films.

2.4 Experimental Design

A factorial experimental design was employed to investigate the effects of polymer composition and palm kernel oil concentration on the mechanical properties of the developed heat-sealable biopolymer films.

The two experimental factors were:

Polymer composition: 0.50, 0.75 and 1.00 g starch.

Palm kernel oil concentration: 0, 1 and 3 drops.

This design enabled the evaluation of the individual effects of polymer composition and oil concentration, as well as their interaction on film performance. Six replicates were prepared for each treatment to ensure statistical reliability.

2.5 Characterization of Heat-Sealable Biopolymer Films

2.5.1 Film Thickness

Film thickness was determined using a calibrated digital micrometer screw gauge. Measurements were taken at several random positions on each film specimen, and the average value was calculated. Thickness was recorded in millimeters (mm). Film thickness was evaluated because it directly influences heat-sealing behavior and mechanical performance.

2.5.2 Tensile Strength

The tensile strength of the films was measured according to ASTM D 882 using a universal testing machine equipped with fabricated tensile grips. Film specimens were cut into standard dimensions and stretched until rupture. Tensile strength (MPa) was calculated as the maximum force sustained divided by the initial cross-sectional area of the specimen. This parameter was used to assess the mechanical resistance of the developed films.

2.5.3 Young's Modulus

Young's modulus was determined from the initial linear region of the stress–strain curve generated during tensile testing. The modulus represents the stiffness of the film and was calculated as the ratio of stress to strain within the elastic deformation region. Higher values indicate greater rigidity and resistance to deformation.

2.5.4 Elongation at Break

Elongation at break was determined simultaneously with tensile strength using the universal testing machine. It was expressed as the percentage increase in specimen length before rupture. This parameter was used to evaluate film flexibility and ductility, which are important characteristics for heat-sealable food-packaging materials.

2.6 Statistical Analysis

Experimental data were analysed using analysis of variance (ANOVA) to determine the effects of polymer composition, palm kernel oil concentration, and their interaction on the measured properties of the heat-sealable biopolymer films. Mean comparisons were performed using Duncan's Multiple Range Test at a 95% confidence level ($p < 0.05$). Statistical significance was

3. Results and discussion

3.1. Effect of formulation composition and palm kernel oil on the mechanical properties of the films

The effects of formulation composition and palm kernel oil concentration on the mechanical properties of the starch–PVA biopolymer films are presented in Table 1. Significant differences ($p < 0.05$) were observed among the formulation levels for Young's modulus and tensile strength, while elongation at break also increased with formulation composition. Increasing the formulation composition from 0.50 to 1.00 g increased Young's modulus from 98.49 ± 0.14 to 123.92 ± 0.11 N/m² and tensile strength from 23.32 ± 0.03 to 27.18 ± 0.11 MPa. Elongation at break increased from 132.88 ± 0.02% at 0.50 g to 147.66 ± 0.03% at 1.00 g. The simultaneous increase in strength and extensibility indicates that increasing the formulation level enhanced the overall mechanical performance of the films.

The improvement in mechanical properties can be attributed to increased interactions between starch and PVA within the film matrix. Both polymers contain abundant hydroxyl groups, which facilitate intermolecular hydrogen bonding and promote formation of a relatively continuous polymer network. Recent reviews have established that starch/PVA blends exhibit favourable molecular compatibility and that the ratio of the two polymers strongly influences the resulting mechanical and functional properties of the films (Abedi-Firoozjah et al., 2023; Deng et al., 2024). In particular, blending PVA with starch can compensate for some of the inherent weaknesses of starch films, including limited mechanical strength and poor flexibility.

The tensile strength obtained in the present study (23.32–27.18 MPa) demonstrates that the developed films possessed appreciable resistance to tensile deformation. Nevertheless, direct comparison of tensile values among starch/PVA films should be made cautiously because mechanical properties are strongly dependent on polymer ratio, plasticizer concentration, moisture content, processing method, film thickness and the degree of intermolecular interaction. For example, Wu *et al.* (2024) reported a tensile strength of 34.5 MPa and elongation at break of 271.8% for starch/PVA films produced using mechanical activation and metal-organic coordination. The enhanced performance was attributed to improved interfacial interactions and compatibility between the starch and PVA phases.

The lower tensile strength obtained in the present study compared with Wu et al. (2024) is therefore reasonable because the two studies employed substantially different formulations and processing strategies. The present films were developed using the formulation conditions investigated in this study, whereas Wu et al. (2024) employed mechanical activation, calcium acetate coordination and extrusion blowing. Such differences can substantially modify polymer-chain organization and intermolecular bonding and, consequently, the mechanical response of the resulting films.

The increase in elongation at break from 132.88 to 147.66% with increasing formulation composition is particularly important for flexible food-packaging applications. Tensile strength describes the resistance of the film to tensile failure, whereas elongation at break reflects its ability to deform before rupture. Therefore, the simultaneous increase in tensile strength and elongation indicates that the higher formulation level improved both resistance to applied stress and deformation capacity. This observation agrees with previous studies showing that the mechanical behaviour of starch/PVA materials depends strongly on polymer compatibility, composition and intermolecular interactions (Abedi-Firoozjah et al., 2023; Deng et al., 2024).

Palm kernel oil produced a contrasting effect on the mechanical behaviour of the films. In the absence of palm kernel oil, Young's modulus and tensile strength were 149.75 ± 0.21 N/m² and 34.25 ± 0.04 MPa, respectively. Increasing palm kernel oil concentration to 0.05 and 0.10 mL progressively reduced Young's modulus to 106.67 ± 0.08 and 85.30 ± 0.03 N/m², respectively, while tensile strength decreased to 21.86 ± 0.16 and 19.17 ± 0.13 MPa. Conversely, elongation at break increased from 102.89 ± 0.03% without oil to 141.54 ± 0.02% and 179.02 ± 0.03% at 0.05 and 0.10 mL oil, respectively.

This behaviour demonstrates a clear strength–flexibility trade-off associated with palm kernel oil incorporation. The reduction in Young's modulus indicates that the films became less stiff as the oil concentration increased, while the increase in elongation indicates enhanced flexibility. Such behaviour is consistent with the general effect of incorporating a dispersed lipid phase into hydrophilic biopolymer matrices. Lipids can modify polymer-chain interactions and introduce regions with greater molecular mobility, thereby reducing rigidity while increasing deformability. Reviews of biopolymer films have similarly shown that incorporation of lipids can substantially modify mechanical and barrier properties, depending on the lipid type, concentration and distribution within the polymer matrix (Castro-Rosas et al., 2016).

The role of palm kernel oil in modifying barrier characteristics is also supported by recent experimental evidence. Zeng et al. (2020) demonstrated that palm kernel oil could impart hydrophobicity and improve water resistance in paper-based packaging materials, while Ng et al. (2025) reported that palm kernel oil nano-emulsion incorporated into gellan-gum films modified film microstructure and improved selected mechanical and water/oxygen barrier properties. These findings indicate that palm kernel oil can interact meaningfully with hydrophilic biopolymer matrices, although the magnitude and direction of the mechanical response depend on the polymer system and oil incorporation method.

The results therefore suggest that palm kernel oil concentration provides a means of tailoring the mechanical characteristics of the developed starch–PVA films. The oil-free film provided the highest strength and stiffness, whereas 0.10 mL palm kernel oil produced the highest flexibility. From a packaging perspective, the preferred formulation should consequently depend on the intended application. Applications requiring greater resistance to tensile loading may favour lower oil concentrations, whereas applications requiring flexibility and resistance to deformation may benefit from moderate or higher oil incorporation.

Table 1: Effect of film compositions on mechanical properties

Factor	Level	Young's modulus (N/m²)	Tensile strength (MPa)	Elongation at break (%)
Formulation composition (g)	0.50	98.49± 0.14 [a]	23.32± 0.03 [a]	132.88± 0.02 [a]
	0.75	119.31± 0.12 [b]	24.78± 0.01 [b]	142.90± 0.04 [b]
	1.00	123.92± 0.11 [c]	27.18± 0.11 [c]	147.66± 0.03 [b]
Palm kernel oil concentration ml	0	149.75± 0.21 [c]	34.25± 0.04 [c]	102.89± 0.03 [a]
	0.05	106.67± 0.08 [b]	21.86± 0.16 [b]	141.54± 0.02 [b]
	0.1	85.30± 0.03 [a]	19.17± 0.13 [a]	179.02± 0.03 [c]

3.2. Effect of formulation composition and palm kernel oil on film thickness and permeability

The physical and barrier properties of the films are presented in Table 2. Increasing formulation composition from 0.50 to 1.00 g increased film thickness from 0.1107 ± 0.02 to 0.1260 ± 0.06 mm. The increase was significant based on the different superscript letters. In contrast, the reported permeability decreased from 1.3956 ± 0.01 to 0.7633 ± 0.01(gm/(m^2sPa)) across the corresponding formulation levels. Opacity increased progressively from 1.2722 ± 0.11 to 1.8778 ± 0.01%, (%) while sealing temperature increased from 155 ± 0.01 to 200 ± 0.02 °C.

The increase in film thickness with increasing formulation composition can be attributed to the greater amount of film-forming material deposited within a given casting area. Film thickness is an important parameter because it can influence mechanical strength, optical behaviour and mass transfer through polymeric films. Abedi-Firoozjah

et al. (2023) identified thickness as an important characteristic of starch/PVA films and noted that it is affected by polymer composition, additives and film-forming conditions.

The decrease in the measured permeability value from 1.3956 to 0.7633 indicates an improvement in the corresponding barrier property, provided that the permeability parameter used in the present study is defined such that lower values represent improved barrier performance. This reduction may be associated with formation of a denser and more continuous polymer matrix at the higher formulation level, which can increase the resistance to molecular transport. However, the specific interpretation depends on the identity of the permeant and the analytical method used to determine permeability.

The importance of polymer organization in controlling barrier performance has been demonstrated in recent starch/PVA research. Wu et al. (2024) reported a water-vapour permeability of 0.704×10^{-12} g cm^{-1} s^{-1} Pa^{-1} for their optimized starch/PVA film and attributed the enhanced barrier behaviour to improved compatibility and interfacial interactions between the two polymer phases. Similarly, Deng et al. (2024) reported that the compatibility and intermolecular hydrogen bonding between starch and PVA contribute to the formation of a continuous blend network capable of improving the functional performance of starch/PVA films.

The observed increase in opacity from 1.2722 to 1.8778 with increasing formulation composition indicates reduced light transmission through the films. This change may be related to the simultaneous increase in film thickness and changes in the organization and distribution of polymer chains within the matrix. Film thickness and composition have previously been identified as important factors governing the optical characteristics of starch/PVA films (Abedi-Firoozjah et al., 2023).

The sealing temperature also increased from 155 °C at 0.50 g to 182 and 200 °C at 0.75 and 1.00 g, respectively. The increase suggests that films produced with higher formulation levels required greater thermal input to achieve the measured sealing response. This characteristic is relevant to packaging because sealability influences the processing conditions required during package formation. However, interpretation of the mechanism should be made cautiously because sealing behaviour is affected not only by film composition but also by sealing pressure, dwell time, film thickness and the criterion used to define an acceptable seal.

3.3. Effect of palm kernel oil on thickness, permeability, opacity and sealing temperature

Palm kernel oil significantly affected the physical and barrier properties of the films. Film thickness increased from 0.1074 ± 0.03 mm in the oil-free film to 0.1183 ± 0.01 and 0.1287 ± 0.01 mm at 0.05 and 0.10 mL oil, respectively. The progressive increase suggests that incorporation of the lipid phase altered the composition and volume of the dried film matrix. Similar changes in physical properties have been observed when lipidic components are incorporated into biopolymer-based films (Castro-Rosas et al., 2016).

The reported permeability decreased from 1.2300 ± 0.13 in the control film to 1.0778 ± 0.02 and 0.9911 ± 0.02 at 0.05 and 0.10 mL palm kernel oil, respectively. Thus, palm kernel oil incorporation improved the measured barrier property. This behaviour is consistent with the hydrophobic nature of palm kernel oil and its ability to reduce the affinity of a hydrophilic matrix for water. Zeng et al. (2020), for example, demonstrated that palm kernel oil substantially improved water resistance when applied to paper-based packaging materials, reducing water-vapour transmission and increasing surface hydrophobicity.

Recent work has also demonstrated the potential of palm kernel oil in biopolymer film systems. Ng et al. (2025) found that incorporation of palm kernel oil nano-emulsion into gellan-gum films improved their water and oxygen barrier characteristics, with higher palm kernel oil concentrations producing stronger barrier performance. Although the polymer matrix and incorporation method differ from those of the present study, the finding supports the general role of palm kernel oil as a hydrophobic phase capable of modifying mass-transfer pathways in hydrophilic biopolymer films.

The reduction in permeability occurred simultaneously with an increase in film thickness. Consequently, both the increased thickness and the presence of palm kernel oil may have contributed to the observed reduction in permeability. It would therefore be inappropriate to attribute the entire improvement solely to the hydrophobicity

of palm kernel oil. Film morphology, oil dispersion, polymer–oil interactions and thickness can act simultaneously to determine the final barrier performance. This is consistent with the broader literature showing that lipid incorporation can modify the mechanical and barrier characteristics of biopolymer films through several interacting mechanisms (Castro-Rosas et al., 2016).

Opacity increased from 1.4633 ± 0.08 in the oil-free film to 1.5722 ± 0.13 and 1.6878 ± 0.06 at 0.05 and 0.10 mL palm kernel oil, respectively. The increase indicates reduced optical clarity following oil incorporation. This behaviour may be associated with changes in the internal morphology of the films and the formation of dispersed oil domains within the starch/PVA matrix. Differences in refractive index between the lipid and polymer phases can increase light scattering and consequently reduce transparency. Nevertheless, confirmation of this mechanism would require microscopic or spectroscopic characterization of the film morphology.

The sealing temperature showed comparatively little variation with palm kernel oil concentration, changing from 198 ± 0.03 °C in the control film to 197 ± 0.03 and 199 ± 0.03 °C at 0.05 and 0.10 mL oil, respectively. Thus, within the investigated concentration range, palm kernel oil exerted a much stronger influence on flexibility, stiffness and the measured permeability than on sealing temperature. This relative stability suggests that incorporation of the oil did not substantially alter the thermal response responsible for the measured sealing behaviour under the conditions used in the present study.

Table 1. Physical, barrier and optical properties of the starch–PVA biopolymer films

Factor	Level	Thickness (mm)	Permeability	Opacity	Sealing Temp. (^{0}C)
Formulation composition (g)	0.50	0.1107± 0.02 [a]	1.3956± 0.01 [a]	1.2722± 0.11 [a]	155± 0.01 [a]
	0.75	0.1178± 0.01 [b]	1.1400± 0.03 [b]	1.5733± 0.21 [b]	182± 0.05 [b]
	1.00	0.1260± 0.06 [c]	0.7633± 0.01 [c]	1.8778± 0.01 [c]	200± 0.02 [c]
Palm kernel oil (ml)	0	0.1074± 0.03 [a]	1.2300± 0.13 [c]	1.4633± 0.08 [a]	198± 0.03 [a]
	0.05	0.1183± 0.01 [b]	1.0778± 0.02 [b]	1.5722± 0.13 [b]	197± 0.03 [a]
	0.1	0.1287± 0.01 [c]	0.9911± 0.02 [a]	1.6878± 0.06 [c]	199± 0.03 [a]

Conclusion

This study demonstrated the potential of cassava starch–polyvinyl alcohol (PVA) composite films incorporating palm kernel oil as heat-sealable and biodegradable materials for sustainable food-packaging applications. The results confirmed that both starch–PVA formulation composition and palm kernel oil concentration significantly influenced the mechanical, physical and barrier characteristics of the developed films. Increasing the starch formulation from 0.50 to 1.00 g improved tensile strength, Young's modulus and elongation at break, while also increasing film thickness and opacity and reducing the measured permeability. These changes indicate that increasing the polymer formulation enhanced the structural integrity and overall performance of the films. Palm kernel oil produced a different but complementary effect. Its incorporation progressively reduced tensile strength and Young's modulus while increasing elongation at break, demonstrating that the oil enhanced film flexibility and reduced rigidity. At 0.10 mL, palm kernel oil produced the highest elongation at break (179.02%), whereas the oil-free formulation exhibited the highest tensile strength (34.25 MPa) and Young's modulus (149.75 N/m²). Palm kernel oil also increased film thickness and opacity and reduced the measured permeability, indicating improved barrier performance within the investigated formulation range.

Recommendation

Further work is required before practical commercial application. Future studies should evaluate the biodegradation behaviour, water-vapour and oxygen permeability using standardized methods, seal strength, thermal and structural properties, oil dispersion and film morphology, as well as the performance of the films during actual storage of fresh produce. Optimization of the starch–PVA–palm kernel oil ratio and evaluation under different temperature and relative-humidity conditions would also provide a stronger basis for determining the most suitable formulation for specific food-packaging applications.

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Multi-Dimensional Flood Vulnerability Assessment: A Systematic Review of Indicators, Weighting Engines, and Spatial Synthesis

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ABSTRACT
Flood risk management has transitioned from single-variable hydraulic modelling to multidimensional vulnerability frameworks that evaluate the interplay between physical hazards, structural exposure, social sensitivity, and coping capacities. Despite rapid methodological growth, significant inconsistencies persist in how multi-dimensional indices are constructed, weighted, and geographically operationalised. This systematic review synthesises two decades (2005-2026) of empirical research on multi-dimensional flood vulnerability assessment, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework across 180+ peer-reviewed studies. The review critically evaluated progress across three methodological pillars: (1) Indicator Selection: deconstructing the physical, socio-economic, infrastructural, and institutional metrics utilised in flood risk indexing; (2) Weighting Engines: comparative performance analysis of subjective (e.g., Analytic Hierarchy Process (AHP), Delphi), objective (e.g., Criteria Importance Through Intercriteria Correlation (CRITIC), Entropy, Principal Component Analysis (PCA)), and hybrid mathematical weighting frameworks; (3) Spatial Synthesis: the evolution of GIS-based multi-criteria overlay and machine learning integrations for mapping vulnerable hotspots. The analysis revealed major methodological bottlenecks in current literature: an over-reliance on static inundation depth while omitting hydrodynamic velocity and duration parameters, widespread selection bias in unvalidated indicator weighting, and a persistent disconnect between spatial vulnerability outputs and actionable adaptation pathways. To bridge these gaps, there is a need for an integrated conceptual framework coupling 2D hydrodynamic hazard parameters, hybrid-weighted indicator engines, and Dynamic Adaptive Policy Pathways (DAPP). To conclude, the paper outlined priority research agendas for high-density, data-sparse basins, emphasising the necessity for open-access geospatial infrastructure and real-time community-validated risk mapping.

KEYWORDS: Flood vulnerability; Multi-criteria decision analysis; Weighting engines; GIS-based multi-criteria decision analysis (GIS-MCDA); Climate adaptation; Systematic review

1. INTRODUCTION

1.1 The Shift from Single-Metric to Multi-Dimensional Vulnerability

Flood risk management has traditionally relied on single-metric hydraulic analysis, using inundation depth, discharge magnitude, and return-period estimates as the principal determinants of risk. This hazard-centric approach treats floods as a purely physical phenomenon, yet two locations with identical inundation depths can experience markedly different outcomes depending on population resilience, early-warning adequacy, and institutional capacity (Rahman et al., 2025). This disjuncture has driven a shift toward multi-dimensional vulnerability frameworks, which treat vulnerability as a composite function of exposure, sensitivity, and adaptive capacity (Birkmann et al., 2013), integrating physical hazard parameters with socio-economic sensitivity and institutional readiness measures, typically operationalised through GIS-based composite indices.

This methodological expansion, however, has not produced convergence in practice. Dhawale, Schuster-Wallace, and Pietroniro (2024) found that normalisation and weighting choices vary so widely across the literature that min-max normalisation and equal weighting alone account for most published approaches, while Chan, Abid, Sulaiman, Nazir, and Azam (2022) documented comparable divergence in GIS-based assessment tools and techniques. Indicator sets, weighting engines, and spatial synthesis methods each vary considerably in composition and assumptions, undermining the comparability of vulnerability assessments across studies, particularly within data-sparse, rapidly urbanising basins typical of sub-Saharan Africa.

1.2 Rationale and Objective of the Systematic Review

Prior systematic reviews of this literature have each confined their scope to a single facet of the assessment process: Chan, Abid, Sulaiman, Nazir, and Azam (2022) reviewed flood vulnerability methods through the lens of GIS integration, while Dhawale, Schuster-Wallace, and Pietroniro (2024) synthesised vulnerability indices across floods and droughts jointly, without a dedicated treatment of weighting-engine performance. None to date has offered an integrated, cross-cutting evaluation of how indicator selection, weighting engines, and spatial synthesis interact to shape vulnerability outputs.

This paper addresses that gap through a PRISMA-guided systematic review of over 180 peer-reviewed studies published between 2005 and 2026, structured around three methodological pillars: (i) indicator selection across physical, socio-economic, infrastructural, and institutional domains; (ii) the comparative performance of subjective, objective, and hybrid weighting engines; and (iii) the evolution of spatial synthesis techniques, from GIS-based multi-criteria overlay to emerging machine learning integrations.

The objectives of the review are to: (i) systematically identify and classify the indicator sets employed across the literature, and assess the extent to which hydrodynamic parameters (beyond static inundation depth) are represented; (ii) critically compare the assumptions, strengths, and limitations of subjective, objective, and hybrid weighting engines used to aggregate vulnerability indicators; (iii) evaluate the progression of spatial synthesis approaches, with attention to the integration of GIS-MCDA with remote sensing and machine learning; and (iv) identify persistent methodological bottlenecks and propose an integrated conceptual framework coupling 2D hydrodynamic hazard parameters, hybrid-weighted indicator engines, and Dynamic Adaptive Policy Pathways (DAPP; Haasnoot, Kwakkel, Walker, & ter Maat, 2013), to guide future research in high-density, data-sparse river basins.

2. THEORETICAL ANALYSIS

2.1 Vulnerability as a Composite Construct

The review is anchored in two theoretical constructs that recur across the literature. The first is the exposure-sensitivity-capacity structure advanced by the MOVE framework (Birkmann et al., 2013), which conceives vulnerability not as a property of hazard alone but as the joint outcome of a system's exposure to a hazard, its sensitivity to harm once exposed, and its capacity to cope with and recover from that harm. This structure provides the organising logic for indicator selection throughout the field: physical and exposure indicators describe what is in harm's way, socio-economic sensitivity indicators describe how harm is differentially experienced, and coping/institutional indicators describe the capacity to absorb and recover from it.

The second construct is the Social Vulnerability Index (SoVI) approach developed by Cutter, Boruff, and Shirley (2003), who reduced a large set of socio-economic and demographic variables to a smaller set of components via factor analysis. SoVI formalised the idea that vulnerability has a measurable social dimension independent of physical hazard exposure, and its factor-analytic logic underpins both the socio-economic indicator sets reviewed in Section 4.1 and the objective weighting engines (principal component analysis in particular) reviewed in Section 4.2.

2.2 Dynamic Adaptive Policy Pathways as an Integrative Lens

Because vulnerability assessments are typically produced under deep uncertainty about future hazard, exposure, and socio-economic conditions, this review also draws on Dynamic Adaptive Policy Pathways (DAPP), a decision-theoretic framework developed by Haasnoot, Kwakkel, Walker, and ter Maat (2013) for planning under conditions where the future cannot be reliably predicted. DAPP treats a decision not as a single fixed plan but as a pathway that can be revised once pre-identified adaptation tipping points, the thresholds at which a given response is expected to fail, are reached.

This theoretical lens matters for the present review because none of the three methodological pillars examined, indicator selection, weighting, or spatial synthesis, is treated in the literature as revisable once produced: vulnerability maps are typically published as static end products rather than as evolving inputs to a decision process. Section 4.4 returns to this construct to propose coupling vulnerability outputs to a DAPP structure, so

that hazard characterisation, weighting choices, and spatial outputs can be revisited as conditions and data availability change.

3. MATERIALS AND METHODS

The review adopted the PRISMA framework to ensure transparency, reproducibility, and methodological rigour in identifying, screening, and synthesising relevant literature (Page et al., 2021). PRISMA was selected for its widespread adoption in environmental and engineering systematic reviews and its structured four-stage process (identification, screening, eligibility, and inclusion), which provides a traceable audit trail from initial search to final synthesis.

3.1 Database Query Protocols and Screening Criteria

The literature search was conducted across four databases (Scopus, Web of Science, ScienceDirect, and Google Scholar), selected for their comprehensive coverage of peer-reviewed engineering, environmental science, and geospatial research. Search strings combined controlled vocabulary and free-text terms across three conceptual clusters: (i) flood vulnerability terminology (e.g., "flood vulnerability", "flood risk index", "multi-dimensional vulnerability assessment"); (ii) weighting and aggregation terminology (e.g., "AHP", "entropy weighting", "CRITIC", "principal component analysis", "composite index"); and (iii) spatial synthesis terminology (e.g., "GIS-MCDA", "spatial vulnerability mapping", "machine learning flood risk"). Boolean operators (AND/OR) and truncation symbols maximised search sensitivity while retaining topical relevance.

The temporal scope was restricted to studies published between January 2005 and September 2026, capturing the period during which multidimensional vulnerability frameworks gained prominence following early conceptual contributions in the mid-2000s.

Screening proceeded in two PRISMA-consistent stages. At title and abstract screening, records were assessed against inclusion criteria: (i) the study presents or applies a composite or index-based flood vulnerability assessment incorporating at least two distinct dimensions (e.g., physical and socio-economic); (ii) publication in a peer-reviewed journal or conference proceeding; and (iii) publication in English within the date range. Exclusion criteria included studies addressing flood hazard alone without a vulnerability component, purely hydraulic or hydrodynamic modelling without indicator aggregation, non-peer-reviewed grey literature (unless justified), and duplicate records. At full-text eligibility, remaining records were assessed for sufficient methodological detail on indicator selection, weighting, and spatial output to permit synthesis. Two reviewers independently screened records, with disagreements resolved through discussion or third-reviewer arbitration to minimise selection bias. The database search identified 742 records across Scopus, Web of Science, ScienceDirect, and Google Scholar. After removing 126 duplicates, 616 records underwent title and abstract screening. Of these, 389 were excluded for failing to meet the inclusion criteria. The full texts of 227 articles were assessed for eligibility, resulting in the exclusion of 41 studies because they focused exclusively on flood hazard, lacked multidimensional vulnerability indicators, or provided insufficient methodological detail. A total of 186 studies were therefore included in the final systematic review.

3.2 Bibliometric Analysis and Spatio-Temporal Trends

Beyond qualitative synthesis, the included studies were subjected to a bibliometric analysis of publication trends across the 2005-2026 period, identifying inflection points linked to major methodological or policy developments, such as the growing accessibility of open-source GIS platforms and climate adaptation policy frameworks. Publication trends were disaggregated by journal outlet and disciplinary focus (hydrology, geography, disaster risk management, engineering) to assess cross-disciplinary uptake.

The spatial distribution of study locations was also mapped to identify geographic gaps in the evidence base. Preliminary categorisation suggests a disproportionate concentration of studies in well-resourced, data-rich basins in Asia, Europe, and North America relative to sub-Saharan Africa and other data-sparse contexts, directly relevant to the research gaps identified. Co-occurrence analysis of author keywords further mapped the conceptual structure of the field, providing an empirical basis for the thematic organisation adopted.

4. RESULTS AND DISCUSSION

4.1 Indicator Selection Frameworks

Consistent with the exposure-sensitivity-capacity structure outlined in Section 2.1, indicator sets across the reviewed literature are most commonly organised into three domains, physical/exposure, socio-economic sensitivity, and coping/institutional capacity, each operationalised to differing degrees of maturity.

Physical hazard and exposure indicators form the most consistently represented domain, typically comprising static topographic and hydrological variables, elevation, slope, drainage density, distance to river or drainage network, land use/cover, and rainfall, readily derived from remote sensing and secondary geospatial datasets. A persistent gap runs through this domain: Maranzoni, D'Oria, and Rizzo (2023) note that rigorous flood hazard assessment requires hydrodynamic modelling to characterise depth alongside flow velocity, arrival time, and duration, yet most indicator-based studies rely on static inundation depth or topographic proxies alone. This over-reliance on depth-only characterisation, flagged in this review's abstract as a central bottleneck, means an index built purely on elevation and drainage density cannot distinguish a slow, shallow inundation from a fast-moving, high-velocity flow, despite markedly different threats to structures, agricultural land, and human safety.

Socio-economic sensitivity indicators trace their lineage to the SoVI construct introduced in Section 2.1 (Cutter, Boruff, & Shirley, 2003), aggregating income, education, age structure, gender, household composition, and employment. This template underpins most subsequent flood vulnerability frameworks reviewed here. However, Hamidi, Novo, Paavola, and Ford (2025), examining 36 studies on social vulnerability to floods, found the field concentrated on a narrow band of recurring indicators, population, income, housing, and employment, while health conditions, disaster preparedness, social connectedness, and gender-minority status remain underrepresented, alongside widespread gaps in how these indicators are normalised and weighted.

Coping and institutional readiness indicators are conceptually the hardest to operationalise, capturing not physical conditions but the arrangements and governance structures that determine how effectively a community can prepare for, absorb, and recover from a flood. Parsons et al. (2021), in constructing the Australian Natural Disaster Resilience Index, distinguish coping capacity, immediate resources, skills, and emergency services, from adaptive capacity, longer-term governance and social-learning arrangements. They found that most nationally available indicators populate coping-capacity themes, while far fewer populate adaptive-capacity themes of governance and institutional leadership, an asymmetry that recurs throughout the literature and is consistent with Rahman et al. (2025), whose household-level assessment in Bangladesh found institutional indicators measurable at community scale but rarely aggregated into standardised, comparable indicator sets.

Table 1. Summary of indicator domains in multi-dimensional flood vulnerability assessment.

Domain	Example Indicators	Foundational / Representative Source	Representation in Literature
Physical hazard and exposure	Inundation depth, flow velocity, arrival time, duration, elevation, drainage density, distance to river, land use/land cover	Maranzoni, D'Oria, & Rizzo (2023); Birkmann et al. (2013)	Strong for static/topographic indicators; weak for dynamic hydrodynamic parameters
Socio-economic sensitivity	Income, education, age structure, gender, household composition, employment, housing	Cutter, Boruff, & Shirley (2003); Hamidi et al. (2025)	Strong, but concentrated on a narrow recurring subset (population, income, housing, employment)
Coping capacity and institutional readiness	Emergency services, community capital, information access, governance and leadership, trust in authorities, early-warning awareness	Parsons et al. (2021); Rahman et al. (2025)	Coping-capacity themes well represented; adaptive-capacity/governance themes thin

4.2 Weighting Engines and Aggregation Protocols

Once an indicator set is selected, it must be combined into a single composite score, and this aggregation step is where much of the methodological divergence identified originates. Weighting engines fall into three families: subjective methods, encoding expert judgement; objective statistical methods, deriving weights from the data itself; and hybrid methods combining both.

The Analytic Hierarchy Process (AHP), formalised by Saaty (2008), remains the most widely used subjective weighting engine, deriving indicator weights from pairwise comparisons resolved via eigenvalue calculation into a priority vector. Chakraborty and Mukhopadhyay (2019) offer a representative application, combining AHP with GIS to assign expert-derived weights in Coochbehar district, India. The principal limitation is reproducibility: because weights depend on the specific experts consulted, two AHP-based studies of the same location can produce different rankings, consistent with the transparency gaps documented by Hamidi et al. (2025).

Objective methods derive weights from the statistical properties of the indicator data itself. CRITIC (Diakoulaki, Mavrotas, & Papayannakis, 1995) derives weights from each indicator's standard deviation (contrast intensity) and its correlation with other indicators (redundancy). Entropy weighting uses a related information-theoretic logic based on distributional dispersion (Chen, 2019). Principal Component Analysis reduces a correlated indicator set to uncorrelated components and derives weights from explained variance, exemplified by the factor-analytic construction of SoVI (Cutter et al., 2003) introduced in Section 2.1. All three share a common vulnerability: because they operate on the indicator matrix rather than external judgement, their weights are sensitive to the normalisation method applied beforehand, helping explain why Dhawale et al. (2024) found min-max normalisation and equal weighting to dominate the literature.

Hybrid engines combine the interpretive strength of subjective methods with the statistical rigour of objective ones. Wu, Chen, and Lu (2022) illustrate this in an AHP-Entropy hybrid model for the Poyang Lake basin, where the composite weights were validated against flood events recorded in July 2020, demonstrating that hybrid weighting can be empirically checked in a way purely expert-derived weights cannot. Hybrid methods are not automatically more robust, however: combining two schemes still requires an often-arbitrary decision on their relative weighting, precisely the kind of choice Saisana, Saltelli, and Tarantola (2005) argue should be tested through formal sensitivity analysis. Across the reviewed literature, such analysis remains the exception, meaning most published vulnerability rankings have not been formally tested against the methodological choices that determine them.

Table 2. Comparison of subjective, objective, and hybrid weighting engines.

Engine Type	Method(s)	Basis for Weights	Key Strength	Key Weakness	Representative Study
Subjective	AHP, Delphi	Expert pairwise comparison / structured expert consultation	Encodes domain knowledge; usable with limited data	Weights depend on which experts are consulted; reproducibility concerns	Chakraborty & Mukhopadhyay (2019)
Objective	CRITIC, Entropy, PCA	Statistical structure of the indicator matrix (variance, correlation, dispersion)	Expert-independent; data-driven	Sensitive to normalisation choice; can obscure domain relevance	Diakoulaki, Mavrotas, & Papayannakis (1995); Chen (2019); Cutter et al. (2003)
Hybrid	AHP-Entropy and similar combinations	Combination of subjective and objective weight sets	Balances expert knowledge with statistical rigour; can be empirically validated	Requires an additional, often arbitrary, decision on how to combine the two weight sets	Wu, Chen, & Lu (2022)

4.3 Spatial Synthesis and Geo-Spatial Modelling

Once indicator selection and weighting produce a composite score, that score must be translated into a spatially explicit output decision-makers can act upon. This step has evolved from simple GIS overlay procedures toward increasingly data-intensive remote sensing and machine learning integrations.

The dominant approach is GIS-based multi-criteria decision analysis (GIS-MCDA), surveyed by Malczewski (2006) across over 300 applications, which established the standard workflow of standardising indicator layers, applying weights from one of the engines discussed, and combining weighted layers through overlay to produce a composite risk surface. Tikuye, Ray, Abeysingha, and Gurau (2025) provide a representative recent application, integrating AHP-derived weights with ten geospatial factors across Texas to produce a statewide susceptibility surface validated against historical storm records. GIS-MCDA's strength lies in transparency, but in practice this transparency is rarely exploited for validation; most outputs report a final map without testing how sensitive the spatial pattern is to the underlying weighting scheme, reproducing the sensitivity-testing gap identified in Section 4.2.

A second generation of methods departs from weighted-overlay logic, training machine learning algorithms directly on remote sensing and geospatial data to predict flood susceptibility. Manyaka, Shoko, Gxokwe, and Dube (2026), reviewing 129 studies (2010-2025), found that random forest, support vector machine, and convolutional neural network models consistently outperformed traditional hydrological approaches on accuracy metrics, while documenting a pronounced regional imbalance: Asia dominates published applications, while Africa and Latin America remain underrepresented. Tehrany, Pradhan, and Jebur (2014) earlier combined a weights-of-evidence model with a support vector machine within GIS to produce an ensemble susceptibility map, showing machine learning can integrate with, rather than replace, conventional GIS-based methods. Despite these gains, machine learning introduces a trade-off relative to GIS-MCDA: its predictions are comparatively opaque and difficult to decompose into transparent, indicator-level reasoning that policymakers can readily scrutinise.

4.4 Methodological Bottlenecks and an Integrated Framework

The three preceding subsections point to a shared pattern. At the indicator stage, physical hazard is still most commonly represented through static inundation depth rather than the fuller set of hydrodynamic parameters that determine actual flood severity. At the weighting stage, subjective, objective, and hybrid engines are each applied without the sensitivity testing needed to establish whether resulting rankings are robust or an artefact of arbitrary normalisation and aggregation choices. At the spatial synthesis stage, the field is splitting into two separate traditions: transparent but static GIS-MCDA overlays, and more accurate but comparatively opaque machine learning models, with little work combining the interpretability of the former with the predictive strength of the latter. These three bottlenecks compound: a vulnerability index built on incomplete hazard representation, weighted through an untested engine, and mapped through a method that cannot be easily interrogated produces an output that looks authoritative but is undemonstrated at every stage of its construction, helping explain the disconnect between published vulnerability maps and their limited uptake in flood adaptation planning.

Addressing these bottlenecks in isolation is unlikely to be sufficient, since the weaknesses identified arise from how the three pillars interact. Drawing on the DAPP lens introduced in Section 2.2, this review proposes an integrated conceptual framework built around three linked components. First, hazard characterisation should be grounded in two-dimensional (2D) hydrodynamic modelling rather than static inundation depth alone, so the hazard layer reflects velocity and duration as well as depth. Second, indicator weighting should default to hybrid engines combining subjective and objective inputs, accompanied by formal sensitivity analysis testing how far vulnerability rankings depend on the specific weighting and normalisation choices made. Third, the resulting vulnerability outputs should be coupled to a Dynamic Adaptive Policy Pathways structure, in which a vulnerability map is treated not as a static end product but as an input for identifying adaptation tipping points, the thresholds at which a given response is expected to fail and a different pathway becomes necessary. A DAPP-linked framework allows the hazard, weighting, and mapping components to be revisited as conditions change, directly targeting the interpretability problem rather than requiring a single opaque model to be trusted wholesale. For high-density, data-sparse basins, such as those characteristic of much of sub-Saharan Africa, this points toward a practical research agenda: open-access geospatial infrastructure and real-time, community-validated risk mapping to close the data gaps currently limiting hydrodynamic modelling and sensitivity testing in these settings.

5. CONCLUSION

This systematic review has synthesised two decades of research on multi-dimensional flood vulnerability assessment across three methodological pillars: indicator selection, weighting engines, and spatial synthesis. Three consistent bottlenecks emerged. First, physical hazard representation remains dominated by static inundation depth, with dynamic parameters such as flow velocity and duration still comparatively rare despite their demonstrated relevance to flood severity (Maranzoni, D'Oria, & Rizzo, 2023). Second, indicator weighting, whether subjective, objective, or hybrid, is rarely accompanied by the sensitivity analysis needed to establish that resulting rankings are robust rather than artefacts of arbitrary normalisation choices (Saisana, Saltelli, & Tarantola, 2005). Third, spatial synthesis methods are diverging into two separate traditions: transparent but static GIS-based overlays (Malczewski, 2006), and more predictive but less interpretable machine learning models (Manyaka, Shoko, Gxokwe, & Dube, 2026), with limited work bridging the two.

These bottlenecks are not independent; they compound across the assessment pipeline, so a vulnerability index can appear methodologically sophisticated while remaining largely untested at every stage of its construction. The integrated framework proposed here, coupling 2D hydrodynamic hazard characterisation, hybrid indicator weighting validated through sensitivity analysis, and a Dynamic Adaptive Policy Pathways structure (Haasnoot, Kwakkel, Walker, & ter Maat, 2013), offers one route toward closing the gap between published vulnerability indices and their limited use in real flood adaptation planning.

For agricultural water resources engineering, and for high-density, data-sparse river basins more broadly, the priority going forward is not simply more vulnerability indices, but the underlying data and validation infrastructure, open-access geospatial datasets, hydrodynamic modelling capacity, and community-validated risk information, needed to make existing and future indices demonstrably reliable rather than merely plausible.

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Paper ID 41:
Effect of Storage Conditions on the Quality of Ground Melon Seed

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ABSTRACT
Ground melon seed (Citrullus lanatus), locally called egusi, is a widely consumed and economically important oilseed product in Nigeria and West Africa, but it is highly susceptible to lipid oxidation, moisture uptake and microbial spoilage once milled. This study evaluated the effect of storage condition (ambient and refrigerated), packaging material (plastic and zip bag) and storage duration (Week 0, Week 2 and Week 4) on the peroxide value, total viable count (TVC), total fungal count (TFC), colour and odour of ground melon seed, using a 2 × 2 × 3 factorial design with three replicates per treatment combination. Results are presented as means with error bars representing the 95% confidence interval (5% significance level). Peroxide value rose from a baseline of 50.00 meq/kg at Week 0 to between 130.00 meq/kg (refrigerated/plastic) and 290.00 meq/kg (ambient/zip bag) by Week 4. TVC increased from about 2,300 cfu/g to between 153,333 and 300,000 cfu/g, and TFC rose from about 14 cfu/g to between 216.67 and 263.33 cfu/g over the same period. Colour darkened from light yellow to brownish yellow, and odour deteriorated from "Good" to "Nasty"/"Smelly", most severely under ambient storage in zip bags. Refrigerated storage in plastic packaging gave the best protection across all quality indices, while ambient storage in zip bags gave the highest peroxide value and TVC. Refrigerated storage in plastic packaging is recommended for ground melon seed.

KEYWORDS: Ground melon seed; storage condition; packaging material; storage quality; shelf life

1. INTRODUCTION

Melon (*Citrullus lanatus*) belongs to the genus *Citrullus*, which comprises four to five species in the family Cucurbitaceae and the tribe Benincaseae, found in Africa (Ogbonna & Ejimofor, 2013). *Citrullus lanatus* is an important crop plant and vegetable in West Africa, widely cultivated for its edible, nutrient-rich seeds, popularly called *egusi* (Yoruba), *egwusi* (Igbo) and *agushi* (Hausa) (Ogunsola *et al.*, 2020). In Nigeria and other West African countries, the crop is cultivated mainly for its seeds, which are widely consumed as a thickening agent in soups and stews. The seeds are nutritionally rich, containing high levels of protein (30 – 35%) and oil (40 – 50%), making them an important source of dietary energy and essential fatty acids (Aremu *et al.*, 2025). The high oil content contributes significantly to household nutrition and food security, particularly in regions where animal protein is limited, and melon seed is widely traded in both rural and urban markets across Nigeria.

Melon seed is processed into ground form using different methods traditional stone grinding, local grinding machines, or mortar and pestle and grinding has become increasingly common owing to consumer preference for convenience and reduced cooking time (Giwa & Akanbi, 2020). However, grinding exposes the highly unsaturated oil and inner seed tissues to environmental factors that accelerate lipid oxidation, moisture uptake and microbial deterioration (Ramya, 2024). Storage plays a critical role in preserving the quality, safety and shelf life of oilseed products such as ground melon seed: temperature, relative humidity, packaging material and storage duration all significantly influence physicochemical and microbiological stability (Forsido *et al.*, 2021). High storage temperatures accelerate lipid oxidation and free fatty acid formation, while high relative humidity promotes moisture uptake and mould growth (Adeniyi & Mushavhanamadi, 2023). In the humid tropical climate of southern and central Nigeria, where ambient temperature is high and relative humidity often exceeds 70% during the rainy season (although it falls markedly in the north during the dry harmattan period), improper storage can rapidly lead to spoilage, nutrient loss and contamination with mycotoxin-producing fungi (Oyebamiji *et al.*, 2023); appropriate packaging materials and controlled storage environments have been shown to reduce deterioration rates in oil-rich agricultural products (Lavanya *et al.*, 2026).

Ground melon seed is used widely in open markets, school campuses and homes across Nigeria particularly to prepare *egusi* soup, a staple delicacy and is commonly stored in polyethylene bags, open bowls or loosely covered containers under ambient tropical conditions. These practices expose the product to fluctuating temperature, high relative humidity, oxygen and possible microbial contamination. Because of its high fat content, ground melon seed is highly prone to lipid oxidation, which results in rancidity and unpleasant taste, while high moisture absorption can promote mould growth, leading to quality deterioration and potential health risks. Without a proper scientific evaluation of these effects, consumers may continue to experience reduced product quality, economic losses and health risks; there is therefore a need to assess how storage conditions affect ground melon seed in order to recommend improved storage methods and packaging materials.

The aim of this study was to evaluate the effects of storage condition, packaging material and storage duration on the quality of ground melon seed. The study was restricted to small-scale storage conditions and did not extend to industrial-scale preservation technologies such as vacuum packaging, modified-atmosphere storage, or chemical preservatives; the findings are therefore most directly applicable to local processors, traders and consumers handling ground melon seed under conventional storage conditions.

2. MATERIALS AND METHODS

2.1 Materials

The following materials were used for this study: melon seeds (*Citrullus lanatus*); packaging materials (polyethylene/zip bags and polypropylene airtight containers); an electric-powered stainless-steel motorized grinding machine (1.5 kW, approximately 2 hp; grinding capacity of 10–20 kg/h); a domestic refrigerator (Haier Thermocool, capacity approximately 150–200 L) and an ambient storage shelf; digital probe and maximum–minimum thermometers (range −10 to 50 °C, accuracy ±0.5 °C); an electronic digital weighing balance (capacity 5 kg, readability 0.01 g); a digital temperature and relative humidity meter (model HTC-1; temperature range −10 to 50 °C, accuracy ±1 °C; relative humidity range 10–99% RH, accuracy ±5% RH); a desiccator; a laboratory steam sterilizing autoclave (operating at 121 °C and approximately 103 kPa (15 psi) gauge pressure); a laboratory bacteriological incubator (adjustable from ambient temperature +5 °C to 60 °C); a digital colony counter (Stuart SC6, with an illuminated counting surface and digital colony-count display); Petri dishes; Nutrient Agar (bacterial count); Potato Dextrose Agar, PDA (fungal count); inoculating loop/wire and Bunsen burner/spirit lamp; sterile peptone water (diluent) and test tubes; glacial acetic acid, chloroform, potassium iodide, sodium thiosulfate and starch indicator (peroxide value determination); burette, conical flasks and pipettes; a Munsell colour chart (Munsell Soil Color Charts, 2009 revised edition); notebooks and pens; and personal protective equipment (hand gloves, nose mask and lab coat).

2.2 Sample Collection and Preparation

Fresh, mature melon seeds (*Citrullus lanatus*), 4 kg, were purchased from North Bank Market in Makurdi Local Government Area, Benue State, Nigeria. At the point of purchase, the seeds were inspected to ensure they were free from visible mould, insect infestation and physical damage, and were transported to the laboratory in clean, sealed polyethylene bags to prevent pre-experimental contamination or moisture uptake during transit.

2.3 Pre-treatment and Preparation of Melon Seeds

On arrival at the laboratory, the seeds were spread on a clean surface and sorted manually to remove broken, discoloured or shrivelled seeds and foreign material such as stones, chaff and dust. The sorted seeds were weighed and ground into a fine, uniform powder using a motorized grinding machine, in preparation for packaging and storage under the treatment conditions described below.

2.4 Experimental Design

The study adopted a 2 × 2 × 3 factorial experimental design comprising: Factor A packaging material (polyethylene zip bag and polypropylene container, hereafter referred to as “zip bag” and “plastic”, respectively); Factor B storage condition (ambient temperature, refrigerated condition); and Factor C storage duration (Week 0, Week 2 and Week 4, over a total storage period of 28 days). The 2 × 2 combination of packaging material and storage condition produced 4 treatment combinations, arranged in a completely randomized design (CRD); each was replicated three times (4 × 3 = 12 experimental units per sampling day), and with sampling on three occasions (Day 0, 14 and 28) a total of 36 experimental units were analysed over the storage period.

2.5 Packaging and Storage Conditions

Following grinding, equal measured quantities (500 g each) of ground melon seed were immediately packaged into the two materials defined by the experimental design. Polyethylene (zip) bags — low-density polyethylene, heat-sealed are the packaging material most commonly used by market vendors and small-scale traders across Nigeria, and offer minimal barrier against moisture and oxygen permeation. Polypropylene containers — airtight, with snap-lock lids offer a higher degree of protection against moisture ingress and oxygen exposure and are increasingly used by urban consumers for food storage. The packaged samples were stored under two conditions: ambient storage (room temperature, 25 ± 2 °C) and refrigerated storage (4 ± 2 °C), with the temperatures monitored throughout the storage period using a thermometer

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2.6 Quality Parameters Assessed

2.6.1 Bacterial Count

Total viable count was determined by the pour plate method on Nutrient Agar (AOAC, 2019) and expressed as colony-forming units per gram (cfu/g).

2.6.2 Fungal Count

Total fungal count was determined on Potato Dextrose Agar using standard procedures (AOAC, 2019) and expressed as cfu/g.

2.6.3 Peroxide Value (PV)

Peroxide value was determined by the standard titrimetric method (AOAC, 2019) and expressed as milliequivalents of peroxide per kilogram of sample (meq/kg).

2.6.4 Colour

Colour was assessed visually against a Munsell colour chart under uniform lighting at Weeks 0, 2 and 4 and classified into descriptive categories (e.g. light yellow, dull yellow, brownish yellow).

2.6.5 Odour

Odour was assessed by sensory evaluation of coded samples at Weeks 0, 2 and 4 and rated as Good, Slightly smelly/Bad or Nasty/Smelly.

2.7 Statistical Analysis

The mean of the three replicates was computed for each treatment combination and presented as bar charts combining storage condition, packaging material and storage duration. Error bars represent the 95% confidence interval of the mean (5% significance level, $p \leq 0.05$), computed from the pooled residual variance of the $2 \times 2 \times 3$ factorial design; treatment means whose error bars do not overlap were considered significantly different. Colour and odour were analysed descriptively.

3. RESULTS AND DISCUSSION

3.1 Baseline Quality of Freshly Milled Melon Seed (Week 0)

At the point of milling (Week 0), before any storage treatment was imposed, the ground melon seed samples were uniform across all treatment groups, with a peroxide value of approximately 50.00 meq/kg, total viable count between 2,100 and 2,500 cfu/g, total fungal count between 13 and 16 cfu/g, a light-yellow colour, and a good (fresh, nutty) odour. This near-uniformity at Week 0 confirms that the raw material used was homogeneous, so that any divergence observed in subsequent weeks can be attributed to the imposed storage treatments rather than to pre-existing variability in the raw material.

The Week 0 peroxide value recorded here is comparatively higher than the 3.13–3.67 meq/kg reported for freshly dried whole melon seeds by Bankole *et al.* (2005), and higher than values reported for some cold-pressed specialty seed oils analysed immediately after extraction (Tarasevičienė *et al.*, 2023). This difference is attributable to the present study analysing peroxide development in ground (milled) melon seed rather than in intact seeds or refined oil: milling ruptures the seed's cellular and oil-body structures, dramatically increasing the surface area of lipid exposed to atmospheric oxygen and to pro-oxidant enzymes (lipoxygenases) released during grinding. This is

consistent with the general principle that particle-size reduction accelerates the onset of lipid autoxidation in oil-bearing seeds, and underscores why ground melon seed is inherently more perishable than either the whole seed or the extracted, refined oil.

3.2 Effect of Storage Condition, Packaging Material and Storage Duration on Peroxide Value

Figure 1 presents the mean peroxide value of the ground melon seed for each combination of storage condition, packaging material and storage duration. Error bars represent the 95% confidence interval of each mean (5% significance level); means whose error bars do not overlap differ significantly.

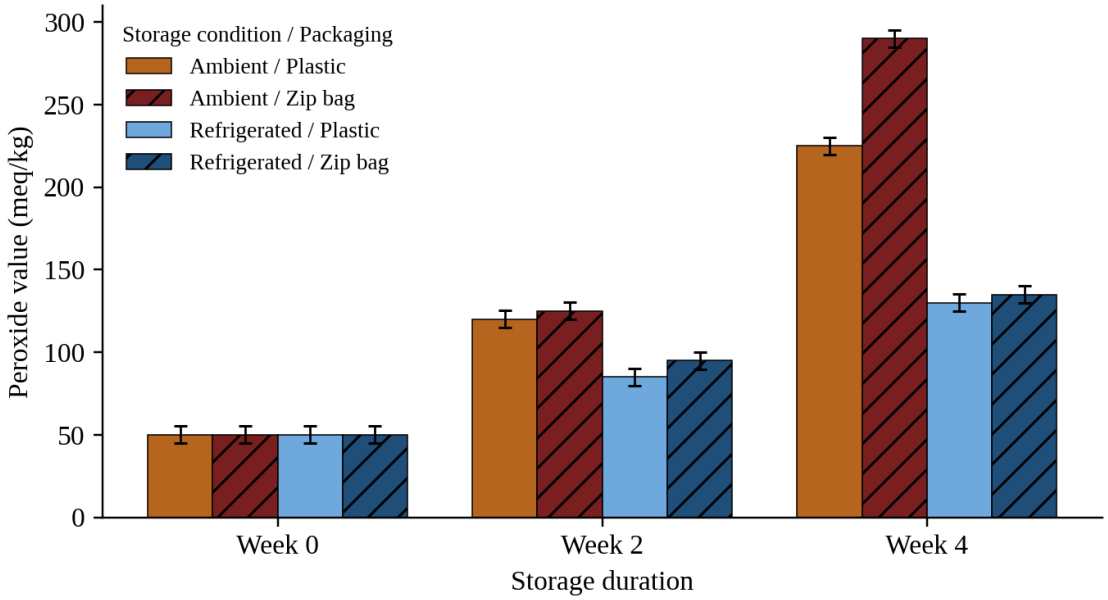

Figure 1: Peroxide value (meq/kg) of ground melon seed as affected by storage condition, packaging material and storage duration. Error bars represent the 95% confidence interval (5% significance level).

The data show a clear, progressive rise in peroxide value across all treatment combinations as storage duration increased, with the lowest terminal value recorded in refrigerated, plastic-packaged samples (130.00 meq/kg at Week 4) and the highest in ambient, zip-bag-packaged samples (290.00 meq/kg at Week 4). Averaged across packaging materials and durations, ambient storage produced a mean peroxide value of 143.33 meq/kg compared with 90.83 meq/kg for refrigerated storage; averaged across storage conditions and durations, zip bag packaging produced a mean peroxide value of 124.17 meq/kg compared with 110.00 meq/kg for plastic packaging.

The error bars in Figure 1 (±5.2 meq/kg) show that peroxide value at Weeks 2 and 4 was significantly higher than the Week 0 baseline in every treatment, and that refrigerated samples were significantly lower than ambient samples of the same packaging material at both Week 2 and Week 4. Packaging material had a significant effect only under ambient storage at Week 4 (225.00 meq/kg for plastic against 290.00 meq/kg for zip bag); under refrigeration, the difference between the two packaging materials (130.00 and 135.00 meq/kg at Week 4) fell within the error bars. The effect of packaging material therefore depended on storage condition, and the effect of storage condition grew with storage duration.

Averaged across all treatments, peroxide value increased from 50.00 meq/kg at Week 0 to 106.25 meq/kg at Week 2 and 195.00 meq/kg at Week 4, confirming that it increased steadily at every successive sampling point, although the rate of increase differed markedly with the combination of storage condition and packaging material.

The progressive increase in peroxide value is a direct chemical signature of lipid autoxidation, the free-radical chain reaction in which the unsaturated fatty acids present in melon seed lipids (chiefly linoleic and oleic acids) react with atmospheric oxygen to form primary oxidation products (hydroperoxides), which the peroxide value assay quantifies. This mirrors the trajectory reported for other oil-rich seed products stored over time:

Tarasevičienė *et al.* (2023) similarly recorded a time-dependent rise in peroxide value in cold-pressed black cumin, safflower and milk thistle seed oils over a four-month storage period, while Kim *et al.* (2025) reported that lipid oxidation indices (acid and peroxide values) in *Perilla frutescens* seed powder rose sharply with storage time once critical moisture/relative-humidity thresholds were exceeded.

The significantly lower peroxide values recorded under refrigeration relative to ambient storage are consistent with the well-established Arrhenius-type relationship between temperature and reaction rate: autoxidation is temperature-dependent, and lowering storage temperature slows the rate of hydroperoxide formation and radical propagation. Lee *et al.* (2021) similarly found that perilla seeds held under lower moisture/temperature-controlled conditions retained higher oxidative stability and lower peroxide and acid values than seeds stored under conditions favouring oxidative deterioration. Refrigeration in the present study therefore functioned as expected in slowing, though not fully arresting, oxidative rancidity of the ground melon seed lipids over the four-week period.

The packaging effect, with zip-bag-packaged samples showing numerically higher peroxide values than plastic-packaged samples at equivalent storage durations, points to differences in the gas-barrier performance of the two formats. Although zip-lock bags are colloquially perceived as more "airtight" because of their re-closable seal, the closure mechanism controls only macroscopic leakage and does not by itself guarantee a low oxygen transmission rate; the barrier performance of a flexible package is governed primarily by the polymer type and film thickness, which determine how readily oxygen diffuses through the material itself (Chen *et al.*, 2024). Where the zip-bag film used in local retail is thinner or more permeable than the plastic (polypropylene) packaging compared against it, more atmospheric oxygen would reach the milled melon seed during storage, accelerating hydroperoxide formation a pattern entirely consistent with the higher peroxide values obtained for zip-bag-packaged samples in this study. The packaging effect was also temperature-dependent: under ambient conditions zip-bag samples were significantly higher than plastic-packaged samples at Week 4 (290.00 against 225.00 meq/kg), whereas under refrigeration the difference was within the error bars. The protective benefit of refrigeration was therefore greatest when combined with the lower-permeability plastic packaging, and weakest when zip bags were used under ambient conditions — the combination that produced the highest peroxide value (290.00 meq/kg) of all treatment groups by Week 4.

3.3 Effect of Storage Condition, Packaging Material and Storage Duration on Total Viable Count (TVC)

Total viable (bacterial) count rose dramatically across the storage period in every treatment group (Figure 2), from an initial mean of about 2,300–2,500 cfu/g at Week 0 to values ranging from 153,333 cfu/g (refrigeration/plastic) to 300,000 cfu/g (ambient/zip bag) by Week 4. Averaged across packaging materials and duration, ambient-stored samples recorded a mean TVC of 98,322 cfu/g against 75,322 cfu/g for refrigerated samples; averaged across storage conditions and duration, zip-bag-packaged samples recorded a mean TVC of 101,656 cfu/g against 71,989 cfu/g for plastic-packaged samples.

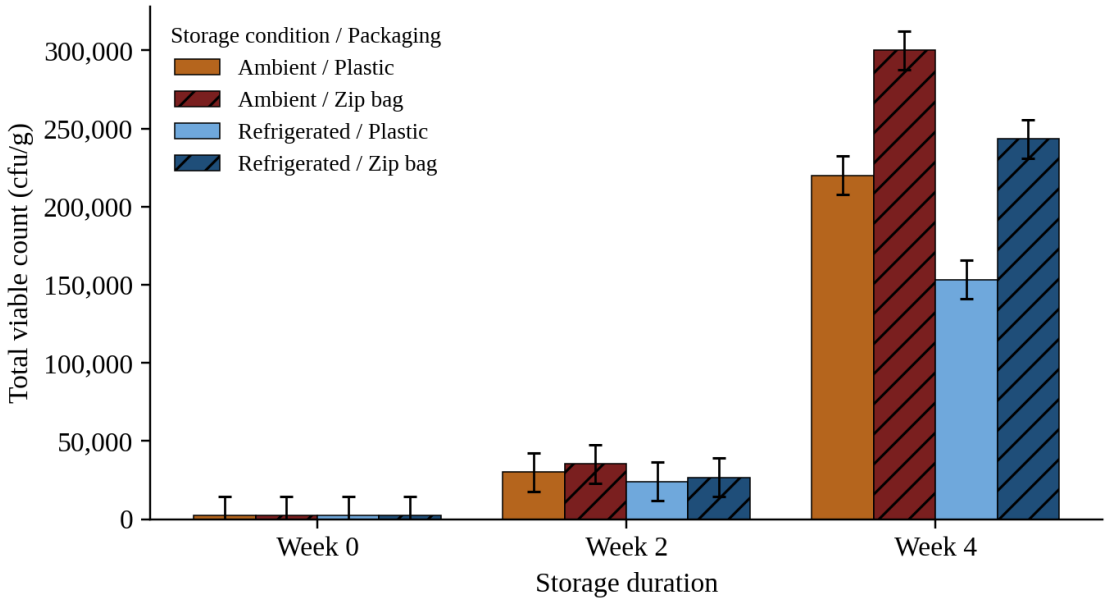

Figure 2: Total viable count (cfu/g) of ground melon seed as affected by storage condition, packaging material and storage duration. Error bars represent the 95% confidence interval (5% significance level).

The error bars in Figure 2 (±12,305 cfu/g) show that TVC at Week 4 was significantly higher than at Weeks 0 and 2 in all treatments. At Week 2, differences among treatments were within the error bars. At Week 4, however, refrigerated samples were significantly lower than ambient samples of the same packaging material (153,333 against 220,000 cfu/g for plastic; 243,333 against 300,000 cfu/g for zip bag), and zip-bag samples were significantly higher than plastic-packaged samples under both storage conditions. Bacterial proliferation therefore became clearly dependent on storage condition and packaging material only after the second week.

Averaged across all treatments, TVC rose from 2,300 cfu/g at Week 0 to 29,000 cfu/g at Week 2 and 229,167 cfu/g at Week 4, confirming an escalating, and by Week 4 near-exponential, pattern of bacterial multiplication. The steep rise in TVC reflects classical microbial growth-curve behaviour, in which an initial lag phase is followed by a period of accelerating (log-phase) multiplication once conditions of moisture, nutrient availability and temperature become favourable. Ground melon seed is a nutrient-dense substrate rich in protein, oil and carbohydrate and milling increases both its surface area and its exposure to environmental micro-organisms, predisposing it to rapid bacterial colonisation once adequate moisture is available. The markedly lower bacterial counts recorded under refrigeration are consistent with the principle that most spoilage bacteria associated with plant-derived foods are mesophiles whose growth rate slows sharply as temperature is reduced toward refrigeration range; comparable temperature-dependent suppression of microbial proliferation has been documented in stored seed products such as perilla seed and perilla seed powder (Lee *et al.*, 2021; Kim *et al.*, 2025).

The higher TVC recorded in zip-bag-packaged samples, and the widening gap between packaging materials by Week 4, suggest that the zip-bag format was less effective than the plastic packaging at excluding moisture and/or dissipating localised humidity generated within the pack as the ground melon seed respired and interacted with ambient air. Because water activity is one of the principal determinants of microbial growth in stored plant products, any packaging configuration that permits greater moisture ingress or retention within the pack will support faster bacterial multiplication (Kim *et al.*, 2025), consistent with wider food-packaging evidence that the specific barrier and moisture-retention properties of a packaging material not simply whether it is "sealed" determine its effectiveness at slowing microbial spoilage of packaged foods (Chen *et al.*, 2024).

3.4 Effect of Storage Condition, Packaging Material and Storage Duration on Total Fungal Count (TFC)
Total fungal count also increased steadily across the storage period (Figure 3), rising from 13–16 cfu/g at Week 0 to between 216.67 cfu/g (refrigeration/plastic) and 263.33 cfu/g (ambient/plastic) by Week 4. A particularly striking feature of the data is the disproportionate early rise in TFC recorded for the ambient/zip-bag combination at Week 2 (183.33 cfu/g), roughly seven times higher than the ambient/plastic combination at the same time point (25.67 cfu/g), even though both had converged to broadly similar counts by Week 4.

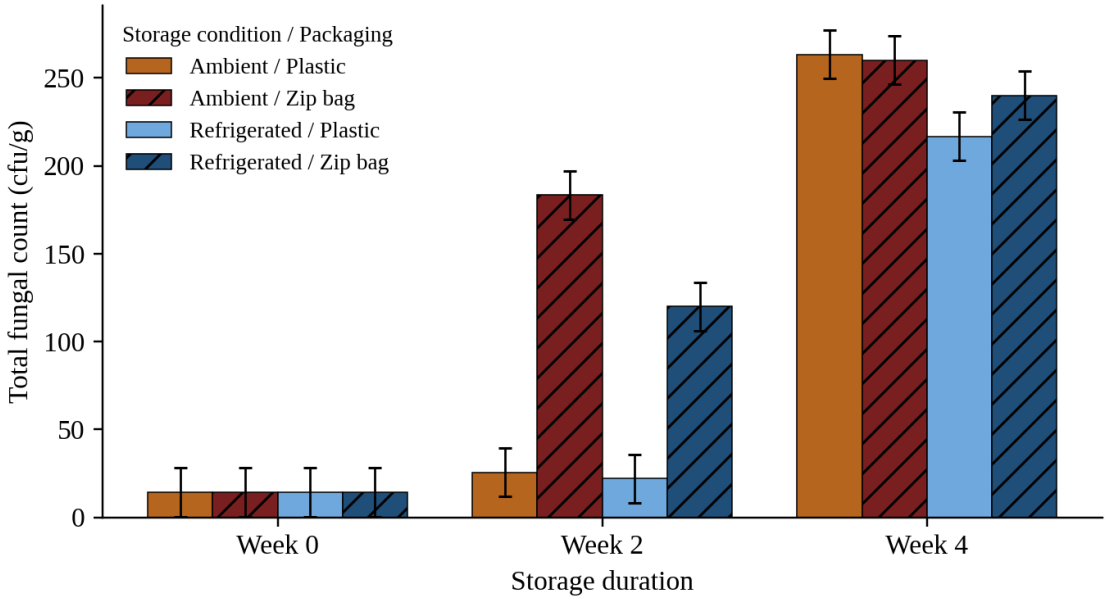

Figure 3: Total fungal count (cfu/g) of ground melon seed as affected by storage condition, packaging material and storage duration. Error bars represent the 95% confidence interval (5% significance level).
The error bars in Figure 3 (±13.8 cfu/g) show that TFC at Week 4 was significantly higher than at Weeks 0 and 2 in all treatments. At Week 2, zip-bag samples had significantly higher TFC than plastic-packaged samples under both ambient (183.33 against 25.67 cfu/g) and refrigerated (120.00 against 22.00 cfu/g) storage, and ambient zip-bag samples were also higher than refrigerated zip-bag samples. At Week 4, only the refrigerated plastic-packaged samples (216.67 cfu/g) were significantly lower than the ambient samples (260.00–263.33 cfu/g). Packaging material therefore influenced fungal proliferation mainly at Week 2, and the differences between packaging materials narrowed by Week 4.

Averaged across all treatments, TFC rose from 14.33 cfu/g at Week 0 to 87.75 cfu/g at Week 2 and 245.00 cfu/g at Week 4.

Fungal growth in stored oilseeds is governed primarily by moisture availability, commonly expressed as water activity or equilibrium relative humidity, with storage fungi such as *Aspergillus* and *Penicillium* species requiring a minimum relative humidity of about 65% (equivalent to roughly 13–15% seed moisture content) to initiate active growth (FAO, 1994). The fungal genera most frequently implicated in the deterioration of stored melon seed and related products are *Aspergillus*, *Penicillium* and *Rhizopus* species, repeatedly isolated from both whole and ground melon seed during storage (Bankole *et al.*, 2005).

The pronounced early spike in fungal count observed in the ambient/zip-bag combination at Week 2 is best explained by moisture micro-climate effects inside the pack. Under fluctuating ambient temperatures, water vapour generated by the respiring, oil- and protein-rich ground melon seed can condense on the inner surface of a flexible pack, and if the packaging material does not allow this moisture to escape (or re-absorbs moisture from the surrounding air more readily than a thicker plastic pack), a locally humid micro-environment favourable to rapid mould colonisation is created well before the bulk moisture content of the whole sample changes appreciably. Kim *et al.* (2025) documented an analogous humidity threshold effect in *Perilla frutescens* seed

powder, in which visible fungal/mould deterioration occurred abruptly once relative humidity exceeded about 69%, whereas products held below roughly 43% relative humidity showed minimal fungal proliferation even after extended storage. By Week 4, when moisture had presumably become more evenly distributed and time-dependent nutrient and oxygen effects came to dominate, the gap between packaging materials under ambient conditions narrowed, consistent with the narrowing of the gap between packaging materials by Week 4 (Figure 3).

Refrigeration slowed, but did not eliminate, fungal proliferation, reflecting the fact that many storage moulds, while mesophilic, can still grow albeit more slowly refrigeration temperatures, particularly once product moisture content is favourable; this is consistent with reports that low-temperature storage extends, rather than completely halts, the lag phase of fungal growth in stored seed and oilseed-derived powders (Kim *et al.,* 2025; Lee *et al.,* 2021).

3.5 Effect of Storage Condition, Packaging Material and Storage Duration on Colour

Visual assessment showed a consistent progression from the fresh light-yellow colour of Week 0 samples toward increasingly dull, brownish-yellow hues by Week 4. Ambient-stored samples browned more severely and more rapidly than refrigerated samples: by Week 4, ambient/zip-bag samples had turned distinctly brownish-yellow, while refrigerated/plastic samples were only slightly dulled from their original light-yellow shade. This colour change parallels, and is mechanistically linked to, the chemical and microbial changes already discussed: browning in stored oil-bearing seed products arises both from the breakdown products of lipid oxidation (secondary oxidation products and their interaction with proteins) and from pigment degradation associated with microbial and enzymatic activity, both of which progressed fastest under ambient storage in zip-bag packaging. The close correspondence between the treatments producing the highest peroxide values and total counts and those showing the most pronounced browning supports the interpretation that colour deterioration in ground melon seed is a visible, integrative indicator of the underlying oxidative and microbial spoilage processes, a relationship also noted for other stored oilseed powders whose colour parameters shift measurably once lipid oxidation and microbial load pass certain thresholds (Kim *et al*., 2025).

3.6 Effect of Storage Condition, Packaging Material and Storage Duration on Odour

Sensory odour scores followed the same directional pattern as the chemical and microbial indices. All samples were rated “Good” at Week 0. By Week 2, ambient-stored samples (both packaging materials) were already rated “Bad”, while refrigerated samples were only “Slightly smelly”. By Week 4, ambient samples were rated “Nasty” while refrigerated samples were rated “Smelly” a comparatively less severe descriptor, indicating that refrigeration slowed, but did not prevent, the eventual onset of off-odours. Off-odours in stored oilseed products typically arise from volatile secondary lipid-oxidation products (aldehydes, ketones and short-chain fatty acids generated as hydroperoxides decompose) and from volatile microbial metabolites; both classes of compound would be expected to accumulate fastest where peroxide value and microbial counts rose fastest, precisely as observed in the ambient/zip-bag treatment combination in this study. This is consistent with reports that oxidative deterioration produces detectable, increasingly unacceptable changes in the odour profile of stored seed oils and seed-based powders as storage time and temperature increase (Tarasevičienė *et al.,* 2023).

3.7 Interactive Effects of Storage Condition, Packaging Material and Storage Duration

Taken together, the results show that the three factors examined did not act independently on the quality of stored ground melon seed; rather, their effects compounded one another. The gap between ambient and refrigerated samples widened with storage duration and was widest for zip-bag packaging (for example, peroxide value of 290.00 against 135.00 meq/kg at Week 4). The highest peroxide value and total viable count, an early and pronounced rise in fungal count, the most pronounced browning and the most offensive odour were recorded in samples stored under ambient conditions in zip-bag packaging, while the mildest overall deterioration was recorded in samples stored under refrigeration in plastic packaging. This agreement across five quality indices (one chemical, two microbiological, and sensory colour and odour) strengthens confidence that the observed treatment effects reflect genuine, biologically coherent spoilage phenomena rather than measurement artefacts, and identifies low-temperature storage combined with lower-permeability packaging as the most protective combination evaluated in this study.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusions

Storage condition, packaging material and storage duration all affected the quality of ground melon seed. Between Week 0 and Week 4, peroxide value rose from 50.00 meq/kg to between 130.00 and 290.00 meq/kg, TVC from about 2,300 cfu/g to between 153,333 and 300,000 cfu/g, and TFC from about 14 cfu/g to between 216.67 and 263.33 cfu/g, while colour darkened and odour deteriorated. Deterioration was fastest under ambient storage in zip bags and slowest under refrigeration in plastic packaging, which gave the best protection, although quality still declined in all treatments over the four weeks.

4.2 Recommendations

Based on the findings of this study, the following two recommendations are made:

1. Ground melon seed intended for storage beyond a few days should be kept under refrigeration rather than at ambient (room) temperature, as refrigeration significantly slowed both lipid oxidation and microbial proliferation over the four-week study period.
2. Ground melon seed should be packaged in plastic packaging (such as airtight polypropylene containers) rather than ordinary zip bags, since zip bags gave higher peroxide values and microbial counts than plastic packaging in this study.

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Paper ID 44:
Optimization of Thermal Processing Conditions and Sugarcane Juice Concentration for Quality Attributes of Tamarind Juice Using Response Surface Methodology

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Abstract
Tamarind juice quality is highly sensitive to pasteurization conditions, yet the interactive effects of temperature, time, and sugarcane juice concentration remain underexplored. This study evaluates the effects of pasteurization temperature (75-95 °C), pasteurization time (10-20 min), and sugarcane juice concentration (30-70% v/v) on ascorbic acid content, total phenolic content, total flavonoid content, titratable acidity, and total soluble solids of tamarind juice. Second-order polynomial models were fitted using response surface regression. Sugarcane juice concentration was the dominant factor governing ascorbic acid retention and total soluble solids, both increasing with higher juice concentration, while pasteurization temperature primarily drove titratable acidity and total phenolic content, with phenolic content improving under moderate heating before declining at higher temperatures. A significant temperature-sugarcane interaction was obtained across several responses. Models for total phenolic content, titratable acidity, and total soluble solids showed strong predictive adequacy (R^2 > 90%), whereas the ascorbic acid and, particularly, the total flavonoid content models showed weaker fit, reflecting the thermal lability and analytical variability of these compounds. Multi-response optimization using the desirability function identified 82.07 °C, 15.45 min, and 70% v/v sugarcane juice concentration as the optimal condition (composite desirability = 0.727), predicting 68.08 mg/100 ml ascorbic acid, 49.32 mg GAE/100 ml total phenolic content, 27.43 mg QE/100 ml total flavonoid content, 0.308% titratable acidity, and 18.99 °Brix total soluble solids. Conclusively, this study demonstrated that tamarind juice can be pasteurized under moderate thermal conditions with minimal nutritional loss when sugarcane juice concentration is co-optimized with temperature.

Keywords: Tamarind juice; Response surface methodology; Sugarcane Juice; Pasteurization; Quality attributes

INTRODUCTION

Tamarind (*Tamarindus indica* L.) is a tropical fruit widely valued for its distinctive sweet-sour flavour and nutritional richness. The pulp is a notable source of tartaric and other organic acids, natural sugars, minerals such as calcium, phosphorus, and iron, and bioactive compounds including ascorbic acid, phenolics, and flavonoids (Bankole *et al.*, 2026; Mishra *et al.*, 2026). Due to this composition, tamarind is widely processed into juices, concentrates, and beverages across tropical and subtropical regions, where a sweetening agent is typically added to balance its natural acidity and improve palatability (Vikram *et al.*, 2023; Laharia, 2024). Sugarcane juice, in particular, is an attractive natural sweetening agent for such formulations, as unlike refined sucrose, it retains residual phenolic compounds, minerals, and other phytochemicals from the cane juice, potentially contributing additional functional and antioxidant value to the final beverage rather than acting as a purely inert sweetener (Azlan *et al.*, 2023). The growing consumer demand for functional, minimally refined sugar beverages with retained antioxidant value has increased interest in both tamarind and sugarcane-based formulations as commercially viable products.

Pasteurization is an essential unit operation in juice processing, required to ensure microbial safety and extend shelf life. However, thermal treatment is a double-edged intervention: while it inactivates spoilage and pathogenic microorganisms and relevant enzymes, it can also degrade heat-labile bioactive compounds, particularly ascorbic acid, phenolics, and flavonoids, which are highly sensitive to temperature and duration of heat exposure (Sanusi *et al.*, 2024; Adhikari *et al.*, 2025). Similarly, the concentration of sugarcane juice incorporated into the formulation can influence solute-solvent interactions, osmotic effects, and the thermal stability of these bioactive compounds, while also affecting titratable acidity and total soluble solids. Optimizing pasteurization conditions

therefore requires a balance between physicochemical quality and retention of nutritionally and functionally important compounds, a balance that is difficult to achieve through single-factor experimentation, since these variables often interact rather than act independently (Sanusi *et al.,* 2025).

Response Surface Methodology (RSM) is a well-established statistical and mathematical technique for modelling and optimizing processes influenced by multiple interacting variables, allowing simultaneous evaluation of main effects, interaction effects, and quadratic effects with a minimal number of experimental runs (Athanasaki *et al.,* 2024). Among RSM designs, the Box-Behnken Design (BBD) is particularly efficient for three-factor systems, as it requires fewer runs than a Central Composite Design while avoiding extreme factor combinations that may be impractical or unsafe in food processing contexts (Gupta *et al.,* 2026). BBD-RSM has been successfully applied to optimize thermal processing conditions in various fruit juices and beverages, enabling researchers to identify optimum conditions that maximize desirable quality attributes while minimizing degradation of sensitive compounds (Abrol *et al.,* 2023).

Despite the reported use of RSM in several fruit-juice processing studies, limited work has systematically applied a three-factor BBD approach to simultaneously evaluate the combined effects of pasteurization temperature, pasteurization time, and sugarcane juice concentration on the quality attributes of tamarind juice. Most existing studies on tamarind processing have focused on single-factor thermal treatments or the use of refined sugar as the sweetening agent, with limited attention to natural juice-based sweeteners as an interacting process variable. The present study therefore applies a three-factor, three-level Box-Behnken design to model and optimize the effects of pasteurization temperature, pasteurization time, and sugarcane juice concentration on ascorbic acid content, total phenolic content, total flavonoid content, titratable acidity, and total soluble solids of tamarind juice.

2. MATERIALS AND METHODS

2.1 Materials

Fresh, mature tamarind (*Tamarindus indica* L.) pods were purchased from a local market in Sokoto, Sokoto State, Nigeria. Sugarcane stalks were procured from Mandate Market, Kwara State, Nigeria, and processed to obtain sugarcane juice, which was used as a natural sweetening agent in the tamarind juice formulations. All chemicals and reagents used for the analyses were of analytical grade and were obtained from Sigma-Aldrich (St. Louis, MO, USA).

2.2 Preparation of Tamarind Juice

Fresh, mature tamarind (*Tamarindus indica* L.) pods were sorted to remove damaged and undesirable materials and manually decorticated to remove the outer shells and fibrous materials. The resulting pulp was collected, and 500 g was weighed for extraction. Hibiscus flowers (10 g) were added to the tamarind pulp, and the mixture was combined with potable water obtained from the University of Ilorin Water Processing Factory, Ilorin, Kwara State, Nigeria, at a ratio of 1:10 (w/v), corresponding to 5 L of potable water per 500 g of tamarind pulp. The mixture was subjected to hot-water extraction by boiling for 20 min. Following extraction, the mixture was filtered through a double layer of muslin cloth to remove the seeds and other insoluble materials, yielding the tamarind–hibiscus extract. Fresh sugarcane (*Saccharum officinarum* L.) stalks weighing 18.86 kg were thoroughly washed, peeled, and cut into small pieces. The prepared stalks were blended progressively in batches using a Kenwood multifunctional commercial blender (Model KW-505; 2 L capacity, 220 V, 50 Hz). A total of 275 ml of potable water was used during the blending process to facilitate disruption of the sugarcane tissue and aid juice release. The filtrate obtained from each batch was subsequently reused as the blending liquid for the next batch to facilitate progressive extraction and maximize juice recovery. This process was continued until all the sugarcane stalks had been processed. The resulting slurry was filtered through a double layer of muslin cloth to remove fibrous residues, and the filtrate obtained was collected as sugarcane juice. The extracted sugarcane juice was incorporated into the tamarind-hibiscus extract at the concentrations specified by the experimental design (Table 1). The resulting formulations were thoroughly mixed to ensure uniform distribution of sugarcane juice and subsequently subjected to pasteurization under the thermal processing conditions specified by the experimental design.

2.3 Experimental Design

A three-factor, three-level Box-Behnken Design (BBD) was employed using Minitab software (version 20.0) to evaluate the individual and interactive effects of pasteurization temperature (X_1), pasteurization time (X_2), and

sugarcane juice concentration (X_3) on the quality attributes of tamarind juice. The independent variables and their coded levels are presented in Table 1, and the complete design matrix, consisting of 15 experimental runs including three replicates at the center point for estimation of pure error, is presented in Table 2.

Table 1. Independent variables and their levels used in the Box-Behnken Design

Independent variable	Symbol	Low (-1)	Middle (0)	High (+1)
Pasteurization temperature (°C)	X_1	75	85	95
Pasteurization time (min)	X_2	10	15	20
Sugarcane juice concentration (% v/v)	X_3	30	50	70

Table 2. Experimental design matrix of the effects of pasteurization temperature, pasteurization time, and sugarcane juice concentration on the quality attributes of tamarind juice

Run	X_1: Temperature (°C)	X_2: Time (min)	X_3: Sugarcane juice concentration (% v/v)
1	75	10	50
2	95	10	50
3	75	20	50
4	95	20	50
5	75	15	30
6	95	15	30
7	75	15	70
8	95	15	70
9	85	10	30
10	85	20	30
11	85	10	70
12	85	20	70
13	85	15	50
14	85	15	50
15	85	15	50

2.4 Pasteurization Treatment

Each juice formulation was subjected to pasteurization in a locally fabricated laboratory pasteurizer at the temperature and time combinations specified in Table 2. Following treatment, samples were rapidly cooled to room temperature and stored in the refrigerator at a temperature of 4 ±1°C prior to analysis, which was carried out immediately to minimize post-processing changes.

2.5 Determination of Ascorbic Acid Content

Ascorbic acid content was determined by the 2,6-dichlorophenolindophenol (DCPIP) titrimetric method according to AOAC Official Method 967.21 (AOAC, 2000). The method is based on the reduction of DCPIP by ascorbic acid, with the endpoint indicated by the persistence of a light pink color. The DCPIP solution was standardized against a freshly prepared L-ascorbic acid standard solution. Results were expressed as mg ascorbic acid/100 ml of juice.

2.6 Determination of Total Phenolic Content

Total phenolic content (TPC) was determined using the Folin-Ciocalteu colorimetric method as described by Sanusi *et al*. (2023), with appropriate modifications where applicable. The absorbance of the reaction mixture was measured using a UV–Vis spectrophotometer at the wavelength specified in the adopted procedure. A calibration curve was prepared using gallic acid as the standard, and the results were expressed as mg gallic acid equivalents (GAE)/100 ml of juice. The Folin-Ciocalteu assay is based on the formation of a colored complex between phenolic compounds and the Folin-Ciocalteu reagent under alkaline conditions.

2.7 Determination of Total Flavonoid Content

Total flavonoid content (TFC) was determined using the aluminium chloride ($AlCl_3$) colorimetric method as described by Sanusi *et al.* (2023), with appropriate modifications where applicable. The absorbance of the reaction mixture was measured using a UV-Vis spectrophotometer at 415 nm. A calibration curve was prepared using quercetin as the standard, and the results were expressed as mg quercetin equivalents (QE)/100 ml of juice.

2.8 Determination of Titratable Acidity

Titratable acidity was determined by titrating a measured volume of juice sample against standardized 0.1 N sodium hydroxide (NaOH) solution using phenolphthalein as the indicator. The titration was continued to the appropriate endpoint, and the titratable acidity was calculated and expressed as percentage tartaric acid equivalents (%). Tartaric acid was used as the reference acid because it is a major organic acid associated with tamarind.

2.9 Determination of Total Soluble Solids

Total soluble solids (TSS) were determined using a calibrated digital refractometer. A homogenized juice sample was placed on the prism, and the reading was recorded at room temperature. Results were expressed as °Brix according to the method described by Obiefuna *et al.* (2025).

2.10 Statistical Analysis

Data obtained from the 15 experimental runs were analyzed using Response Surface Methodology (RSM) with Minitab software (version 20.0). A second-order polynomial model was fitted to the response variables to evaluate linear, quadratic, and interaction effects of the independent variables:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3$$

where Y is the predicted response, β_0 is the model intercept, β_1, β_2, β_3 are linear coefficients, β_{11}, β_{22}, β_{33} are quadratic coefficients, and β_{12}, β_{13}, β_{23} are interaction coefficients. Analysis of variance (ANOVA) was performed to determine the significance of the model and individual terms at $p < 0.05$, and model adequacy was evaluated using the coefficient of determination (R^2), adjusted R^2, lack-of-fit test, and adequate precision. Pareto plots were generated to visualize the significant effects of the independent variables on each response, and multi-response optimization was performed using the desirability function approach to identify the optimum processing conditions.

3. RESULTS AND DISCUSSION

3.1 Quality attributes of tamarind juice as affected by processing conditions

The quality attributes of tamarind juice produced under the combined effect of pasteurization temperature, pasteurization time, and sugarcane juice concentration are presented in Table 3. Ascorbic acid content ranged from 25.78 to 88.28 mg/100 ml, with the highest retention observed at the lowest pasteurization temperature (75 °C) combined with the highest sugarcane juice concentration (70% v/v), while total soluble solids increased consistently with increasing sugarcane juice concentration (13.50-19.00 °Brix), consistent with the direct contribution of sugarcane solutes to the juice. This corroborates with the findings of Nour *et al.* (2026), who

worked on the physicochemical changes in sugar during processing stages and storage stability of molasses. Titratable acidity ranged from 0.24 to 0.49%, increasing markedly with pasteurization temperature. The increase in titratable acidity with pasteurization temperature is consistent with heat-induced breakdown of pectic substances and sugars into organic acids, degradation of ascorbic acid to acidic by-products, and partial water loss that concentrates the acids. The highest total phenolic content (53.07 mg GAE/100 ml) occurred at 95 °C, 15 min, and 30% v/v sugarcane juice. The highest temperature but lowest sugarcane concentration tested indicates that high sugarcane concentration was not required to achieve the highest total phenolic content under these conditions. The highest total flavonoid content (44.46 mg QE/100 ml), by contrast, occurred at 95 °C, 15 min, and 70% v/v sugarcane juice, the highest temperature and highest sugarcane concentration combined, indicating that flavonoid content benefited from both high heat and a greater sugarcane contribution to the juice matrix simultaneously.

Table 3. Effects of pasteurization temperature and time, and sugarcane juice concentration on quality attributes of tamarind juice

Sugarcane Pasteurization Temp. (°C)	Pasteurization Time (min)	Juice Conc. (%)	Total Phenolic Content (mg GAE/100 ml)	Total Flavonoid Content (mg QE/100 ml)	Ascorbic Acid Titratable Acidity (◦Brix)	Soluble Solids (%)
75	10	50	29.22±0.09^{j}	42.77±0.04^{g}	17.06±0.03^{h}	0.30±0.00^{f}	15.50±0.50^{cd}
95	10	50	49.51±0.09^{d}	52.77±0.04^{ab}	10.85±0.03^{j}	0.45±0.02^{b}	15.50±0.50^{cd}
75	20	50	25.78±0.09^{l}	42.84±0.04^{g}	9.78±0.03^{k}	0.26±0.00^{g}	15.00±1.00^{de}
95	20	50	43.90±0.09^{e}	46.70±0.04^{e}	23.83±0.03^{e}	0.45±0.01^{b}	16.50±0.50^{cd}
75	15	30	34.29±0.09^{h}	38.45±0.04^{h}	6.17±0.03^{m}	0.32±0.02^{ef}	14.00±0.00^{ef}
95	15	30	36.65±0.09^{g}	53.07±0.04^{a}	17.75±0.03^{g}	0.43±0.01^{b}	14.00±0.00^{ef}
75	15	70	88.28±0.09^{a}	44.58±0.04^{f}	25.16±0.03^{d}	0.24±0.01^{g}	18.50±0.50^{a}
95	15	70	54.40±0.09^{c}	50.11±0.04^{cd}	44.46±0.03^{a}	0.49±0.01^{a}	18.75±0.25^{a}
85	10	30	27.95±0.09^{k}	46.02±0.04^{ef}	21.23±0.03^{f}	0.33±0.00^{de}	13.50±0.50^{f}
85	20	30	33.21±0.09^{i}	48.83±0.04^{d}	28.20±0.03^{b}	0.36±0.01^{c}	13.50±0.50^{f}
85	10	70	49.51±0.09^{d}	51.17±0.04^{bc}	9.15±0.03^{l}	0.32±0.00^{ef}	18.00±0.00^{ab}
85	20	70	57.30±0.09^{b}	50.49±0.04^{cd}	16.36±0.03^{i}	0.32±0.00^{e}	19.00±0.00^{a}
85	15	50	43.17±0.09^{f}	49.10±2.10^{d}	27.26±0.04^{c}	0.35±0.00^{cde}	15.50±0.50^{cd}
85	15	50	43.17±0.09^{f}	49.12±0.04^{d}	27.18±0.03^{c}	0.36±0.00^{cd}	15.50±0.50^{cd}
85	15	50	43.17±0.09^{f}	49.16±0.01^{d}	27.19±0.04^{c}	0.36±0.01^{c}	15.00±1.00^{de}

Values are presented as mean ± standard deviation). Means within the same column with different superscript letters are significantly different at $p < 0.05$. Where PST is the pasteurization

3.2 Adequacy of the fitted second-order polynomial models

The results of the response surface regression are presented in Table 4. The model for titratable acidity showed the strongest fit of all five responses (R^2 = 97.72%, R^2(pred) = 94.46%), followed by total phenolic content (R^2 = 90.71%) and total soluble solids (R^2 = 93.40%), both of which explained a high proportion of variability with reasonable agreement between R^2 and predicted R^2. The lack-of-fit test was significant ($p < 0.05$) for ascorbic acid, total phenolic content, and total flavonoid content, but the pure error was very small owing to highly reproducible center-point replicates (Table 3). As the F-test is highly sensitive to pure error, even a modest lackof-fit can appear significant despite the high variance explained by the models, as similarly reported by Onwuakor and Nwokafor (2026). This is noted as a statistical caveat rather than evidence that the fitted equations are unusable. The total flavonoid content model remained the weakest of the five, with a marginally non-significant overall model ($p = 0.060$) and a low R^2 (50.61%).

Table 4. Statistics for the fitted second-order polynomial models

Response	S	R^2 (%)	R^2(adj) (%)	R^2(pred) (%)	Model pvalue	Lack-of-fit pvalue
Ascorbic acid (mg/100 ml)	8.703	77.60	67.52	42.65	0.000	0.000*
Total phenolic content (mg GAE/100 ml)	1.484	90.71	86.54	79.63	0.000	0.000*
Total flavonoid content (mg QE/100 ml)	8.254	50.61	28.39	0.00	0.060	0.000*
Titratable acidity (%)	0.0124	97.72	96.70	94.46	0.000	0.045
Total soluble solids (°Brix)	0.594	93.40	90.43	84.50	0.000	0.674

3.3 Effect of process variables on ascorbic acid content

The fitted second-order polynomial model for ascorbic acid content in terms of uncoded (actual) factors was:

$$Ascorbic\ acid\ (mg/100\ ml) = -42 - 2.03(X1) + 11.20(X2) + 2.60(X3) + 0.0267(X1)^2 - 0.350(X2)^2 + 0.01891(X3)^2 - 0.0109(X1X2) - 0.0453(X1X3) + 0.0063(X2X3)$$

Analysis of variance indicated that sugarcane juice concentration was the only significant linear term ($p = 0.000$), while the quadratic effect of pasteurization time ($p = 0.013$), the quadratic effect of sugarcane juice concentration ($p = 0.028$), and the interaction between temperature and sugarcane juice concentration ($p = 0.008$) were also significant. Neither the linear effects of temperature or time nor the quadratic effect of temperature were individually significant ($p > 0.05$). The Pareto chart of standardized effects (Figure 1A) confirmed sugarcane juice concentration as the dominant standardized effect on ascorbic acid retention, followed by the temperature × sugarcane interaction, the quadratic time effect, and the quadratic sugarcane effect. This is consistent with the highest ascorbic acid retention (88.28 mg/100 ml) occurring at the highest sugarcane juice concentration (70%) combined with the lowest pasteurization temperature (75 °C), suggesting that sugarcane juice contributes directly to the measured ascorbic acid pool while also plausibly exerting some protective effect against thermally induced oxidation at lower processing temperatures (Sreedevi et al., 2020; Amaro and Tadini, 2021).

3.4 Effect of process variables on total phenolic content

$$Total\ phenolic\ content\ (mg\ GAE/100\ ml) = -250.9 + 5.507(X1) + 2.72(X2) + 1.041(X3) - 0.02384(X1)^2 + 0.0076(X2)^2 + 0.00119(X3)^2 - 0.0307(X1X2) - 0.01137(X1X3) - 0.00873(X2X3)$$

Pasteurization temperature exerted the strongest linear effect on total phenolic content ($p = 0.000$) and a highly significant quadratic effect ($p = 0.000$), while sugarcane juice concentration was also a significant linear term ($p = 0.003$). Two-factor interactions involving temperature (temperature × time, $p = 0.008$; temperature × sugarcane, $p = 0.000$) were significant (Figure 1B). Moderate thermal treatment appeared to enhance measurable phenolic content, likely reflecting heat-induced release of matrix-bound phenolics, a phenomenon reported in thermally processed fruit juices such as Nguyen et al. (2026), while the significant negative quadratic term indicates that phenolic content would be expected to decline beyond an optimal temperature range due to thermal degradation. This model showed strong adequacy ($R^2 = 90.71\%$, R^2(pred) = 79.63%).

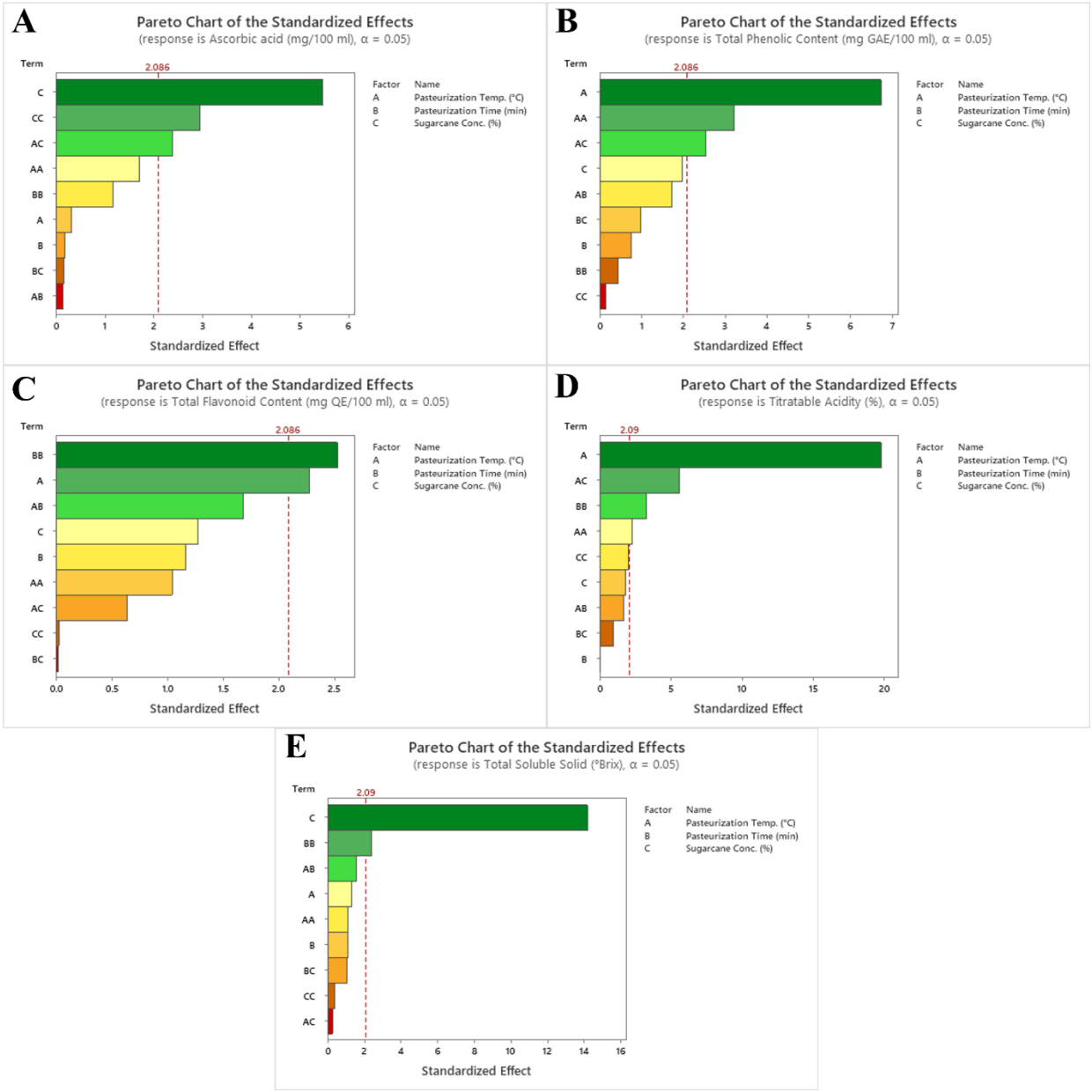

Figure 1. Pareto chart of standardized effects of pasteurization conditions and sugarcane juice concentration on ascorbic acid content (A), total soluble solids (B), total phenolic content (C), total flavonoid content (D) and titratable acidity (E)

3.5 Effect of process variables on total flavonoid content

$$Total\ flavonoid\ content\ (mg\ QE/100\ ml) = -193 + 4.58(X1) + 1.75(X2) - 0.63(X3) - 0.0359(X1)^2 - 0.330(X2)^2 - 0.00059(X3)^2 + 0.1013(X1X2) + 0.0097(X1X3) + 0.0006(X2X3)$$

Only the linear effect of pasteurization temperature ($p = 0.029$) and the quadratic effect of pasteurization time ($p = 0.013$) were individually significant (Figure 1C); the overall model was not significant at $\alpha = 0.05$ ($p = 0.060$), and the low predicted R^2 (0.00%) confirms that flavonoid response under these processing conditions was not reliably described by the fitted quadratic surface. This may reflect greater inherent analytical variability in flavonoid quantification or the influence of factors and interactions beyond those captured within the studied experimental range and is presented here as an identified limitation rather than a validated predictive relationship.

3.6 Effect of process variables on titratable acidity

$$Titratable\ acidity\ (\%) = 1.908 - 0.03869(X1) + 0.00675(X2) - 0.01238(X3) + 0.000213(X1)^2 - 0.000600(X2)^2 - 0.000012(X3)^2 + 0.000175(X1X2) + 0.000169(X1X3) - 0.000075(X2X3)$$

This was the best-fitting model overall (R^2 = 97.72%, adjusted R^2 = 96.70%, predicted R^2 = 94.46%). Pasteurization temperature was by far the dominant factor (F = 748.83, p = 0.000), corroborated by the Pareto chart (Figure 1D), followed by its quadratic term (p = 0.000), its interaction with sugarcane juice concentration (p = 0.000), the quadratic effect of time (p = 0.004), and the linear effect of sugarcane extract concentration (p = 0.017). Titratable acidity increased consistently and substantially with increasing pasteurization temperature, from as low as 0.24% at 75 °C to as high as 0.49% at 95 °C, likely reflecting concentration effects from moisture loss and/or thermally induced release of bound organic acids.

3.7 Effect of process variables on total soluble solids

$$Total\ soluble\ solids\ (°Brix) = -11.4 + 0.514(X1) + 0.088(X2) + 0.054(X3) - 0.00365(X1)^2 - 0.02708(X2)^2 + 0.000026(X3)^2 + 0.0075(X1X2) + 0.00031(X1X3) + 0.0025(X2X3)$$

Sugarcane juice concentration was overwhelmingly the dominant factor influencing total soluble solids (F = 262.73, p = 0.000), consistent with its direct contribution of soluble sugars and solutes to the juice matrix (Figure 1E). The quadratic effect of pasteurization time was also significant (p = 0.006), while the linear effects of temperature and time and all two-factor interactions were non-significant. This model showed strong adequacy (R^2 = 93.40%, R^2(pred) = 84.50%, non-significant lack-of-fit, p = 0.674) and can be considered reliable for predictive purposes for total soluble solids within the studied range.

3.8 Multi-response optimization of processing conditions

The response optimization plot for the desirability functions of the process condition and quality attributes of Tamarind juice is as shown in Figure 2. The optimum processing condition identified was a pasteurization temperature of 82.07 °C, a pasteurization time of 15.45 min, and a sugarcane juice concentration of 70% v/v, yielding a composite desirability of 0.727. Under these conditions, the model predicted total soluble solids of 18.99 °Brix (individual desirability = 0.999), titratable acidity of 0.308% (d = 0.729), total flavonoid content of 27.43 mg QE/100 ml (d = 0.555), total phenolic content of 49.32 mg GAE/100 ml (d = 0.742), and ascorbic acid content of 68.08 mg/100 ml (d = 0.676). The comparatively lower individual desirability for total flavonoid content reflects the weaker predictive strength of its underlying model. Therefore, this composite desirability value (0.727, on a 0-1 scale) indicates a satisfactory overall compromise among the five response criteria. Schiassi *et al. (2020) and* Wanyonyi *et al.* (2025) reported similar values for fruit juice.

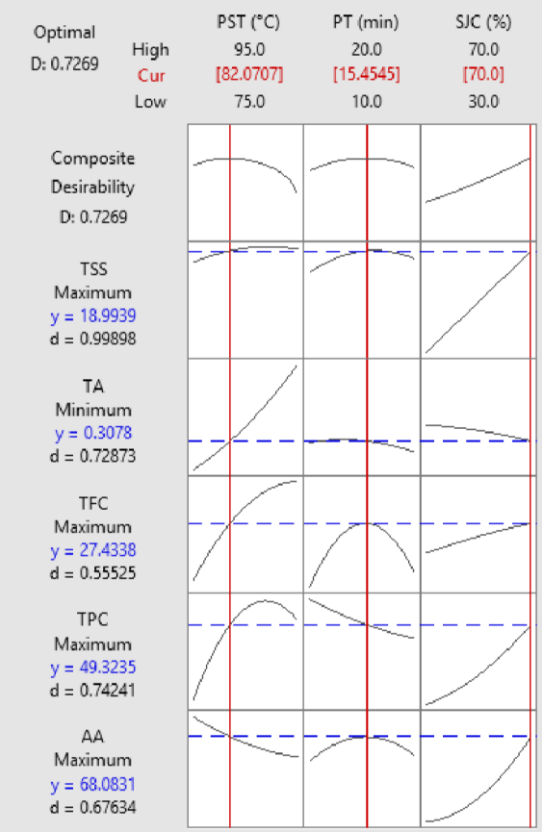

Figure 2. Response optimization plot showing the composite desirability and individual desirability functions of the effect of pasteurization temperature (PST), pasteurization time (PT), and sugarcane juice concentration (SJC) on the Total Soluble Solid (TSS), Titratable Acidity (TA), Total Flavonoid Content (TFC), Total Phenolic Content (TPC) and Ascorbic Acid (AA) of the Tamarind juice

CONCLUSIONS

This study modelled and optimized the effects of pasteurization temperature, pasteurization time, and sugarcane juice concentration on quality attributes of tamarind juice. Sugarcane juice concentration was the dominant factor governing ascorbic acid content and total soluble solids, both increasing with higher juice concentration. Pasteurization temperature was the primary driver of titratable acidity, which increased consistently with higher temperature, and also significantly influenced total phenolic content, which improved under moderate heating before declining at higher temperatures. Total flavonoid content was influenced mainly by the linear effect of temperature and the quadratic effect of time, though its model showed weaker predictive strength, reflecting the compound's sensitivity to processing conditions. A significant temperature-sugarcane interaction was obtained for ascorbic acid, phenolic content, and titratable acidity. Model adequacy varied across responses: total phenolic content, titratable acidity, and total soluble solids were well described by their fitted models (R^2 > 90%), while the ascorbic acid and, particularly, the total flavonoid content models showed comparatively weaker fit, reflecting the thermal lability and analytical variability of these compounds. Multi-response optimization identified 82.07 °C, 15.45 min, and 70% v/v sugarcane juice concentration as the optimal processing condition (composite desirability = 0.727), predicting 68.08 mg/100 ml ascorbic acid, 49.32 mg GAE/100 ml total phenolic content, 27.43 mg QE/100 ml total flavonoid content, 0.308% titratable acidity, and 18.99 °Brix total soluble solids. This study confirms that tamarind juice can be pasteurized under moderate thermal conditions without substantial loss of nutritional and functional quality when sugarcane juice concentration is co-optimized with temperature.

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Paper ID 45:
Impact of Agricultural Engineering on Nigeria's Economy: A Review

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ABSTRACT
Agricultural Engineering has transformed agricultural practices from subsistence-level to commercial largescale production through mechanization in developed nations. In Nigeria, it plays a key role in economic development by increasing agricultural productivity, creating employment, and stabilizing food security. This review addresses three questions: what is the impact of agricultural engineering on Nigeria's economic growth? What is the acceptability of agricultural engineering innovations among smallholder farmers? What is the impact of Nigeria's large irrigation dams on small-scale farmers? This review uses data from the National Agricultural Extension and Research Liaison Services (NAERLS) database to estimate agricultural post-harvest losses from 2021 to 2025, focusing on grain and cereals (rice, sorghum and maize), root and tuber (cassava and yam) and vegetable (tomato). These crop groups are justified by their foundational role in national food security and extreme vulnerability to post-harvest handling. It further narrows its focus to the three branches most directly linked to Gross Domestic Product (GDP) data: farm power and mechanization, irrigation and water engineering, and post-harvest and processing engineering. The review finds that farm mechanization contributes a mean of 29.93% to Nigeria's agricultural GDP, while no comparable GDP figure exists for irrigation/water engineering or post-harvest/processing engineering, despite decades of documented activity in both areas. Across all three branches, smallholder adoption remains low, driven by financial constraints, weak policy implementation, and limited farmer confidence in new technology. It concludes by recommending standardized GDP data record-keeping for agricultural engineering, coordinated through professional bodies such as the Nigeria Institution of Agricultural Engineers (NIAE).

KEYWORDS: Agricultural engineering; Agricultural GDP; Farm mechanization; Post-harvest losses; Smallholder Farmers

INTRODUCTION

Agricultural engineering has important roles to play in boosting the Nigerian economy and securing food sustainability. Makanjuola (1977) defines agricultural engineering as "that field of engineering in which the physical and biological sciences are utilized to find and apply better ways of exploiting natural resources for the production, handling, processing and storing of food and fodder." This implies that agricultural engineering is the systematic approach an agricultural engineer applies to solve agricultural challenges and harness natural resources for greater economic efficiency. An agricultural engineer optimizes, processes, and applies technological innovation related to crop cultivation, food processing, and livestock management, contributing to global food security and sustainability (Lal, 2009). As FAO (2022) notes, agricultural engineering contributes significantly to revamping agriculture by providing innovative solutions that enhance productivity and efficiency, spanning mechanization, renewable energy application, irrigation and water resources management, post-harvest handling and storage, and emerging technologies such as precision agriculture and smart farming.

Agricultural engineering is inherently interdisciplinary. Sultan (2024) identifies its main branches as farm power and machinery (drone spraying, robotic agriculture, harvesting machinery), irrigation and drainage (drip, sprinkler, and centre-pivot irrigation), agriculture and environment (air pollution, water treatment, wastewater management), and agriculture and energy systems (post-harvest storage, soil-less agriculture, next-generation Green-houses, poultry housing). More recently, Pathare (2026) shows that the incorporation of machine learning (ML) and artificial intelligence (AI) into agricultural engineering has significantly improved agricultural sustainability. These branches play a critical role in Nigeria's economic development by increasing productivity,

reducing post-harvest losses, and creating employment across the value chain (Adelekan, 2007). Nwosu, *et al* (2026) similarly framed agricultural engineering as a means of maximizing resource utilization and improving value-chain performance through reduced post-harvest losses. Mechanized farming has significantly boosted productivity and fueled GDP growth. As reported by Adelekan (2007), these technological advancements helped push Nigeria's agricultural growth rate to 12.2% over the prior decade.

Agriculture is the largest contributor to Nigeria's GDP, with crops accounting for 80%, livestock 13%, forestry 3%, and fishery 4% of agricultural GDP (Izuchukwu, 2015). ADB (2025) reports West Africa's real GDP growth at 4.5% in 2024, projected to soften slightly to 4.3% in 2025–2026, with Nigeria among a small group of countries expected to grow below the regional 5% benchmark, suggesting that agriculture's strong contribution has not yet translated into Nigeria matching regional growth performance.

Given this breadth, and to keep the review analytically tractable, this study narrows its focus to the three branches for which GDP-linked evidence exists in the literature: farm power mechanization, irrigation and water engineering, and post-harvest and processing engineering. Renewable energy applications and precision/smartfarming technologies are acknowledged as part of the discipline's scope but are not treated as separate review sections here, since the literature search returned no Nigeria-specific GDP data for them.

SPECIALIZED FIELDS OF AGRICULTURAL ENGINEERING

Farm Power and Mechanization Adoption and GDP Growth

Farm mechanization refers to the overall application of farm tools, implements, and powered machinery (Clarke, 2000). Efficient use of these tools has a significant impact on farm productivity, labor savings, environmental sustainability, and economic growth. Castelein *et al*. (2022) found that adopting farm machinery such as threshers and harvesters in rice cultivation reduced harvest losses, increased paddy yield per hectare by 14% (approximately 479 kg of paddy), saved more than 200 labor-hours in Nigeria. Farm mechanization mean contribution to Nigeria's GDP is 29.93% (Festus *et al*., 2020). Despite this demonstrated benefit, adoption remains low: Onomu and Aliber (2021) sampling 280 respondents across Delta and Benue states, found that 72% of farmers do not use tractors, and Olaoye (2010) recorded mechanization levels of only 31.3% and 28.6% in Ogun and Osun states respectively.

Productivity and Operational Impact of the Adoption of Agricultural Mechanization

Land preparation efficiency: More land can be cultivated and harrowed efficiently within short time with less fatigue with the use of Mechanized agricultural tools and machinery, thus enabling farmers to perform other tasks (Maheshwari *et al*., 2026; Tahir, A. D., Jibril, S. A. and Idi, 2025).

Post-Harvest Loss Reduction: Mechanical shellers, as reported by Kirui *et al*. (2025) reduced the amount of broken grains and process faster. Mechanical threshing yielded a 6.5% increase in efficiency and post-harvest losses of 0.93% in comparison of 9.55% using manual method (Castelein *et al*., 2022).

Crop diversification: Mechanization increases Economics of Scope (EOS) that is the economic possibility of multi-cropping system, Takeshima *et al* (2020) researched on the economics of scope of rice and non-rice crops, and their study reveals the economic viability of crop production in heterogeneous environments such as rice and non-rice combination.

Monetary Impacts on Farm Operation

Atilade and Adetarami (2025) conducted a comparative analysis on the profitability on rice production using manual and mechanized farming methods. **Table 1;** shows the differences in monetary impact of both mechanized and manual farm operations.

Table 1: Monetary Impact on Farm Operation

Financial/operational metrics	Manual farming baseline	Mechanized farming output
Labor cost/hectare	High, variable seasonal wages	30 - 45% lower total seasonal outlay

Average output (kg/ha)	1185.03	6133.41
Capital requirement	Low entry barrier	Capital intensive

Source: Atilade and Adetarami (2025)

Sustainable Policies and Access to Model (TOHFAN/TOHAN)

The Tractor Owners and Hiring Facilities Association of Nigeria (TOHFAN) was established in 2003 with 9 Tractors and 36 members and it grew to 262 tractors and 757 members across 21 states by December, 2016 to increase access to tractors and mechanized services for smallholder farmers, who make up about 70% of Nigeria's farming population (Issa, 2017).

Issa (2017) assessed how TOHFAN manages the problems of Tractor frequent breakdown, high inefficiency and funding failures common in public tractor schemes using qualitative assessment method in four (4) states namely; Kaduna, Nassarawa, Niger States and the FCT, and the findings shows that TOHFAN serves as guarantors to connect farmers to commercial banks for a 36-months tractor procurement loans, and the association operates under four (4) services models;

Model 1 (Hiring agent); the TOHFAN agent hires a tractor from the owner for a daily rate of ≥₦20,000, pays the operators, mechanics, fuel the tractors, and provide direct services to the farmers.

Model 2 (Booking agent); A farmer is linked directly to the tractor owner by a commission agent, for a fee of 10%.

Model 3 (Direct-owner farmer); in this case the tractor owner takes care of fueling, operator fees and service delivery.

Model 4 (TOHFAN as booking agent); Large commercial farms or cooperate bodies are attended to by the TOHFAN agent directly deploying members' tractors. Furthermore, the study finds high and unstable interest rate linked to foreign exchange volatility and bank inflexibility as the key challenge faced by small-scale farmers.

Umar *et al*. (2021) argues that while mechanization comes with financial and labor displacement risks, tractor adoption significantly increases crop yield, raise farmers' incomes and expand cultivated lands. However, high acquisition cost makes direct ownership a mirage by smallholders and government-run tractor schemes have greatly collapsed, unskilled technical personnel and scares spare parts. Over 70,000 tractors are needed to meet service demand where Nigeria averages only 6.8 tractors per 100 km^2 of arable land in comparison to Kenya's 26.9 and a global average of 195.3.

The performance evaluation, management and operational challenges of the Federal Capital Territory (FCT) tractor hiring Scheme in Nigeria was studied using data from smallholder farmers and farm managers, revealed that 95% of farmers are unable to access tractors when requested and about 47% of the available tractors are over 10 years old. Further, critical technical decisions are carried out by undertrained operators whom rely on roadside mechanics.

Additionally, 79% of the scheme managers lack agricultural engineering background and as such recommends a functional engineering division to oversee technical management, regular maintenance and operator trainings (Alabadan andYusuf, 2013).

Irrigation and Water Engineering

Sojka and Bjorneberg (2002) define irrigation as the practice of applying water beyond what rainfall provides, to enable or enhance plant growth, yield, and harvestable output. In Nigeria, irrigation is organized into three categories: government-executed public schemes, farmer-owned schemes, and floodplain-based Fadama schemes (Adelodun and Choi, 2018). Rice is the predominant crop under fadama irrigation, Adelodun and Choi (2018) reached a similar conclusion from a different angle, arguing that despite heavy investment, irrigation in Nigeria,

the country has fallen short of its goals due to inconsistent government policy, limited farmer technical knowhow, and delayed financial support, rather than a shortage of physical infrastructure. This is consistent with Adeniran *et al*. (2021), who report that despite Nigeria's large agricultural land area (70,800 hectares) and more than 160 dams, only 41% of that land is irrigated, indicating that infrastructure exists but is underutilized. **Table 2** shows the summary of planned irrigable area of some Existing large dams in Nigeria and the percentage of unutilized area (Adewumi, 2006). This 2006 estimate is the most recent irrigable-area data identified in the literature; given two decades of subsequent dam investment since then, the figures in Table 2 are presented as indicative rather than current.

Table 2: Summary of planned irrigable area for some existing large dams in Nigeria

Name of Dam	Planned development (Ha)	Actual development (Ha)
Zobe (Katsina state)	8,200	5,000
Goronyo (Sokoto state)	69,000	17,000
Challawa (Kano state)	40,000	12,500
Tiga (Kano state)	22,000	26,000
Jibiya (Katsina state)	7,000	3,500
Ikere Gorge (Oyo state)	15,000	650
Oyan (Ogun state)	12,000	250
Omi (Kogi state)	4,100	1,500
Bakolori (Zamfara state)	23,000	22,000

Source: Adewumi, 2006

Irrigation to supplement rain-fed agriculture represents the main focus of these dams; other notable economic benefits cardinal to the economic development of the country are also being harnessed. These include hydropower generation, fishing, flood control, and sport and recreation (Adeniran *et al*., 2021). Results from **Table 2,** depicts that Bakolori dam in Sokoto state is the only dam having its irrigable area almost 100% utilized which is about 22,000Ha out of 23,000Ha, while Oyan dam in Ogun state is having the least utilized irrigable area of 250Ha out of 12,000Ha. Conversely, Raphael, Adekanye, and Alhassan (2016) affirmed that the Oyan dam was designed and constructed primarily to generate hydropower electricity, and also to the irrigation of 3,000Ha under the lower Ogun irrigation project added later as a secondary, still-ongoing objective.

Economic Impacts of the Large Dams

Table 3, shows commonly produced crops around the large dams in Nigeria and the gross margin of some of the crops obtained from researchers. This information was sourced from different literatures, however, some information were not accessible.

Table 3: Gross Margin of Crops on Irrigation Scheme around Dams

Dam, Location and Capacity (million m^3)	Commonly produced crop	Gross margin/hectare (₦)
Zobe – Katsina state, 177 [a]	Maize, Cotton, Guinea corn, Vegetables (Onion, Pepper, Tomato)a	N/A

Goronyo – Sokoto state	Rice, Maize, Cowpea and Tomato [c]	R-₦68,049.87, M-₦51,623.75, C-₦9,504.62 and T-₦81,803.70 [c]
Challawa – Kano state, 996 [h]	Rice, Tomato, Pepper, Wheat, Maize, Onion	N/A
Tiga – Kano state, 2 billion m³ [e]	Rice, Tomato, Onion, Wheat, Maize	₦238,018 [j]
Jibiya – Katsina state, 142 [f]	Wheat, Cowpea, Groundnut, Onion, Maize and Tomato [f]	₦95,817.75–190,329.36 [f]
Ikere Gorge – Oyo state, 565[d]	N/A	N/A
Oyan – Ogun state, 270 [d]	Maize, Cowpea, and Vegetables [i]	N/A
Omi (Kampe) – Kogi state, 250 b	N/A	N/A
Bakolori – Zamfara state, 450g[k]	Rice, Millet, Sorghum, Groundnut, Maize, Cassava, Sweet potato, Pepper and Tomato [k]	N/A

R – Rice, **M** – Maize, **C** – Cowpea, **T** – Tomato [a](Jamda Saidu *et al*., 2019), [c](Mohammed, *et al* 2017), [d](Abegunrin *et al*., 2021), [e](Ismail, 2025) [f](Musa, *et al* 2014), [d](Adeboye *et al*., 2026), [g](Olokesusi andAredta 1995), [h](Shanono, N.J., *et al*. 2024), [i](Adekalu andOgunjimi 2003) [k](Egwuma *et al*., 2024), [j](Wudil *et al*., 2023) [b](Oriola, 2012)

Table 3 reflect the economic impact of the dams to the farmers utilizing them. Musa, *et al* (2014) studied the economic analysis of crop production of under Jibiya Irrigation Project using descriptive statistics and farm budgeting model, on crops mostly produced such as wheat, cowpea, groundnut, onion, maize and tomato found the crops to be profitable with the gross margin ranges from ₦95,817.75/ha to ₦190,329.36/ha, with cowpea been the most profitable. However, the study outlined key factors that if implemented will enhance the efficiency and economic viability of their farming activities such as timely provision of farm input at subsidized rate by the Federal Government like fertilizer, credit facilities, and equity in water distribution by the project management.

Similarly, Mohammed, *et al* (2017) assessed the profitability of arable crops enterprises under Goronyo dam irrigation project using the multi-stage sampling technique in their research and obtained the inserted gross margin values in the **Table 3**, with gross margin value for tomato being the highest (₦81,803/ha) and Cowpea being the lowest (₦9,504.62/ha). The low cowpea gross margin can be attributed to increase in cost of production by the

farmers, hence, the study recommends reduction in the cost of production through the use of cost saving mechanisms for increased profitability.

More recently, Wudil *et al*. (2023) recommends the use of different modern technological irrigation innovations such as deficit irrigation to manage irrigation water use, in their study. The study compared irrigation rice cultivation using canal water and tube-well water, using stochastic frontier analysis approach and found the canal water and tube-well water saving potential were 24% and 30% respectively. The production cost/acre and net

income/acre of canal and tube-well water were $486.44, $415.56 and $547.81, $364.83 respectively. Hence, it can be deduced that the gross margin/hectare in this present time (2026) with 1$ equivalent to ₦1,359 as ($486.44 – $415.56)/0.4047hectare x ₦1,359 = ₦238,018/hect. The study found that farmers using tube-well water were slightly more productive physically per unit of water than the farmers using the canal water for irrigation. However, the canal irrigation is considerably cheaper, thus given the canal irrigation farmers more economic advantage and returns.

Irrigation farming along the constructed dams shows positive impact to the local farmers as shown in the **Table 3** , although, more needs to be done to revamp the full potential of these dams and other dams not reviewed to increase food security and GDP of the nation. Multiple studies have identified key problems and recommended that provision of soft loan by the federal governments to farmers, subsidizing farm inputs such as fertilizer and chemicals, provision of adequate security within the farming community and adaptation of climate change (Musa *et al* (2014); Sani (2024), could aid in harnessing Nigerian dams for optimum benefits for local farmers and the nation at large.

Post-Harvest and Processing Engineering

Hodges *et al*. (2011) define post-harvest food loss (PHL) as a measurable qualitative and quantitative loss occurring anywhere along the supply chain, from harvest to consumption. For optimum longevity of the agricultural produce the post-harvest handling such as cleaning, sorting, grading, pre-cooling, packaging, storing and transportation are key principles to be adhered (Pokhrel, 2020). Multiple studies have been conducted on postharvest losses- This section grouped the dominant agricultural crops reviewed. These are; fruit and vegetables, roots and tuber and grains and legumes as presented in **Tables 4, 5** and **6**. The 5-years postharvest losses data was accessed from the National Agricultural Extension and Research Liaison Services (NAERLS) database. However, some data are not available, for this reason we used the prominent crops. The tables also show the losses for each year, and the monetary equivalent in accordance to Ministry of Agriculture and Food Security (MAFS).

Table 4: Roots and Tubers (Cassava, Yam)

Year	Total harvest (MMT)	Postharvest loss volume (MMT)	Avg. market price/ton (₦)	Total monetary loss value (₦)
2021	117.16	29.16	171,860	4.3 Trillion
2022	120.80	56.46	601,065	31.6 Trillion
2023	116.47	49.66	405,000	18.2 Trillion
2024	118.94	14.07	852,500	11.97 Trillion
2025	121.17	51.82	405,000	18.97 Trillion

Sources: Sani (2025), NAERLS (2024a), NAERLS and FMARD (2021). MMT = Million metric tonnes

Table 5: Cereals (Rice, Maize, and Sorghum)

Year	Total harvest (MMT)	Postharvest loss volume (MMT)	Avg.market price/ton (₦)	Total monetary loss value (₦)
2021	27.72	4.02	348,813	1.24 Trillion
2022	26.46	5.74	558,490	1.96 Trillion
2023	26.36	7.34	414,333	3.17 Trillion
2024	26.76	12.71	1,150,000	13.86 Trillion
2025	27.31	7.46	643,000	4.97 Trillion

Sources: Sani (2025), NAERLS (2024a), NAERLS and FMARD (2021). MMT = Million metric tonnes

Table 6: Fruit (Tomato)

Year	Total harvest (MMT)	Postharvest loss volume (MMT)	Avg. market price/ton (₦)	Total monetary loss value (₦)
2021	3.48	1.67	414,830	0.69 Trillion
2022	3.13	2.72	265,410	0.72 Trillion
2023	3.68	3.20	814,160	2.61 Trillion
2024	3.74	1.12	1,123,000	0.46 Trillion
2025	4.60	4.00	814,160	3.26 Trillion

Sources: Sani (2025), NAERLS (2024a), NAERLS and FMARD (2021). MMT = Million metric tonnes

Comparing the **Tables 4, 5** and **6**, Fruit (tomato) face the most severe percentage loss relative to production. In 2023 and 2025, over 86% of tomato harvested were lost (4.00 MMT out of 4.60 MMT harvested in 2025). Roots and tuber experience massive absolute losses, peaking at 56.46 MMT in the year 2022 nearly 47% of total production. the monetary loss value is heavily amplified by the market prices rather than loss volume alone, for

cereals, despite the postharvest loss volume dropping from 12.71 MMT in 2024 to 7.46 MMT in 2025, the total monetary loss remained high; 4.97 trillion due to sustained price elevation (₦643,000/ton). Across all three categories, 2024, saw unprecedented spikes in average market price per ton, peaking at ₦852,500 for roots and tuber, ₦1,150,000 for cereals and ₦1,123,000 for fruit (tomato). Roots and tuber heat a massive loss, peak in 2022 at ₦31.6 Trillion while cereals their monetary loss peak in 2024 at ₦13.86 Trillion.

Each of these staple crops has its own peculiar stage of common causes of loss and occurrence; however, they are similar in most respects. For example, cereal losses are commonly caused by pests/diseases, drought, mechanical damage, theft and poor drying, with the common loss points being during harvesting, milling, in the field, in the warehouse and at home, and the stages include storage, processing, drying and harvesting (NAERLS, 2024b).). Similarly, roots and tubers are mostly lost due to pests and disease or lack of processing facilities, as is tomato (NAERLS, 2024b).

Critically looking into the computed combined monetary losses across the three crops categories regularly reaches tens of Trillions of Naira directly fueling food insecurity and domestic inflation. Hence, addressing these challenges will boost the economy by increasing its GDP, improve food security and sustainable development. Tahir *et al* (2025), noted that for a country, especially a developing country, to reduce its post-harvest loss in fruit (tomato), it must introduce modern post-harvesting technologies and practices to local farmers, covering the chain from harvesting through pre-cooling, cleaning or disinfecting, sorting and grading, packaging, storage and transportation of the tomato

Farm Structures

'Farm structures can be defined as one of the branches of agricultural engineering that deals with planning, design and construction of farm buildings and other structures in the farm and outside the farm environment' (Ojedele *et al*., 2018). The branches of this structures are mainly; farm houses, livestock structures, crop production buildings, agricultural processing buildings, storage structures, equipment, tools and supplies building, and miscellaneous structures (Ojedele *et al*., 2018). Each of these farm structures plays a vital role in boosting the economy of a nation when given due consideration.

Green-house structures

Green-houses also known as Controlled Environment Agriculture (CEA) is a metal frame agricultural building used for cultivation and/or protection of plants. It is covered with translucent plastic film prevents the passage of rain into the structure. The purpose is to create the most suitable ambient conditions for the growth and development of crops established inside with some independence of the external environment, and whose dimensions allow the work of the people inside. Greenhouses can have a total plastic enclosure and side vents (Ponce *et al*. (2014)

Green-houses are used for all kinds of vegetable cultivation, such as tomato, cucumber, chilli pepper, green pepper and lettuce; because the crop is grown in a controlled environment, there is strong control over the environmental conditions relevant to growth and development, such as temperature, humidity, solar radiation, and wind (Paucek *et al*., 2023). Green-houses structures also serve as protection from harmful pest and diseases. Considering the characteristics features of the green-house structure in boosting the economy of a nation, several researches have highlighted the impacts of its adoption, especially when it's fully automated as Smart Green-house. In the world today, China, Japan and Korea top the list of the adoption by 80% (Ojedele *et al*., 2018), while in the developing countries like Nigeria it is slowly gaining acceptance, its mostly found in the Universities, research institutes, the rich and influential political elite farms.

Nafiu *et al* (2025) studied the profitability analysis of green-house tomato production, attested that green-house tomato farming is highly lucrative and have a postharvest loss of 20%. The study found the investment makes a Benefit cost ratio of 3.99; that is a return of ₦3.99 for every ₦1 invested. However, the researchers mentioned high initial cost of investment, water scarcity and market competition as the bottleneck.

Hydroponics- a type of greenhouses that uses water soluble nutrients as the medium of crop cultivation is called soilless agriculture, its commercial profitability reveals a payback period of 1.2 years and benefit cost ratio of 5.07, although, sensitive to price drop- small-scale hydroponics becomes unprofitable if vegetable market price

drop by 15%, and need reliable power supply for its management (Azeez *et al*., 2023). Contrary to the findings of Azeez *et al*. (2023) and Nafiu *et al* (2025), Saltuk (2019) mentioned economic loss can be faced by greenhouse owner if the greenhouse structure is constructed without following/doing all necessary engineering calculations, and highlighted SAP2000 as computerized program that can be used in such task. The research stressed the importance of the SAP2000 program in addition to saving the structure from engineering damages also save cost of its construction and thus recommends the supervision of an agricultural engineer in the design and construction of the greenhouse structure, following Turkish standards.

CONCLUSION

This review finds that the impact of agricultural engineering on Nigeria's economic growth is asymmetric: farm mechanization has a quantified GDP contribution (a mean value of 25.93%), while irrigation/water engineering and post-harvest/processing engineering, despite decades of documented activity and clear productivity benefits, have no corresponding GDP figures in the literature. The review also finds the relevance of the TOHFAN body in providing smallholder farmers access to farm machinery such as tractors and to bank loans, while revealing persistent challenges, notably low tractor density (6.8 tractors per 100 km² of arable land) and a shortage of agricultural engineers in managerial roles for technical decisions. Nigeria's large dams are found to have a positive economic impact on smallholder farmers, which the implementation of supportive government policy could further strengthen to improve food security. Postharvest loss was found to be high in 2024, rising further in 2025, a trend that, if addressed, would further strengthen GDP and reduce reliance on imported food. Farm structures, particularly greenhouses, face challenges of high initial installation cost, unstable power supply, and a shortage of qualified agricultural engineers for design and construction. On overall acceptability of agricultural engineering innovations among smallholder farmers, the three subtopics converge on a consistent answer: adoption is consistently low, with financial constraints, weak policy implementation, and low trust in new technology recurring across all three branches rather than being specific to any one of them, suggesting that low adoption is a structural issue for Nigerian agricultural engineering as a whole, not an isolated problem within any single branch.

RECOMMENDATIONS

1. Further review should extend beyond mechanization, irrigation, and post-harvest engineering to include renewable energy and precision/smart-farming technologies, for which Nigeria-specific GDP data is currently absent from the literature.

2. Professional bodies such as the Nigeria Institution of Agricultural Engineers (NIAE) should coordinate standardized GDP data record-keeping for agricultural engineering's sub-branches, from state to national level, to close the evidence gaps identified in irrigation and post-harvest engineering.

3. Given that financial constraint and low trust in new technology recur as adoption barriers across all three branches, targeted financing and farmer-education interventions may have a larger economy-wide effect than branch-specific interventions.

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Paper ID 47:
Interactive Mechanistic Simulation of Municipal Wastewater Treatment Unit Operations for Engineering Education

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Abstract
Municipal wastewater treatment is difficult to teach because governing processes occur inside opaque vessels. Static schematics show where units sit but not what happens within them, while professional simulators are costly and require expertise that learners lack. The objective of this study was to develop an interactive, browser-based simulator, driven by a validated engineering model, that renders these mechanisms visible and quantitatively accurate for learners. The application is a single self-contained HTML/CSS/JavaScript file rendered on the HTML5 canvas with no external libraries or servers. The process model couples the Crites– Tchobanoglous settling relation, steady-state Monod formulation for activated sludge, Chick–Watson disinfection law, and oxygen and biomass balances, with coefficients from recognised design references. Additional modules address sizing, cost, diurnal dynamics, energy and carbon accounting, and comparisons with ponds and wetlands. For a design flow of 10 ML/d from 100,000 persons at 96 L/capita·d, the model reduced biochemical oxygen demand from 300 to 5.2 mg/L and total suspended solids from 250 to 5.0 mg/L—removals of 98.3% and 98.0%—with a 5.4-log faecal-coliform reduction and effluent meeting national limits of 30 mg/L. Validation against accepted literature gave a mean absolute percentage error of 7.1 within accepted bands. Energy intensity was 0.35 kWh/m³ (aeration 55%, anaerobic digestion offsetting 37%); ponds required only 0.02 kWh/m³ but 3.0 m²/capita, quantifying the energy–land trade-off governing technology selection in developing regions. The work demonstrates that a lightweight, model-driven web simulator is technically feasible and quantitatively accurate, offering an accessible medium for teaching wastewater treatment mechanics and quantitative behaviour. Its effect on learning outcomes remains to be measured.

Keywords: Wastewater treatment, Interactive simulation, Process modelling, Aeration energy, Engineering education

1. Introduction

Wastewater treatment protects surface water from organic and microbial pollution, safeguards public health and, where the treated effluent is applied to land, returns water and plant nutrients to agriculture. The process is executed by a sequence of unit operations: screening, grit removal, sedimentation, biological oxidation, clarification, filtration and disinfection, each performing a distinct physical, chemical or biological function, and each driven by mechanical plant: rakes, scrapers, screw conveyors, mixers, pumps and blowers (Metcalf & Eddy, 2014). For the agricultural engineer, the treatment works is of interest on two counts. It is an assembly of machines whose selection, sizing, power demand and maintenance are engineering problems of exactly the kind the discipline addresses; aeration alone typically accounts for between 45 and 75 per cent of the electrical demand of an activated-sludge plant (Henze *et al*., 2008; Metcalf & Eddy, 2014). It is also a producer of two agricultural resources: an effluent suitable for irrigation and a sludge that, after anaerobic digestion, yields both a soil conditioner and biogas convertible to rural energy (von Sperling, 2007; WHO, 2006).

The difficulty in teaching the subject is that almost none of the processes are visible or, better put, the process adopts a black box approach. For instance, a settling tank is a concrete box; an aeration basin is a turbulent surface, whereas the mechanisms that matter the separation of a sludge blanket, the flocculation of microbial biomass, the transfer of oxygen from a rising bubble occur inside vessels that cannot be seen over time scales from minutes to weeks (Metcalf & Eddy, 2014; Droste & Gehr, 2018). Students therefore must reason about processes they have never observed. Simulation is the established remedy: reviews consistently find that well-designed simulations improve conceptual understanding, particularly where the subject matter is invisible, and

most strongly where the learner can manipulate parameters and observe the consequences (Kefalis *et al*., 2025; Negahban, 2024).

There are two available tools currently in use as simulations too. While their applicability is verified, inherent limitations exist that prevent their adoption for explaining concepts. For instance, professional simulators have been used to implement the full Activated Sludge Model family (Henze *et al*., 2000) and are quantitatively authoritative; however, their complexity creates a high barrier to entry that keeps them out of reach of a learner who has not yet acquired the prerequisite modelling background (Wang *et al*., 2025). Educational animations, on the other hand, are accessible but are illustrative rather than computational: the picture is static despite changes in operational parameters because no underlying model is embedded in it. The present tool is intended to close that gap: unlike a professional simulator, it asks nothing of the learner beyond a web browser, and its coefficients are traceable to the same design references an instructor would already teach from; unlike a static animation, its picture is generated by that same defensible engineering model and recomputes in real time as parameters change, so the visualisation and the underlying physics can never disagree. That gap is sharper in a developing-region context, where the choice between an energy-intensive compact process and a land-intensive passive one is the central design decision, and where plants built to the compact pattern have frequently failed because electricity and operator skill were not sustainable (Mara, 2003).

The objective of this study was therefore to develop an interactive, browser-based mechanistic simulator of the unit operations of municipal wastewater treatment, in which a process model founded on established sedimentation, biological and disinfection relations drives an animated plant view and responds in real time to user-adjustable parameters, for use in engineering education. The simulator is self-contained, openly available and quantitatively validated, every coefficient is traceable to a recognised design reference, and conventional and low-cost technologies are compared for a common duty under developing-region conditions.

2. Materials and Methods

2.1 Design Approach

The application was developed on the principle that the visualisation and the computation must be the same object. Rather than illustrating a process and separately reporting numbers, the model is evaluated first, and its results determine what is drawn: the concentration reported for each unit, the state of the animation, the equation displayed, and the compliance verdict all derive from a single evaluation of the process model, so that no discrepancy between picture and number is possible. Development proceeded from formulation of the model, through verification of its outputs against worked examples in the source references and construction of the visualisation layer, to validation of the assembled model against accepted literature ranges.

2.2 Design Basis

Every quantity used in the model is either a coefficient taken from a recognised design reference or a value derived from such coefficients by explicit calculation. The complete design basis is given in Table 1. The design flow conditions and every other quantity were derived rather than assumed. Taking a wastewater generation of 96 L/capita·d, which lies within the range reported for domestic wastewater by Metcalf and Eddy (2014) and reflects an urban water supply of about 120 L/capita·d with the customary 80 per cent return to sewer, a design population of 100,000 persons yields the design flow given in Equation 1:

$Q = 100{,}000 \times 96 \times 10^{-3} = 9{,}600 \approx 10{,}000\ m^3/d$ (1)

This is the scale at which a single works is typically built to serve a district of a large Nigerian city, and it is at this scale that engineers must actively choose between a compact, energyintensive technology such as activated sludge and an extensive, land-intensive one such as waste stabilisation ponds.

Table 1. Design basis: model inputs and their sources

Parameter	Symbol	Value	Unit	Source
Design flow	Q	10,000	m³/d	Derived, Equation 1
Design population	—	100,000	persons	Derived, Equation 1
Wastewater generation	—	96	L/capita·d	Metcalf & Eddy (2014)
Influent BOD	S_0	300	mg/L	Metcalf & Eddy (2014)

Influent TSS	—	250	mg/L	Metcalf & Eddy (2014)
Influent total N and P	—	40 and 8	mg/L	Metcalf & Eddy (2014)
Influent faecal coliforms	N_0	1.0×10^7	per 100 mL	von Sperling (2007)
Settling coefficients, BOD	a, b	0.018, 0.020	—	Crites & Tchobanoglous (1998)
Settling coefficients, TSS	a, b	0.0075, 0.014	—	Crites & Tchobanoglous (1998)
Max. substrate utilisation	k	5.0	d^{-1}	Metcalf & Eddy (2014)
Half-velocity constant	Ks	60	mg/L	Metcalf & Eddy (2014)
Yield coefficient	Y	0.6	mg VSS/mg BOD	Metcalf & Eddy (2014)
Endogenous decay coefficient	kd	0.06	d^{-1}	Metcalf & Eddy (2014)
Solids retention time	θc	10	d	Metcalf & Eddy (2014)
Aeration retention time	θ	6.0	h	Metcalf & Eddy (2014)
Mixed-liquor suspended solids	X	2,000	mg/L	Metcalf & Eddy (2014)
BOD_5 to ultimate BOD factor	f	0.68	—	Metcalf & Eddy (2014)
Chlorine dose and contact time	C, t	5.0 and 30	mg/L, min	Metcalf & Eddy (2014)
Chick–Watson rate constant	k′	0.070	L/mg·min	Metcalf & Eddy (2014)
Effluent BOD and TSS limits	—	30	mg/L	FEPA (1991)

[a] *Coefficients are the mid-range values recommended by the cited source for medium-strength domestic wastewater at 20°C. BOD = Biochemical Oxygen Demand; TSS = Total Suspended Solids; VSS = Volatile Suspended Solids.*

2.3 Process Model

The model couples four established relations, one for each principal mechanism of the train. Removal in the primary settling tank follows the rectangular hyperbola of Crites and Tchobanoglous (1998), in which percentage removal R is a function of retention time t alone:

$$R = \frac{t}{(a+b+t)} \quad (2)$$

With coefficients a and b of (0.018, 0.020) for Biochemical Oxygen Demand and (0.0075, 0.014) for suspended solids. Secondary treatment is modelled as a complete-mix activatedsludge system at steady state. Combining the Monod (1949) saturation relation with a mass balance over the reactor gives the effluent soluble substrate concentration S as a function of the solids retention time θc:

$$S = \frac{s(1 + kd\cdot\theta c)}{\theta(Y\cdot k - kd) - 1} \quad (3)$$

The net biomass production, which determines the sludge wasting rate and the load on the sludge line, is given by

$$Px = \frac{Y\cdot(S_0 - S)}{1 + kd\cdot\theta c} \quad (4)$$

The oxygen the blowers must deliver is obtained from a balance over the reactor, accounting for the substrate oxidised, the oxygen recovered in the biomass synthesised and the demand of nitrification:

$$R_o = \frac{Q(S_0 - S)}{f} - 1.42P_x + 4.57\ Q.N_{ox} \quad (5)$$

where f converts five-day to ultimate Biochemical Oxygen Demand, 1.42 is the oxygen equivalent of cell tissue and 4.57 the oxygen required per unit of nitrogen oxidised (Metcalf & Eddy, 2014). Pathogen inactivation follows the Chick–Watson law (Chick, 1908; Watson, 1908), in which the logarithm of survival is proportional to the product of disinfectant concentration C and contact time t:

$log10(N/N0) = -k' \cdot C \cdot t$ (6)

2.4 Chamber Sizing

Each chamber is sized from the design flow and its retention time, and the resulting geometry is checked against the governing loading criterion for that unit. The volume follows from

$V = Q \cdot t$

and the surface overflow rate of a settling unit from $SOR = Q/A$,

while the organic loading on the aeration basin is expressed by the food-to-microorganism ratio

$$\frac{F}{M} = \frac{(Q \times S_o)}{(V \times X)} \quad (7)$$

For the secondary clarifier the solids loading is computed on the combined forward and return flow, (Q + Qr)·X/A, since it is the total solids flux rather than the forward flow alone that determines the thickening duty. Each computed value is displayed against its accepted range and the application reports whether the criterion is satisfied. Because the retention times are under user control, the consequence of changing a chamber volume is visible immediately as a movement of the loading criterion toward or beyond its limit.

a. Cost, Dynamic, Energy and Validation Modules

The cost module combines daily operating expenditure with annualised capital cost, the capital sum being annualised by the capital recovery factor evaluated at a discount rate

$$CRF = \frac{(1+i)^n \cdot}{(1+i)^n - 1} \quad (8)$$

of 12 per cent over a design life of 25 years; the unit rates are indicative and user-adjustable, establishing the relative weight of the cost components rather than predicting an absolute price. The dynamic module integrates a time-dependent mass balance over the aeration basin through a twenty-four-hour cycle, with a diurnal flow and load pattern and an optional shock load, to demonstrate buffering capacity a steady-state calculation cannot express. The energy module converts the computed oxygen requirement into blower power, adds pumping, mixing and sludge-line demand, and credits electricity recoverable from digester gas. The validation module compares six principal outputs with accepted literature ranges.

b. Implementation and Deployment

The application was written in HyperText Markup Language, Cascading Style Sheets and JavaScript and is delivered as a single self-contained file of approximately 170 kilobytes. All graphics are drawn programmatically on the HTML5 canvas; no image assets, external libraries or server component are used. Three-dimensional cutaway views use an orthographic projection with painter's-algorithm face ordering implemented directly on the two-dimensional canvas, avoiding the hardware requirements of WebGL. A service worker and web application manifest make the application installable and able to operate without a network connection, addressing intermittent connectivity and machines on which the user lacks installation rights. Three configurations are provided for the same duty: conventional activated sludge, waste stabilisation ponds, and a subsurface-flow constructed wetland — the latter two represented at the level of overall performance and resource footprint using values reported by von Sperling (2007), Mara (2003), Kadlec and Wallace (2009) and Vymazal (2011). The application is openly available under an MIT licence and archived with a persistent identifier (Sulaiman, 2026).

3. Results and Discussion

3.1. The Developed Application

The completed application runs in any modern browser without a separate installation step, which is of particular value where connectivity or administrative rights to install software are limited, and it continues to operate without a network connection once loaded. It presents the treatment train as an animated plant view with

magnified and rotatable internal views of every unit, together with seven analytical views and an embedded concept assessment. The general arrangement is shown in Figure 1.

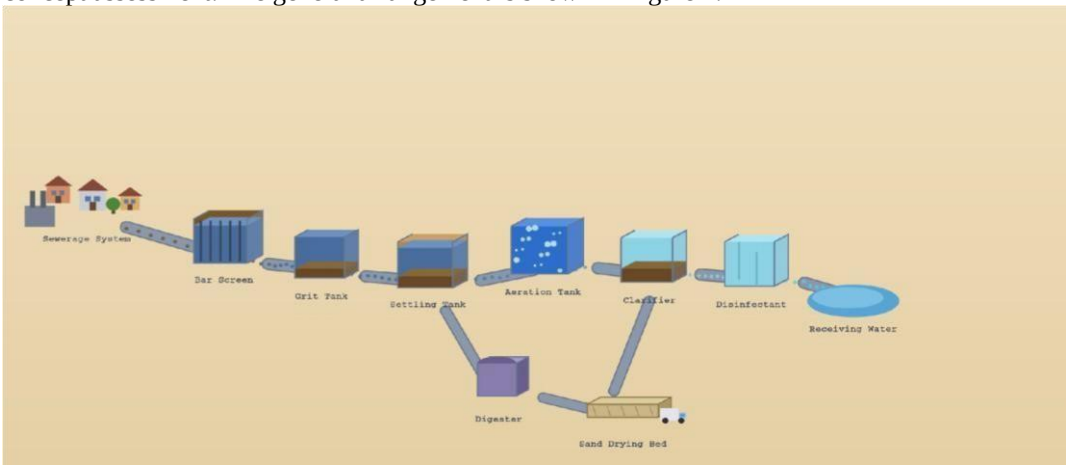

Figure 1. The interactive plant view, showing the animated treatment train with the computed state of the selected unit reported in the dashboard at left

3.2. Modelled Treatment Performance

The computed stage-by-stage water quality is given in Table 2 and Figure 2. The train reproduces the expected progressive reduction of pollutants: Biochemical Oxygen Demand falls from 300 mg/L in the raw influent to 5.2 mg/L in the final effluent (98.3 per cent removal), Total Suspended Solids from 250 to 5.0 mg/L (98.0 per cent), and the faecal-coliform count by 5.4 orders of magnitude. Primary sedimentation removes 34.5 per cent of the Biochemical Oxygen Demand and 56.3 per cent of the suspended solids (Equation 2), and the activated-sludge stage gives the largest single reduction (Equation 3), leaving 8.8 mg/L at the secondary clarifier and 5.2 mg/L after tertiary filtration. The effluent satisfies the national discharge limit of 30 mg/L for both determinants (FEPA, 1991).

Table 2. Modelled stage-by-stage treatment performance, activated-sludge configuration

Stage	BOD (mg/L)	TSS (mg/L)	TN (mg/L)	TP (mg/L)	FC (per 100 mL)
			40	8.0	
Raw influent	300	250	1.0 × 10⁷		
Preliminary	291	230	40	8.0	9.5 × 10⁶
Primary	190.7	100.5	36	7.2	7.6 × 10⁶
Aeration (mixed liquor)	—	2,000	—	—	—
Secondary clarifier	8.8	15.0	12	3.0	1.9 × 10⁶
Tertiary	5.2	5.0	10	2.0	9.5 × 10⁵
Final effluent	5.2	5.0	10	2.0	4.0 × 10¹

[a] Computed from Equations 2 to 6. TN = Total Nitrogen; TP = Total Phosphorus; FC = faecal coliforms. [b] The aeration-basin TSS is the mixed-liquor inventory, not a pollutant load.

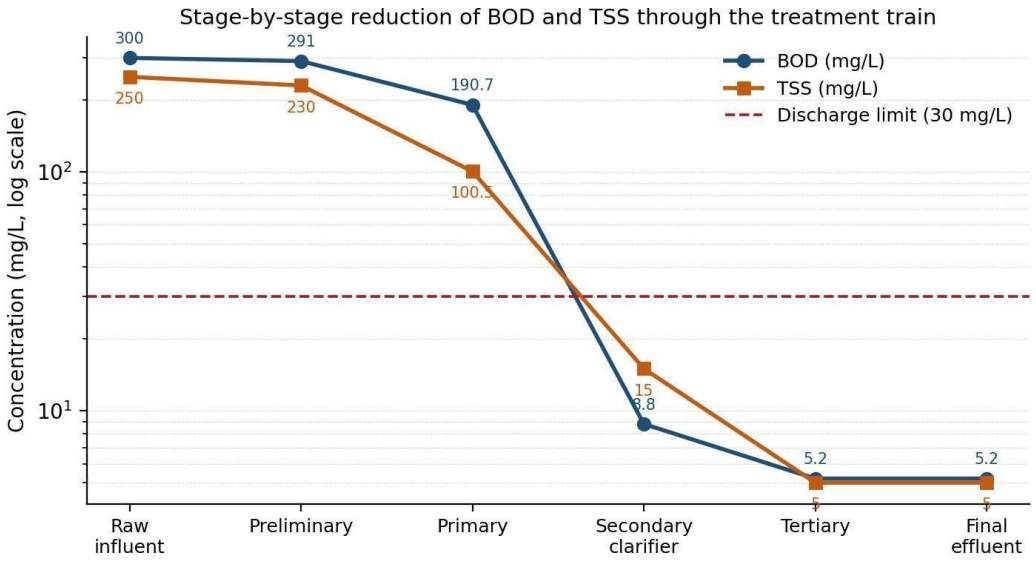

Figure 2. Stage-by-stage reduction of BOD and TSS through the treatment train (log scale).

3.3. Chamber Sizing, Sensitivity and Cost

The computed chamber volumes total approximately 5,000 m³ over an estimated footprint of 1,300 m², and every governing loading criterion falls within its accepted range at the default retention times (Table 3). Because each criterion recomputes as the user changes a retention time or volume, the consequence of a design choice is immediately visible: reducing the aeration retention time from six hours to three halves the basin volume (2,500 to 1,250 m³) but doubles the food-to-microorganism ratio from 0.38 to 0.76 kg BOD per kg mixed-liquor suspended solids per day, outside the accepted range of 0.2 to 0.6, whereas a twelve-hour retention time gives an under-loaded basin at 0.19. Likewise, imposing a secondary efficiency of 50 per cent in place of the computed 95.4 per cent raises the final effluent from 5.2 to 56.3 mg/L (an overall efficiency of 81.2 rather than 98.3 per cent), and the application reports failure against the discharge limit, making the dominance of the biological stage apparent. The indicative treatment cost is about NGN 172 per cubic metre (NGN 583 per kilogramme of BOD removed), of which electricity accounts for roughly 72 per cent of daily operating expenditure; the unit rates are user-adjustable and should be set to local tariffs before figures are quoted.

Table 3. Computed chamber sizing and check against governing loading criteria

Chamber	Volume (m³)	Criterion	Computed	Accepted range	Status
Grit chamber	21	Horizontal velocity (m/s)	0.30	0.25–0.40	Satisfied
Primary settler	833	Surface overflow rate (m³/m²·d)	36.0	30–50	Satisfied
Aeration basin	2,500	F/M (kg BOD/kg MLSS·d)	0.38	0.2–0.6	Satisfied
Aeration basin	2,500	Volumetric loading (kg BOD/m³·d)	0.76	0.3–0.8	Satisfied
Secondary clarifier	1,667	Surface overflow rate (m³/m²·d)	24.0	16–28	Satisfied
Secondary clarifier	1,667	Solids loading (kg/m²·d)	120	70–140	Satisfied

[a] Accepted ranges from Metcalf and Eddy (2014). [b] Clarifier solids loading is computed on the combined forward and return flow.

3.4. Dynamic Response to Load Variation

The dynamic module illustrates how the biological stage behaves under the time-varying loading of a real plant (Figure 3). Over a twenty-four-hour cycle the influent flow swings between 6,500 and 13,500 m³/d and the strength reaching aeration spikes under an injected shock load, yet the modelled effluent Biochemical Oxygen Demand moves only between 7.6 and 16.4 mg/L and never approaches the 30 mg/L limit, because the aeration basin acts as a buffer. Recovery from the shock is complete within a few hours. This demonstrates a property difficult to convey with a static diagram the resilience the large biological reactor confers and is the justification for sizing such a reactor in hours rather than minutes.

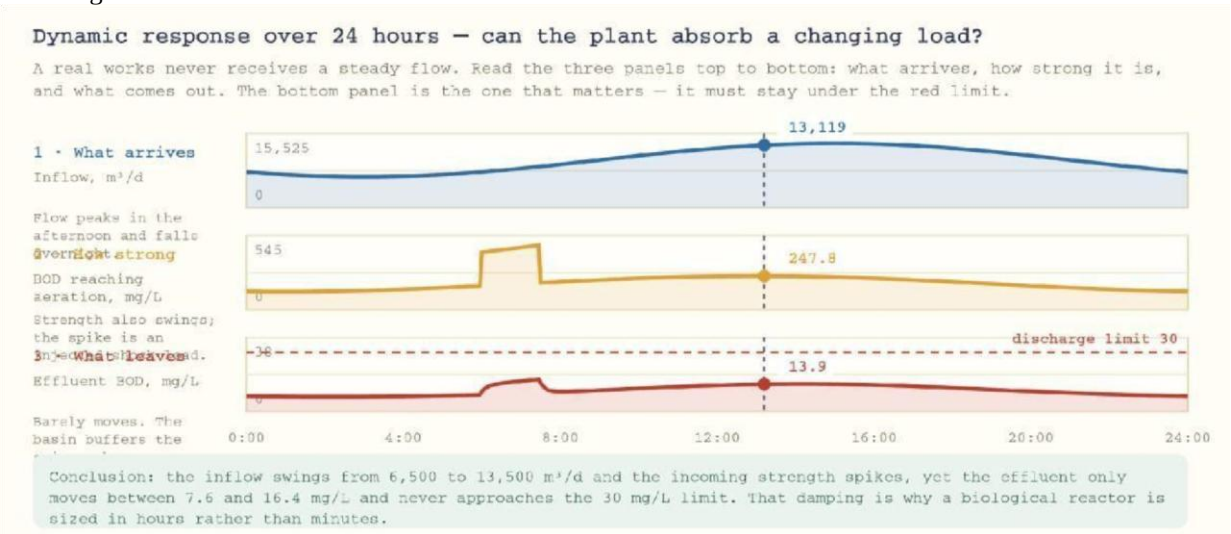

Figure 3. Dynamic response of the activated-sludge stage over 24 hours to diurnal loading and a shock load.

3.5. Energy and Sustainability

The energy module estimates a total electricity demand of about 3,514 kWh/d for the 10 ML/d plant, an energy intensity of 0.35 kWh/m³, of which aeration accounts for roughly 55 per cent (Figure 4). Anaerobic digestion of the sludge yields about 609 m³ of biogas per day, which a combined heat and power unit converts to around 1,300 kWh/d, offsetting some 37 per cent of demand; the associated energy-related carbon footprint is about 0.10 kg of carbon dioxide per cubic metre treated. Because aeration dominates demand, sludge age and basin volume carry more cost leverage than any other design decision, and where electricity supply is the binding constraint this is the principal determinant of whether the works will function at all.

Figure 4. Energy and sustainability balance: electricity demand, biogas recovery credit and derived energy and carbon indicators.

3.6. Model Validation

The model was validated by comparing its principal outputs with accepted design and operating ranges from the literature (Table 4). Across six parameters (the primary and secondary removals and the overall efficiencies) the mean absolute percentage error against the mid-range reference value was 7.1 per cent, and all six values fell within the accepted range. The largest deviation was for the secondary effluent Biochemical Oxygen Demand, which the model places at the optimistic end of the reported band, consistent with a steady-state formulation that does not represent the transient upsets of an operating plant. This agreement, obtained without site calibration, supports the use of the model for teaching and preliminary estimation; however, the model has been verified against literature-reported ranges and not validated against field measurements, so it is not a substitute for a calibrated design model.

Table 4. Model validation against accepted literature ranges

Parameter	Model	Reference	Accepted range	Error (%)
Primary BOD removal (%)	34.5	33	25–40	4.5
Primary TSS removal (%)	56.3	58	50–65	2.9
Secondary effluent BOD (mg/L)	8.8	12	5–20	26.7
Secondary BOD removal (%)	95.4	93	85–96	2.6
Overall BOD removal (%)	98.3	96	92–99	2.4
Overall TSS removal (%)	98.0	95	90–99	3.2

[a] *Reference is the mid-range value reported by Metcalf and Eddy (2014) and von Sperling (2007). Mean absolute percentage error = 7.1 per cent; all six values fall within the accepted range.*

3.7. Technology Comparison and Application

The scenario library quantifies the trade-offs between the three configurations for the same duty (Table 5). Activated sludge gives the lowest effluent Biochemical Oxygen Demand and the smallest footprint but the highest energy demand (0.35 kWh/m³) and operating cost, whereas ponds and wetlands need almost no energy (0.02 and 0.03 kWh/m³, literature-typical values rather than model outputs) but one to two orders of magnitude more land. For a district of Ibadan, where waterworks have been reported to operate below capacity partly because of the cost and reliability of electricity, the electricity demand of activated sludge is the principal risk to the scheme, although biogas from the digester returns about 37 per cent of it. A pond system is largely insulated from this risk,

at the cost of about three square metres of land per person, which is prohibitive in a dense urban core but obtainable on the periphery.

The agricultural outcome is equally specific. Ten million litres a day is sufficient to irrigate some two hundred hectares and carries roughly one hundred kilogrammes of nitrogen and twenty kilogrammes of phosphorus daily, so the effluent is both an irrigation supply and a fertiliser input, provided its pathogen log-removal permits reuse (WHO, 2006). Because ponds achieve high log-removal passively (4.5 log units, against 2.5 for the wetland), they are often preferred over wetlands where reuse is intended, although their effluent Biochemical Oxygen Demand is higher; technology selection therefore cannot be reduced to one parameter.

Table 5. Appropriate-technology comparison for a common 10 ML/d duty

Indicator	Activated sludge	Constructed wetland	Waste stabilisation ponds
Effluent BOD (mg/L)	6	25	20
Effluent TSS (mg/L)	5	45	18
Energy (kWh/m³)	0.35	0.02	0.03
Land (m²/capita)	0.3	3.0	4.0
Pathogen removal ($\log_{10}$)	5.4	4.5	2.5
Operating cost (US$/m³)	0.28	0.05	0.08
Capital cost	High	Low	Low–moderate

[a] Sources: von Sperling (2007); Mara (2003); Kadlec and Wallace (2009). [b] Values are literature typicals for each technology at this duty; the 6 mg/L quoted for activated sludge is the generic literature value and is consistent with the 5.2 mg/L computed for this specific design in Table 2.

4. Discussion

The significance of these results lies less in any single figure than in what the coupling of model and picture makes possible. Because the visualisation is generated by the model rather than drawn alongside it, a change in a design parameter is seen simultaneously as a change in mechanism and in outcome, so the causal link that static schematics leave implicit becomes the object the learner manipulates. This is the condition under which reviews of digital simulation in STEM and engineering education find simulation most effective (Kefalis *et al*., 2025; Negahban, 2024). The design also follows established multimedia and cognitive-load principles, presenting each mechanism with a concise verbal explanation rather than decorative animation and giving immediate feedback by recomputing on every parameter change (Mayer, 2009; Sweller, 1988). The simulator also occupies a gap between existing resources. Professional simulators that implement the Activated Sludge Model family are quantitatively authoritative (Henze *et al*., 2000), but their complexity limits their use by learners without a modelling background, and platforms such as SIMPO have sought to make wastewater modelling more accessible (Wang *et al*., 2025). The present tool complements them by requiring only a web browser and by tracing every coefficient to standard design references (Henze *et al*., 2008; Metcalf & Eddy, 2014). The technology comparison reflects developing-region experience that compact, electricitydependent plants frequently fail where power and operator skill are not sustainable (Mara, 2003), and that ponds and constructed wetlands offer low-energy alternatives at the cost of land (von Sperling, 2007; Kadlec & Wallace, 2009; Vymazal, 2011). Setting the walkthrough in a named city further changes its character: the learner is asked not to accept an abstract works but to weigh whether a real district is better served by a compact plant that depends on electricity or by a land-hungry pond system that does not.

The study has clear limitations. The model is a steady-state, lumped-parameter representation except for the single dynamic reactor, and does not capture full activated-sludge dynamics, temperature effects or detailed nutrient kinetics. Its coefficients are representative literature values rather than measurements from a specific plant, so

validation is against accepted ranges rather than site data. The low-cost scenarios are represented at the level of overall performance rather than by mechanistic sub-models. These simplifications are appropriate for an educational tool but limit its use as a design instrument. A formal classroom evaluation of learning outcomes, although enabled by the embedded pre-test and post-test instrument, has not yet been carried out and is the principal direction for further work.

5. Conclusions

An interactive, browser-based simulator of municipal wastewater treatment was developed in which the visualisation is driven by a validated engineering model. The treatment train was translated into an animated, clickable plant with magnified and rotatable internal views of each unit; a model founded on the Crites–Tchobanoglous settling relation, Monod kinetics and the Chick–Watson law computes effluent quality in real time from user-adjustable parameters, every coefficient being traceable to a recognised design reference; and chamber-sizing, cost, dynamic-response, energy and validation modules were added, with a comparison of activated sludge against ponds and constructed wetlands.

For a 10 ML/d design basis the model reduced Biochemical Oxygen Demand from 300 to 5.2 mg/L and suspended solids from 250 to 5.0 mg/L, overall removals of 98.3 and 98.0 per cent, with a compliant effluent and a faecal-coliform reduction of 5.4 log units. Validation gave a mean absolute percentage error of 7.1 per cent with all six parameters inside their accepted bands, and energy intensity was 0.35 kWh/m³ with aeration accounting for 55 per cent and biogas offsetting 37 per cent.

The work demonstrates that a lightweight, model-driven web simulator is technically feasible and quantitatively accurate, and is designed to serve as an accessible medium for communicating the mechanics and quantitative behaviour of wastewater treatment on the hardware and connectivity actually available in the region. It is recommended that the model be calibrated against measured data from an operating Nigerian plant, and that the tool be evaluated in class using the embedded assessment instrument so that its effect on learning can be measured.

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Paper ID 48:
Development of Motorized Two-Row Irish-Potato Planter as Appropriate Technology for Improved Productivity among Smallholder Farmers in Nigeria

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ABSTRACT
Irish potato (Solanum tuberosum L.) is a globally important food and cash crop that contributes significantly to food security, income generation, and nutrition, particularly in developing economies. Despite its importance, Irish potato production in many regions remains constrained by labourintensive traditional planting methods that result in poor seed placement, inconsistent planting depth, and reduced field efficiency. Agricultural mechanisation of planting operations offers a viable pathway for improving productivity, uniformity, and timeliness of operations, especially for smallholder farmers. This study presents the design, development, and performance evaluation of a motorized Irish potato planter suitable for small- to medium-scale farming systems. The planter was developed using locally available materials and evaluated under field conditions such as tractor tilled sandy-loam soil, flat topography, and different operating speeds of 1.8 kmh^{-1}, 2.5 kmh^{-1}, 3.0 kmh^{-1} for seed spacing accuracy, planting depth uniformity, field capacity, field efficiency, and seed damage. Performance results demonstrate significant improvements in planting uniformity of 307 ± 20 mm and operational efficiency of 83 % when compared with manual planting practices. The study demonstrated that the developed Irish potato planter performed satisfactorily under field conditions, achieving optimum performance at an operational speed of 2.5 km h^{-1} with a metering efficiency of 95%. The findings further indicate that the adoption of the planter has significant potential to improve Irish potato production while providing a technically feasible and economically affordable planting option for smallholder farmers.

KEYWORDS: Agricultural mechanisation; Solanum tuberosum L; Irish-potato planter; Metering efficiency; Planting uniformity; Smallholder farming.

I. INTRODUCTION

1.1 Background of Study

Irish potato (*Solanum tuberosum L.*) is one of the most important food crops worldwide and is recognized by the United Nations as a strategic crop for global food security (Devaux *et al.,* 2014). The crop is cultivated in more than 100 countries across Africa, Asia, Europe, and the Americas, where it serves as a staple food and an essential source of carbohydrates, vitamins, and minerals (Burlingame *et al.,* 2009; FAO, 2021). Global potato production exceeds 300 million metric tonnes annually, with more than one billion people depending on the crop for food and income (Dongyu, 2022).

In Sub-Saharan Africa, Irish potato production plays a crucial role in rural livelihoods and national food systems. However, yields in many developing regions remain significantly lower than global averages due to constraints such as limited access to improved seed, poor agronomic practices, and inadequate mechanisation (Devaux *et al.,* 2014, Gildemacher *et al.,* 2009). Among these constraints, planting operations represent a major bottleneck.

Modifying an existing power-tiller mounted Irish potato planter by integrating fibre-based metering cups offers a practical and cost-effective solution to minimize seed tuber injury during planting. Fibrereinforced or flexible materials provide gentler handling of tubers, leading to improved planting quality without compromising operational efficiency.

This modification is particularly relevant for smallholder farmers, as power tillers are already widely accessible due to their affordability and versatility. By improving the precision and efficiency of the planting process, this project supports increased productivity, better resource use, and enhanced food security. The study also contributes to the advancement of sustainable agricultural mechanization suited to small-scale farming systems.

1.2 Aim and Objectives of the Study

This study seeks to modify and evaluate the field performance of a power- tiller mounted Two-Row Irish potato planter.

The specific objectives of the project include:

1.To identify key parameters relevant to Irish potato cultivation, including planting depth, spacing, and tuber size.
2.To modify and redesign an existing power-tiller mounted Irish potato planter by incorporating fiberbased metering cups to reduce tuber bruises.
3.To assess the expected performance of the modified planter through theoretical evaluation, focusing on planting efficiency, Intra-row spacing, Field Efficiency, Theoretical Field Capacity, Effective Field Capacity and bruises reduction.

II. MATERIALS AND METHODS

2.1 Description of the Two-Row Irish Potato Planter

The developed Irish potato planter consists of the land wheel, metering device, feeders, frame, sprocket, and chain arrangement. The metering mechanism consists of tubers cups (buckets) attached to the upper rotating shaft, these shafts are driven by a chain and sprocket system that is mechanically linked to the land wheel. Figure 1 below is the isometric drawing of the two-row Irish potato planter showing the component parts, and Figure 2 shows the exploded orographic view of each of the components. While Figure 3 is the dimensional view of the planter. The planter is power tiller-mounted by first attaching it to the frame of the planter, which is hitched to either of the linkage as shown in Figure 4.

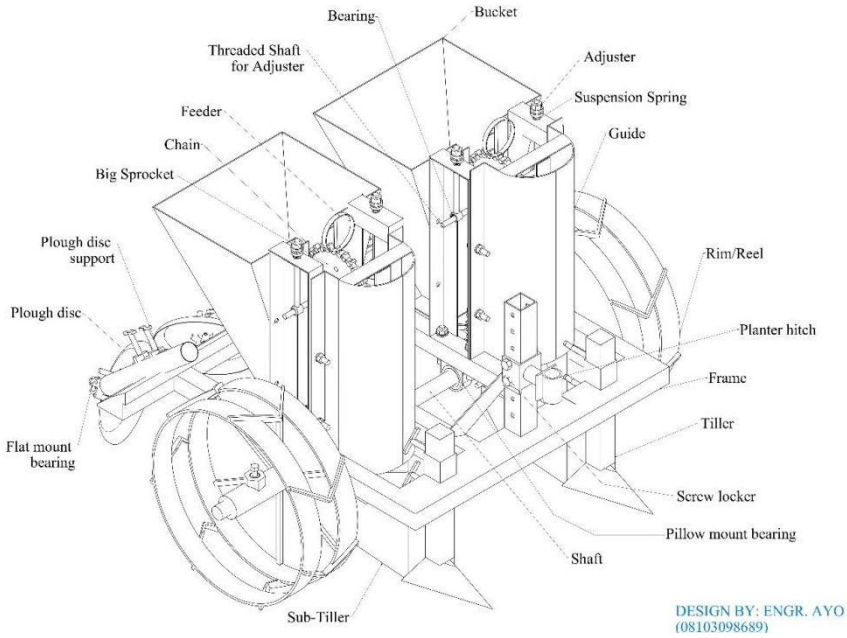

Figure1: Isometric view of the Two-row Irish potato planter

As the planter moves forward, the wheels' rotation drives the chain, causing the shafts and tubers cups to rotate. The tubers cups scoop up potato tubers from the hopper and release them into guide pipes, which direct them accurately into the furrows. The metering unit is driven by the land wheel and can meter eight (four per row) Irish potato tubers per revolution of the land wheel with an average spacing of 280mm. The land-wheel has a diameter of (420mm) and covers a distance of 1.12 meters in a revolution, allowing four Irish potato tubers pieces to be planted on each row.

2.2 Method of Administering Planting

Firstly, the field was prepared by ploughing and harrowing using a 60 hp Massey Ferguson tractor coupled with a three-disc plough and a 16-disc harrow to achieve a well-pulverized sandy-loam seedbed suitable for planter operation. Thereafter, ridges were formed using a tractor-mounted ridger with an adjustable row spacing of 750 mm and a second pass with planter attached to the 14-kW power tiller for the planting operation. Medium-sized

Irish potato seed tubers with an average diameter of 3555 mm and average weight of 40-80 g were used for the planting trials.

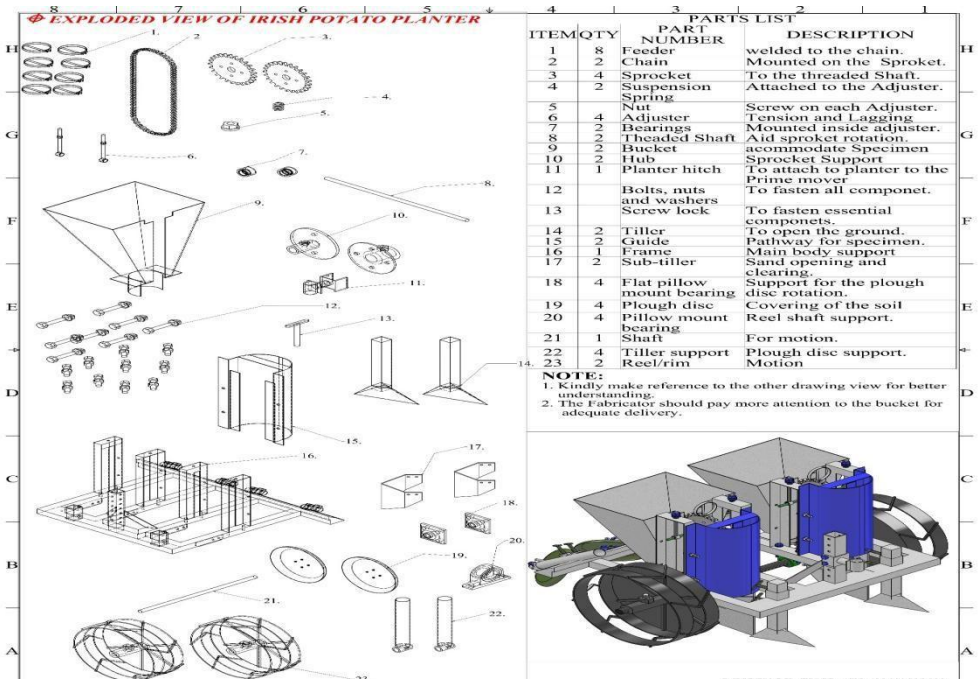

Figure 2: Exploded Orthographic View of Each Components

The Irish potato tubers pieces loaded in the hopper flow in a continuous pattern, dropping into the guide pipe that guides the potato directly into the ridge at a depth of 100mm. The tiller, a component attached to the forefront of the planter, is adjustable to suit the farmer's planting depth specifications. It opens the ridge to create a furrow so that Irish potato tubers dropped on the ridges do not fall off to the bare ground. The guide pipe guides the Irish potatoes safely into the furrow created by the tiller. When the Irish potato tubers piece drops into the furrow, the coverer completes the planting by burying the Irish potato tubers piece with the soil.

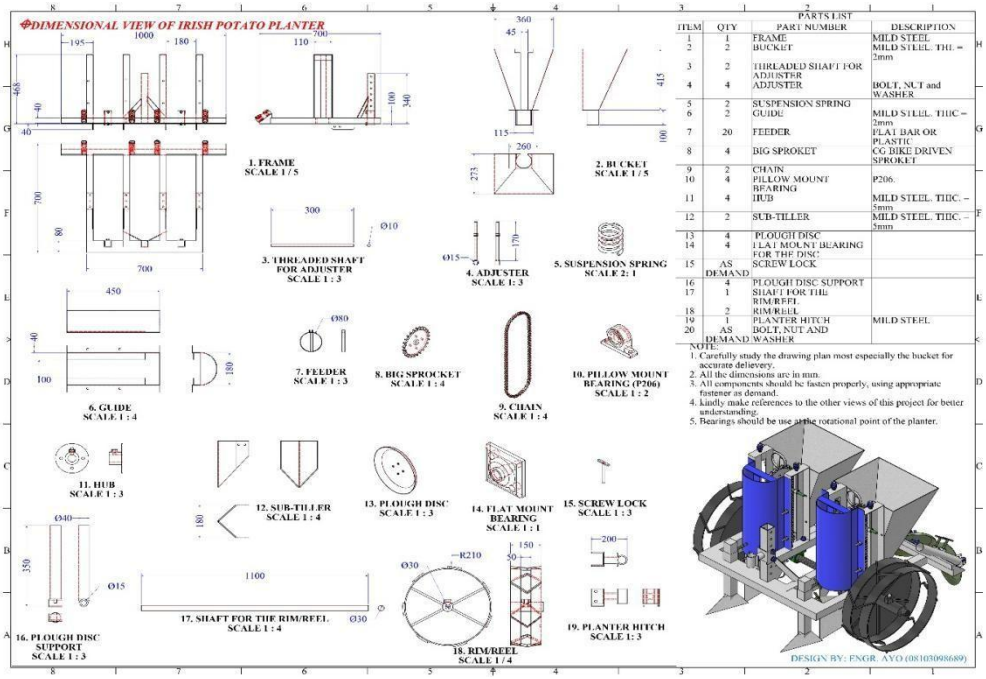

Figure 3: Dimensional view of the Planter

The coverer comprises four discs plough adjusted at angles of 45° and 30°, respectively. The 30° disc first collects the soil to partly cover the Irish potato tubers, while the 45° disc collects the soil that finally buries the tubers (Makolo *et al.*, 2019). This metering mechanism, with its various adjustable components, minimizes tubers wastage and ensures even spacing and optimal plant growth conditions by providing precise and reliable tubers placement.

Figure 4: View of the Fabricated Two-Row Irish Potato Planter Hitched to a Power

Tiller

2.3 Determination of Parameter Relevant to Irish Potato Planting

The design parameters relevant to Irish potato planting were determined and considered in the design of the Irish potato planter. Table 1 shows the specification of the two-row Irish-potato planter. These parameters or properties determined include the mean length, width, thickness, angle of repose, mean roundness, mean surface area, and volume. A number of instruments were used in various measurements and determination of the dimensions and properties of the selected Irish potato varieties. The equipment used for determining the physical and mechanical properties of the Irish potato tubers included a digital Vernier caliper with a measuring range of 0-150 mm and accuracy of ±0.01 mm for measuring tuber length, width, and thickness, a wooden frame box of dimensions 500 mm × 500 mm × 500 mm used for determining the angle of repose, an electronic weighing balance with a capacity of 5 kg and sensitivity of ±0.01 g for measuring tuber weight, and a measuring cylinder (2000 ml capacity) for volume determination.

2.3.1 Determination of geometric mean diameter

The geometric mean diameter of the potato was determined from the measured dimensions of the potato given in Equation (1) (Saleh and Awolola, 2022).

$D =$ [redacted] **(1)**

Where L = length or longest side of the potato (mm)
W = width or minor axis of the potato (mm)
T = thickness of the potato (mm)
D = geometric mean diameter (mm)

2.3.2 Sphericity determination

The sphericity of the potato was determined from the potato dimensions that were earlier determined in the previous equation (1) from Equation (2) (Loghavi *et al.*, 2011):

$$\Phi = \frac{di}{dc} \quad \textbf{(2)}$$

Where Φ = Sphericity of the object di = diameter of the largest inscribed circle dc = diameter of the smallest circumscribed circle **Table 1: Specification of the Two-Row Irish Potato Planter**

Parameter	Specification
Length of Machine	1000mm
Width of Machine	1000mm
Height of Machine	1000mm
Weight of Machine	300.4kg
Metering Device Capacity	8 Irish Potatoes tubers
Average Planting Space	280mm
Draw Pull	14kw

Theoretical Field Capacity 11.95hr/ha

2.3.3 Surface area determination

The surface area was determined using the potato geometric dimensions given by Equation (3) (Mohsenin, 2010):

$A = \pi$ **(3)**

Where: As = surface area (mm2)

Dg = geometric mean diameter (mm)

2.3.4 Volume determination

Due to the irregular shape of the potatoes, their volume was determined by taking the three different dimensions; length, width and thickness, then the volume was estimated by using Equation (4) (Mohsenin, 2010):

$V = \frac{\pi . L.W.H}{6}$ (4)

Where: V = volume, mm3 L = length of potato, mm
W = width of potato, mm
H = thickness, mm

2.3.5 Bulk density determination

Equation (5) was used to determine the bulk density (Saleh and Awolola, 2022).

$\rho b = \frac{weigth\ of\ packed\ material}{known\ volume}$ **(5)**

Where ρ = the bulk density in kg/m3

2.3.6 Weight determination

The weight of a single potato tuber was determined by the use of an electronic mettle balance. The Irish Potato tubers were placed on the balance one by one and the weight recorded (Saleh and Awolola, 2022).

2.3.7 Angle of repose determination

The angle of repose was determined using the method described by (Mohsenin, 2010). In this method, a frame box is mounted on a flat wooden surface and then gently tilted until the Irish potato just begins to slide then it will be measured as the angle of repose for the potatoes. The angle of repose was found to be 28°.

2.4 Evaluation of Planter

The performance of the power tiller-mounted two-row Irish potato planter was evaluated based on the metering efficiency, planting depth, intra-row spacing uniformity, operational speed, field capacity and fuel consumption. The planting depth and intra-row spacing were determined by measuring the furrow depth and the distance between two Irish potato seeds using a graduated tape as shown in Figure 5. While metering efficiency was determined by feeding a known number of Irish potato seeds in the hopper and taken note of the number seeds that were successfully planted.

Table 2 presents the metering efficiency of the developed motorized two-row Irish potato planter at operational speeds of 1.8, 2.5, and 3.0 km h^{-1}. The mean metering efficiencies obtained were 98%, 95%, and 92%, respectively. The result indicates that metering efficiency decreased with increase in forward speed. At lower operational speed of 1.8 km h^{-1}, the planter achieved the highest metering efficiency because the seed metering cups had adequate time to pick and release the potato tubers properly into the delivery tubes. However, as the operational speed increased to 3.0 km h^{-1}, vibration and rapid rotation of the metering mechanism resulted in occasional misses and irregular seed release, thereby reducing the metering efficiency. Similar observations were reported by Kumar *et al*. (2018),

Figure 5: Intra-Row Spacing of Irish Potato using a Tape

III RESULTS AND DISCUSSION

who observed that increased forward speed reduced the precision of potato seed delivery in a power tiller-operated potato planter. Nevertheless, the minimum metering efficiency of 92% obtained in this study compares favourably with the 82% reported by Makolo *et al.* (2019) for a two-row yam sett planter and confirms the suitability of the developed planter for smallholder potato production systems.

Table 2: Metering Efficiency at Different Speeds

Operational Speed (km/h)	Replication			Mean Metered Tubers	Metering Efficiency (%)
	1st	2nd	3rd		
1.8	98	99	97	98.0	98.0
2.5	95	94	96	95.0	95.0
3.0	92	93	91	92.0	92.0

The corresponding ANOVA result presented in Table 3 showed an F-value of 27.0, which exceeded the F-critical value of 5.14, with a p-value of 0.001 less than 0.05. This implies that operational speed had a statistically significant effect on metering efficiency. Therefore, the variation in metering efficiency across the tested operational speeds was not due to random error but due to the influence of forward speed on the planter metering mechanism. The optimum metering performance was achieved at 1.8 km h^{-1}.

Table 3: Metering Efficiency ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	54	2	27	27	0.001	5.143253
Within Groups	6	6	1			
Total	60	8				

Table 4 presents the planting depth consistency of the planter at different operational speeds. The mean planting depths obtained were 49 mm, 50 mm, and 52 mm at operational speeds of 1.8, 2.5, and 3.0 km h^{-1}, respectively, compared with the target planting depth of 50 mm. The selected target depth was based on agronomic recommendations for Irish potato cultivation, where planting depths between 50 and 100 mm promote proper tuber emergence, moisture conservation, and root establishment (Temesgen *et al.*, 2017). The result showed that the planter maintained relatively uniform planting depth across all operational speeds. The operational speed of

2.5 km h^{-1} produced the most accurate planting depth with exact conformity to the target value. The slight increase in planting depth observed at 3.0 km h^{-1} may be attributed to increased penetration force and vibration of the furrow opener during operation. Similar findings were reported by Temesgen *et al.* (2017), who observed that consistent planting depth enhances germination uniformity and crop establishment in Irish potato cultivation.

Table 4: Planting Depth Consistency

Operational Speed (km/h)	Replication		Mean (mm)	Variance	Std. Dev (mm)
	1st	2nd 3rd			
1.8	48	50 49	49.0	2	1.41
2.5	51	49 50	50.0	2	1.41
3.0	52	53 51	52.0	0.5	0.71

***Target Depth = 50 mm**

The ANOVA result shown in Table 5 gave an F-value of 4.33, which was lower than the F-critical value of 9.55, while the p-value of 0.130 was greater than 0.05. This indicates that operational speed had no statistically significant effect on planting depth. Therefore, despite slight numerical variations in depth values, the planter was able to maintain satisfactory depth uniformity under all the tested speeds. This demonstrates the stability and effectiveness of the furrow opening and covering mechanisms of the developed planter.

Table 5: Planting Depth ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13	2	6.5	4.333333	0.130395	9.552094
Within Groups	4.5	3	1.5 Total	17.5	5	

Table 6 shows the intra-row spacing uniformity obtained during planter evaluation. The mean spacing values recorded were 295 mm, 305 mm, and 315 mm at operational speeds of 1.8, 2.5, and 3.0 km h^{-1}, respectively, against the target spacing of 300 mm. The target spacing was selected based on recommended agronomic spacing for Irish potato cultivation to ensure adequate plant population, nutrient utilization, and tuber development. The result indicates that increasing operational speed caused a corresponding increase in spacing between planted tubers. This may be attributed to increased forward travel velocity, which reduced the synchronization between tuber release and planter movement. The spacing obtained at 2.5 km h^{-1} was closest to the target spacing and therefore considered the most suitable operational speed for optimum planting accuracy. The average spacing value of 305 mm obtained at this speed agrees closely with the recommended planting geometry for mechanized Irish potato production reported by Kumar *et al.* (2018).

Table 6: Intra-Row Spacing Uniformity

Operational Speed (km/h)	Replications		Mean (mm)	Variance	Std. Dev (mm)
	1st	2nd 3rd			
1.8	292	298 295	295.0	9	3.0
2.5	308	302 305	305.0	9	3.0
3.0	316	314 315	315.0	1	1.0

***Target spacing = 300 mm**

The ANOVA result presented in Table 7 showed an F-value of 47.37, which was significantly higher than the F-critical value of 5.14, while the p-value of 0.00021 was less than 0.05. This confirms that operational speed

significantly influenced intra-row spacing uniformity. Similar observations were reported by Kumar *et al*. (2018), who stated that excessive planter speed adversely affects seed spacing accuracy due to irregular seed drop and machine vibration. Therefore, lower to moderate operational speeds are preferable for achieving better planting precision.

Table 7: Intra-Row Spacing ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	600	2	300	47.37	≤0.05	5.14
Within Groups	38	6	6.33			
Total	638	8				

Table 8 presents the relationship between operational speed and field capacity of the planter. At operational speeds of 1.8, 2.5, and 3.0 km h^{-1}, the theoretical field capacities obtained were 0.216 ha h^{-1}, 0.300 ha h^{-1}, and 0.360 ha h^{-1}, respectively, while the corresponding effective field capacities were 0.180 ha h^{-1}, 0.240 ha h^{-1}, and 0.270 ha h^{-1}. Similarly, the field efficiencies recorded were 83.3%, 80.0%, and 75.0%, respectively. The results indicate that theoretical and effective field capacities increased with increase in operational speed due to the larger area covered per unit time. However, field efficiency decreased as speed increased. The reduction in field efficiency at higher speeds may be attributed to increased turning losses, vibration, seed misses, and operational interruptions during planting. Similar trends were reported by Ziblim *et al*. (2025), who observed that field efficiency decreases with increase in travel speed due to increased operational losses.

Table 8: Operational Speed and Field Capacity

Operational Speed (km/h)	Replications			Mean Theoretical FC (ha/h)	Mean Effective FC (ha/h)	Field Efficiency (%)
	1st	2nd	3rd			
1.8	0.215	0.217	0.216	0.216	0.180	83.3
2.5	0.300	0.301	0.299	0.300	0.240	80.0
3.0	0.361	0.358	0.360	0.360	0.270	75.0

*TFC = $\frac{speed \times width}{10}$; EFC = $\frac{Area\ covered}{time\ teken}$; FE = $\frac{EFC}{TFC} \times 100$

*Working width = 1.2 m

Comparing the three operational speeds, 2.5 km h^{-1} provided the best compromise between field capacity, metering efficiency, and planting accuracy. Although 3.0 km h^{-1} produced the highest field capacity, the associated reduction in metering efficiency and spacing accuracy makes it less suitable for precision planting operations. The effective field capacity of 0.240 ha h^{-1} obtained at 2.5 km h^{-1} represents a significant improvement over manual Irish potato planting operations commonly practiced by smallholder farmers.

The ANOVA result shown in Table 9 gave an F-value of 10,819.46, which greatly exceeded the Fcritical value of 5.14, while the p-value of 2.13×10^{-11} was far below 0.05. This confirms that operational speed had a highly significant effect on field capacity. Therefore, increasing speed significantly improved area coverage per unit time, although excessive speed reduced planting precision and field efficiency.

Table 9: Operational Speed and Field Capacity ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.031	2	0.02	10819.46	2.13E-11	5.143
Within Groups	8.66667E-06	6	1.44E-06			
Total	0.031264889	8				

Figure 6 below illustrates the relationship between operational speed and field efficiency. The Figure showed that field efficiency declined progressively from 83.3% at 1.8 km h^{-1} to 75.0% at 3.0 km h^{-1}. The decrease in efficiency with increase in speed is associated with greater machine vibration, increased wheel slippage, and higher turning losses during operation. This trend agrees with the findings of Ziblim *et al.* (2025), who reported that excessive operational speed adversely affects machine efficiency under field conditions.

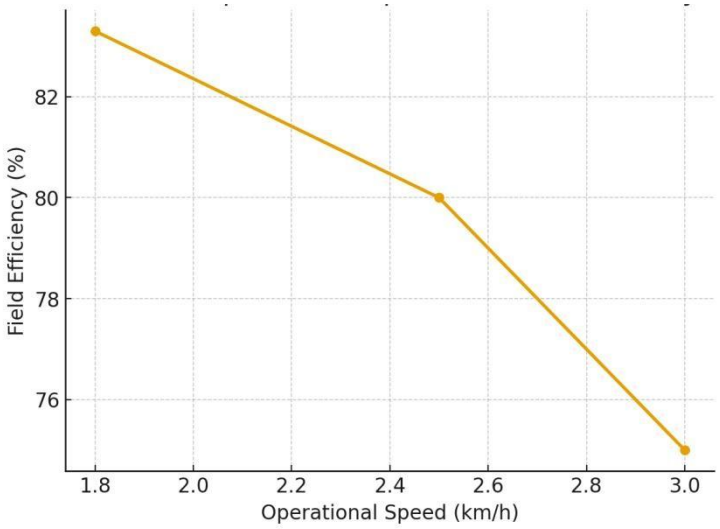

Figure 6: Relationship between Operational Speed and Field Efficiency

Table 10 presents the fuel consumption rates of the planter at different operational speeds. The average fuel consumption values obtained were 1.03 L h^{-1}, 1.30 L h^{-1}, and 1.60 L h^{-1} at operational speeds of 1.8, 2.5, and 3.0 km h^{-1}, respectively. The result showed that fuel consumption increased with increase in speed because higher engine power was required to overcome additional draft, vibration, and rolling resistance at higher operational speeds. However, the operational speed of 2.5 km h^{-1} provided a balance between planting performance, field capacity, and fuel economy. At this speed, the planter achieved satisfactory metering efficiency of 95%, field efficiency of 80%, and acceptable fuel consumption of 1.30 L h^{-1}. This suggests that moderate operational speed is preferable for achieving efficient and economical planting operation in smallholder Irish potato production systems (Mengui et al., 2019).

Table 10: Fuel Consumption Rate

Operational Speed (km/h)	Replications			Mean Fuel Consumption (L/hr)
	1st	2nd	3rd	
1.8	1.0	1.11.0		1.03
2.5	1.3	1.41.2		1.30
3.0	1.6	1.71.5		1.60

IV CONCLUSIONS

4.1 Conclusions It was concluded that:

1. The modification and evaluation of the power-tiller mounted two-row Irish potato planter demonstrated satisfactory technical feasibility and operational efficiency under field conditions.
2. The planter achieved optimum performance at an operational speed of 2.5 km h^{-1} with a metering efficiency of 95%, effective field capacity of 0.240 ha h^{-1}, and field efficiency of 80%.
3. The planter maintained an average intra-row spacing of 305 mm and planting depth of 50 mm, indicating satisfactory planting uniformity and effective depth control.
4. Increasing operational speed improved theoretical field capacity up to 0.360 ha h^{-1} at 3.0 km h^{-1} but resulted in reduced metering precision and increased fuel consumption of 1.60 L h^{-1}.
5. The replacement of metallic metering components with fibre-reinforced materials minimized tuber bruising while maintaining satisfactory seed delivery performance.
6. The developed planter significantly reduced labour demand, improved planting accuracy, and enhanced field productivity compared with traditional manual planting methods.

Overall, the planter provides a practical, technically feasible, and economically affordable mechanisation option suitable for sustainable Irish potato production in smallholder farming systems.

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Raised-Bed Configuration versus Deficit Irrigation in Wheat: An Evidence Synthesis of Yield, Water Productivity and Context-Dependent responses

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Abstract
Water scarcity increasingly constrains irrigated wheat production, particularly in semi-arid environments where conventional surface irrigation can result in evaporation, runoff and deep-percolation losses. Raised-bed planting and deficit irrigation have each been investigated as strategies for improving agricultural water use; however, their interaction and the conditions under which their combination produces favorable yield–water-productivity outcomes require clearer synthesis. This review examines the combined influence of raised-bed configuration, deficit-irrigation intensity and irrigation timing on wheat grain yield and water productivity. Particular attention is given to the mechanisms through which bed geometry modifies soil-water redistribution and root-zone conditions under controlled water stress, and to the roles of soil, climate, cultivar and irrigation management in modifying crop response. Evidence in the supplied literature indicates that raised beds can improve irrigation efficiency and root-zone conditions, while moderate deficit irrigation can improve water productivity when stress is controlled and appropriately timed. However, responses are not universal: bed width, soil texture, irrigation method, deficit intensity, deficit timing and local environmental conditions can alter the balance between yield and water productivity. The central knowledge gap is therefore not whether either practice can save water, but how their interaction can be optimized for specific production environments. The review further highlights the need for context-specific evidence for irrigated wheat production in Northern Nigeria and proposes a framework linking bed configuration, deficit regime, environmental conditions and crop response.

Keywords: wheat, raised beds, flat-basin irrigation, deficit irrigation, grain yield, water productivity.

Introduction

Wheat (Triticum aestivum L.) is an important staple crop, while irrigated production is increasingly challenged by water scarcity, climate variability and competition for agricultural water. The review identifies conventional flat-basin and flood-irrigation practices as important sources of non-productive water losses through evaporation, runoff and deep percolation. It therefore considers two management levers: land configuration through furrow-irrigated raised beds, and deficit irrigation through deliberate reduction of water supplied to the crop.

Raised-bed planting changes the spatial relationship among soil, water and roots. The reviewed literature associates bed systems with reduced irrigation-water requirements, improved nitrogen-use efficiency, reduced lodging and, in several settings, grain-yield gains relative to flat planting. At the same time, the evidence is not uniformly positive. The review notes that bed geometry can influence soil temperature and early tillering, and that reported advantages depend on management and environmental conditions. (Fahong et al., 2004; Sarker et al., 2014; Feng et al., 2010).

Deficit irrigation addresses the quantity and timing of water supplied to the crop. Its effects are strongly stage-dependent. Water shortage during early vegetative growth may reduce tillering but can be partly compensated for by later growth, whereas stress around stem elongation, heading and grain filling can more directly affect reproductive development and final grain yield. This means that the same seasonal reduction in applied water can have different consequences depending on when the deficit occurs.

These observations lead to the central argument of this review: raised-bed configuration and deficit irrigation should be examined as interacting components of one crop–soil–water management system. Bed geometry affects where irrigation water moves and where roots develop, while deficit irrigation determines the amount and timing of water available to that root system. The literature includes evidence from factorial comparisons showing that

the performance of raised beds can depend on the irrigation regime rather than being an unconditional effect of bed geometry.
Accordingly, the review asks: under what combinations of bed configuration, deficit intensity and deficit timing can wheat maintain acceptable grain yield while improving irrigation water productivity, and how are these outcomes modified by soil, climate and management conditions?

Although previous studies have investigated raised-bed planting and deficit irrigation as strategies for improving wheat production and water productivity, their combined effects remain dependent on bed geometry, irrigation deficit intensity, timing, soil characteristics and climatic conditions. The reviewed literature also indicates a geographical imbalance, with substantial evidence originating from wheat-producing regions outside Nigeria. Consequently, there is a need for context-specific field investigations in Northern Nigeria to quantify the interaction between raised-bed configuration and deficit irrigation, determine their effects on wheat grain yield and water productivity, and evaluate their economic feasibility. Such evidence would support the development of locally appropriate irrigation-management recommendations under increasing water scarcity.

The objectives are to: (i) synthesize evidence on raised-bed effects on wheat yield and water productivity; (ii) examine how deficit magnitude and timing affect wheat response; (iii) interpret evidence on the interaction between bed configuration and deficit irrigation; (iv) identify environmental and management factors that explain inconsistent results; and (v) derive research and management implications for irrigated wheat, with particular attention to Northern Nigeria.

Review Methodology

Literature Search Strategy

Relevant literature was identified from the references cited in the manuscript, focusing on studies examining raised-bed planting, deficit irrigation and their effects on wheat grain yield, yield components and water productivity. The search strategy was structured around combinations of the following keywords: *wheat*, *raised-bed planting*, *furrow-irrigated raised beds*, *deficit irrigation*, *irrigation scheduling*, *grain yield*, *water productivity* and *water-use efficiency*. Boolean operators (AND and OR) were used to combine related terms when searching electronic databases and scholarly search engines. The reference lists of relevant publications were also considered to identify additional studies. Particular attention was given to research investigating the interaction between raised-bed configuration and irrigation deficit, as well as studies reporting evidence from semi-arid environments and Northern Nigeria.

Selection Criteria

Studies were considered relevant if they investigated wheat (*Triticum aestivum* L.) and addressed at least one of the following: raised-bed planting, deficit irrigation, their combined effects, or the influence of soil, climatic and management factors on crop response. Eligible publications were required to provide information relevant to grain yield, yield components, irrigation-water use, water productivity or water-use efficiency. Relevant field experiments, modelling studies and review articles were considered. Publications unrelated to wheat irrigation management, studies without relevant outcome information, and duplicate records were excluded. Studies conducted outside Nigeria were retained where they provided useful evidence for understanding crop responses under comparable irrigated or semi-arid conditions.

Review Period

The review focused primarily on literature published between January 2000 and October 2024, reflecting the contemporary evidence base on raised-bed planting, deficit irrigation and wheat water productivity. Earlier foundational publications, including Sayre and Moreno Ramos (1997), were retained where they provided important background on raised-bed technology. The review included studies from different wheat-producing regions, with particular attention to evidence relevant to irrigated wheat production in Northern Nigeria.

Raised-Bed Configuration and Wheat Response

Raised-bed planting separates crop rows from irrigation furrows and changes the distribution of water within the soil profile**.** The literature describes potential improvements in soil aeration, reduced waterlogging, root

development, nutrient uptake and irrigation efficiency. These mechanisms can be especially relevant where excess irrigation water is otherwise lost below or beyond the effective root zone.

The magnitude of the response depends on bed geometry. The reviewed studies include different bed widths and configurations, indicating that 'raised bed' is not a single treatment. Bed width changes the distance between crop rows and furrows, the proportion of the field receiving direct wetting, and the spatial distribution of roots. Consequently, yield and water productivity should be interpreted alongside bed dimensions rather than as a simple bed-versus-flat comparison. (Tewabe et al., 2020; Tang et al., 2024).

The review reports examples of substantial irrigation savings and improved water productivity under raised-bed management. It also reports yield improvements in several studies. However, these outcomes should be interpreted as study-specific responses. The evidence does not support a universal claim that raised beds always increase yield. (Ashifa Soomro et al., 2017; Tewabe et al., 2020; Ismail et al., 2021).

An important mechanism is the interaction between root-zone aeration and water availability. Raised beds can reduce prolonged saturation around the crop row, while furrows provide a localized source of irrigation water. Under controlled deficit irrigation, this spatial arrangement may allow roots to access stored moisture while reducing the volume of soil and surface area exposed to unnecessary wetting. (Feng et al., 2010; Mohammed Karrou, 2012).

Deficit Irrigation: Intensity and Timing

Deficit irrigation is not simply 'less irrigation'. Its effect depends on the magnitude of the deficit and the growth stage at which water becomes limiting. The literature distinguishes moderate deficits from severe deficits and emphasizes the greater sensitivity of reproductive processes during stem elongation, heading and grain filling. (Si et al., 2023; El-Hendawy et al., 2024).

Moderate seasonal deficits, including treatments around 70–85% of crop evapotranspiration in the supplied studies, are reported to maintain yield relatively close to fully irrigated treatments in some environments while increasing water productivity. More severe deficits, particularly around 40–50% of full water requirement, are associated with larger yield reductions. These ranges should be treated as evidence from particular experimental conditions rather than as universal prescriptions. (Abdelraouf et al., 2021; Bayisa et al., 2024; Saad et al., 2023).

The timing of the deficit is equally important. Early vegetative stress may reduce tiller formation but can sometimes be followed by partial compensation when water becomes available. Later stress can reduce grain number, fertility or grain-filling duration and may therefore be less recoverable. The practical implication is that deficit irrigation should be scheduled according to crop developmental stage rather than expressed only as a seasonal percentage. (El-Hendawy et al., 2024; Al-ghobari and Dewidar, 2018; Ouda et al., 2021).

Yield and Water Productivity: The Central Trade-off

Grain yield and water productivity measure different dimensions of irrigation performance. Grain yield describes the quantity of harvested grain, whereas water productivity relates output to water consumed or applied, depending on the definition used by the study. A treatment can therefore increase water productivity without increasing yield if the proportional reduction in water is greater than the reduction in grain production. (Zwart and Bastiaanssen, 2004).

The review reports water savings under raised beds and improved water productivity under moderate deficit irrigation. The most useful synthesis is therefore a trade-off framework rather than a search for one universally optimal treatment. (Ashifa Soomro et al., 2017; Bayisa et al., 2024).

Table 1: Irrigation deficit level, interpretation and Implication

Response zone	Water supply	Expected interpretation	Management implication
High-yield zone	Near full irrigation	Yield protection is prioritized; water productivity may be lower.	Relevant where water is relatively available and yield loss is costly.
Moderate-deficit zone	Moderately below full requirement	Potential for water saving with limited yield penalty in suitable environments.	Requires appropriate timing and irrigation control.
High-saving/ yield-penalty zone	Strong deficit	Water productivity may rise while grain yield declines materially.	Useful only where water scarcity justifies the yield trade-off.
Severe-stress zone	Very low water supply	Large yield losses can undermine production value.	Generally signals that deficit intensity or timing is too severe for the studied environment.

Interaction Between Raised-Bed Configuration and Deficit Irrigation

The principal contribution of the revised review is to treat land configuration and irrigation scheduling as interacting management variables. Raised beds alter the spatial distribution of irrigation water and roots; deficit irrigation alters the amount and timing of that water. Their combined outcome therefore depends on whether the bed system can maintain adequate root-zone water availability during the selected deficit period.

This interaction provides a more defensible interpretation than the statement that the two practices 'work better together' in every environment. The appropriate conclusion is conditional: their combined performance can be favorable when bed geometry, irrigation control, deficit intensity and deficit timing are compatible with soil and climatic conditions. (Rady et al., 2021; Zaman et al., 2017).

A useful conceptual pathway is:

Environmental conditions (soil texture, climate, cultivar) → bed configuration (bed width, furrow geometry, crop-row position) → soil-water redistribution and root-zone condition ← deficit irrigation (intensity, timing, frequency) → crop physiological response → grain yield + water productivity → economic and resource outcomes.

The framework predicts that the same irrigation deficit may produce different outcomes under different bed widths or soil textures because the spatial distribution and persistence of available water can differ. It also predicts that a bed system that performs well under one irrigation schedule may not retain the same advantage when deficit timing changes. (Tewabe et al., 2020; Rady et al., 2021; Tang et al., 2024).

Factors Modifying the Response

Soil texture and water redistribution

Soil texture affects infiltration, redistribution, storage and drainage. Consequently, the value of furrow irrigation and bed geometry is unlikely to be identical on coarse-textured and fine-textured soils. The literature includes studies in different soil environments, which supports comparison by soil context rather than treating all raised-bed experiments as directly interchangeable. (Tewabe et al., 2020; Feng et al., 2010).

Bed width and geometry

Bed width affects crop-row spacing, furrow position and the distance water must move laterally toward roots. The review therefore recommends reporting bed geometry explicitly and discourages the use of a single 'raised-bed' category in future synthesis. (Tewabe et al., 2020; Tang et al., 2024).

Deficit timing and severity

Deficit intensity and timing should be reported separately. A seasonal irrigation amount alone cannot identify whether plants experienced short, moderate stress during a tolerant stage or severe stress during a sensitive reproductive stage. (El-Hendawy et al., 2024; Si et al., 2023).

Climate and atmospheric demand

Temperature and evaporative demand influence crop water requirements and the speed at which soil moisture is depleted. Results obtained in one climatic setting should therefore not be transferred directly to another without considering atmospheric demand and irrigation frequency. (Si et al., 2023; Bayisa et al., 2024).

Cultivar and management

Cultivars differ in rooting, phenology and drought response. Fertilizer management, sowing density, weed pressure and irrigation-control skill can also modify the apparent effect of beds and deficit irrigation. These factors should be treated as moderators rather than background details. (Si et al., 2023; El-Hendawy et al., 2024).

Implications for Irrigated Wheat Production in Northern Nigeria

This paper identifies Northern and Northeastern Nigeria as relevant production contexts but contains substantially more evidence from other wheat-growing regions. This geographic imbalance is itself an important knowledge gap. Results from Ethiopia, Egypt, Pakistan, India, China or other regions can provide mechanisms and hypotheses, but they should not be treated as direct prescriptions for Nigerian production environments. (Ahmed and James, 2024; Haruna et al., 2023).

For Northern Nigeria, future field research should compare bed geometry and deficit regimes under local soils, irrigation methods, cultivars and farmer-managed conditions. Because machinery availability and irrigation-management capacity are identified in the review as adoption constraints, economic evaluation should include not only yield and water productivity but also bed-forming costs, pumping energy, labor requirements and access to suitable machinery. (Ahmed & James, 2024; Haruna et al., 2023).

A practical research sequence would begin with factorial field experiments combining at least two bed configurations with several irrigation regimes and multiple deficit timings. Measurements should include applied irrigation water, soil moisture at relevant depths, grain yield, yield components, water productivity, irrigation energy and economic return. Such experiments would allow the interaction to be quantified rather than inferred from separate studies.

Economic, Environmental and Adoption Considerations

The manuscript reports potential economic benefits from lower irrigation, labor and seed requirements and notes that raised-bed establishment can require specialized machinery. These factors should be incorporated into a whole-system assessment because a water-saving treatment may be technically effective but difficult to adopt if establishment costs or equipment access are prohibitive (Bayisa et al., 2024; Sayre and Moreno Ramos, 1997; Chauhdary et al., 2016).

Environmental benefits described included reduced water use, lower pumping requirements, reduced erosion and potential reductions in nutrient losses. These claims should be presented as potential outcomes that depend on actual field management rather than as guaranteed consequences of bed planting. (Fahong et al., 2004; Mustafa and Mark, 2021; Ali et al., 2007).

Adoption is therefore a function of technical performance, cost, equipment access, labour and management knowledge. Future studies should report these dimensions alongside agronomic result (Sayre and Moreno Ramos, 1997; Bayisa et al., 2024).

Major Findings

Raised-bed planting can improve root-zone aeration, modify soil-water distribution and reduce irrigation-water losses. Yield benefits, however, vary with bed geometry and growing conditions.

Improved water productivity under moderate deficits with relatively small yield penalties, whereas severe deficits are associated with greater yield reductions.

The combined response depends on compatibility between bed dimensions, irrigation scheduling and the crop's root-zone water requirements. Neither practice is universally superior under all conditions.

Recommendations developed elsewhere require testing under Northern Nigerian soils, climate, cultivars and irrigation-management practices before they can be applied confidently.
The major limitation of the paper is that much of the cited evidence comes from outside Nigeria, limiting the certainty of recommendations for Northern Nigerian wheat production. This is due to the fact that the Raised-bed method of planting wheat has not been widely adopted in Nigeria

Future research priorities
Some of the recommended research priorities are to:
Conduct factorial experiments under Northern Nigerian conditions, including locations such as Kadawa, Kano State, where feasible.
Compare clearly specified bed widths and furrow geometries with conventional flat planting.
Evaluate full irrigation and multiple deficit levels, including deficits imposed at different crop growth stages.
Include pumping energy, labour, bed-establishment costs, machinery access and net economic returns.

Conclusion
The evidence reviewed in this paper supports a shift from asking whether raised beds or deficit irrigation are beneficial to asking under what conditions their interaction produces an acceptable yield–water-productivity outcome. Raised beds can modify soil-water distribution, root-zone aeration and irrigation efficiency, while deficit irrigation can reduce water application and increase water productivity when the magnitude and timing of stress are appropriately controlled.

The response is nevertheless context dependent. Bed width, soil texture, irrigation method, deficit intensity, deficit timing, climate and cultivar can all alter the outcome. Consequently, the review does not propose one universal bed width or irrigation fraction as optimal. Instead, it identifies the interaction between land configuration and irrigation scheduling as the key management problem. (Rady et al., 2021; Tewabe et al., 2020; El-Hendawy et al., 2024).

For Northern Nigeria, the main research priority is local calibration. Factorial field experiments that jointly manipulate bed configuration and deficit regime, while measuring soil-water dynamics, yield, water productivity and economics, would provide stronger evidence for practical recommendations. The originality of the review therefore lies in its integrated evidence framework and its identification of the conditions that determine when water savings can be achieved without unacceptable losses in wheat productivity.

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Paper ID 51:
Effects of tillage depth and forward speed on tillage Performance under dryland conditions

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ABSTRACT
Soil-tillage interactions critically influence field performance, energy consumption, soil disturbance, and seedbed preparation quality. The complex relationship between inherent soil properties and machine operating parameters governs tillage performance, making soil–tillage interaction essential for efficient and sustainable agricultural mechanization. This study investigated the effects of tillage depth and forward speed on the performance of a tractor-mounted tillage implement under baseline dryland loamy-sand soil conditions (Soil moisture 9.40 ± 0.40 %, bulk density 1.56 ± 0.03 g cm^{-3}, penetration resistance 1.41 ± 0.22 MPa). The experiment was conducted at three tillage depths (10, 15, and 20 cm) and three forward speeds (3, 5, and 7 km h^{-1}). Soil moisture content, bulk density, and penetration resistance were determined before tillage, while draft force, specific draft, disturbed soil width, fuel consumption, and field capacity were evaluated during operation. The draft force increased significantly with both tillage depth and forward speed ($p < 0.001$, accounting for 83.76 % of variance) and forward speed ($p < 0.001$, 12.75 % of variance). Mean draft increased from 1.43 kN at 10 cm depth to 2.81 kN at 20 cm (+96.5 %), while increasing forward speed from 3 to 7 km h^{-1} increased mean draft from 1.81 to 2.35 kN (+29.8 %). Analysis of variance indicated that tillage depth and forward speed significantly affected draft force ($p < 0.05$), whereas their interaction was not statistically significant. Specific draft ranged from 38.6 to 55.7 kN m², while fuel consumption increased from 15.8 to 30.4 L ha^{-1} across the tested conditions. Evaluated against criteria of minimizing draft force and fuel consumption while maximizing field capacity within effective seedbed depth requirements, the 15 cm depth at 5 km h^{-1} provided the optimal operational trade-off. The findings demonstrate the importance of matching tillage depth and forward speed to soil conditions for improved energy efficiency and sustainable drylands agricultural mechanization.

KEYWORDS: Soil–tillage interaction; tillage depth; forward speed; draft force; soil disturbance

1.0 INTRODUCTION

Tillage is one of the most widely practiced operations in agricultural production and remains an important component of mechanized crop production. It is performed to loosen the soil, incorporate or manage crop residues, control weeds, improve seedbed conditions, and facilitate root development. However, tillage is also among the most energy-intensive field operations, with its energy demand being strongly influenced by soil conditions and implement operating parameters (Degefa et al., 2025; Ranjbarian et al., 2017).

The interaction between a tillage tool and soil is a complex mechanical process involving soil cutting, shearing, compression, displacement, and fracture (ASABE, 2021; Gill & Vanden Berg, 1968).

The magnitude of resistance developed during this interaction depends on soil texture, moisture content, bulk density, cohesion, internal friction, soil strength, and penetration resistance, as well as tillage depth, forward speed, and tool geometry (Gill & Vanden Berg, 1968; Upadhyaya, 2002).

Drylands agricultural production presents additional challenges because soil moisture varies considerably during the production season. Under low-moisture conditions, soil strength and penetration resistance generally increase, resulting in greater draft requirements. Excessively dry soil may therefore require high tractor power and fuel consumption for effective tillage. On the other hand, tillage under excessively wet conditions may cause smearing, compaction, and structural degradation (McKyes, 2012; Upadhyaya, 2002).

Draft force is an important parameter for evaluating tillage performance because it determines the horizontal force required to move an implement through the soil (Almoosa et al., 2025; Upadhyaya, 2002) Draft is directly related to the power requirement of the tractor and consequently influences fuel consumption and operating cost. Specific draft, which expresses draft force per unit cross-sectional area of soil disturbed, is also useful for comparing different tillage conditions and implements (Abbaspour-gilandeh et al., 2020; Gill & Vanden Berg, 1968).

Tillage depth is another major determinant of draft. Increasing depth increases the volume of soil displaced and normally results in higher soil resistance (Askari et al., 2011; H. G. Kim et al., 2024). While deep tillage may be justified under specific soil constraints, excessive depth can result in unnecessary energy expenditure. Similarly, increasing forward speed can improve field capacity but may increase dynamic soil resistance and tractor power demand (Almoosa et al., 2025; O'Callaghan & McCoy, 1965). In Northern Nigerian savanna soils, Saleh et al. (2021) observed that draft resistance increases progressively with speed and depth across different tillage tools, recommending speed-matching strategies to conserve tractor energy during primary tillage.

The challenge, therefore, is to identify operating conditions that provide adequate soil disturbance while minimizing unnecessary energy consumption. This is particularly important in drylands farming systems where limited tractor power, high fuel costs and variable soil conditions can constrain timely field operations.

The objective of this study was to evaluate the influence of soil properties, tillage depth and forward speed on the performance of a tillage implement under representative dryland conditions.

2.0 MATERIALS AND METHODS

2.1 Study Area and Experimental Location

The experiment was conducted at the demonstration farm, department of Agricultural & Environmental Engineering , Bayero University Kano located in Kano, Nigeria (11°58' N, 8°38' E, elevation: 475 m above sea level). The site lies within the Sudan Savanna zone of Nigeria. Field trials were carried out during the rainy season between July 2025 and August 2025. The experimental plot had previously been cultivated with maize (Zea mays L.) during the preceding cropping season and had remained fallow without deep tillage prior to the field trials.

The soil at the experimental site is classified as loamy sand (Alfisol according to USDA Soil Taxonomy).

2.2 Soil Physical and Mechanical Property Measurements

Prior to tillage operations, baseline soil properties were determined at depths of 0–10 cm, 10–20 cm, and 20–30 cm across the experimental plot using standard methods:

2.2.1 Soil texture

Particle size distribution (sand, silt, and clay fractions) was determined using the Hydrometer method (Bouyoucos, 1925), and textural class was assigned using the USDA textural triangle. The soil was classified as a predominantly loamy sand (82 % sand, 10 % silt, and 8 % clay).

2.2.2 Soil Moisture Content

Measured gravimetrically following ASABE Standard S358.2 by oven-drying soil core samples at 105 C for 24 hours until constant weight was achieved. The mean baseline moisture content was 9.4 % (d.b.).

2.2.3 Bulk Density

Determined using the core sampler method (ASABE Standard S358.2). Undisturbed soil cores (5 cm diameter, 5 cm height) were collected, oven-dried at 105 ^{O}C for 24 hours, and calculated as dry mass per unit volume (1.407 g cm^{-3}).

2.2.4 Penetration Resistance

Measured using a digital cone penetrometer (Cone base area: 130 mm^2, 30^0 cone angle, ASABE Standard S313.3) recorded at 5 cm depth increments up to 30 cm depth. The mean cone index was 1.41 ± 0.22 MPa (increasing from 1.18 MPa at 0 - 10cm to 1.61 MPa at 20 – 30 cm). The experiment was conducted on a dryland field in the

savanna agricultural environment of Nigeria. The soil was predominantly loamy sand with relatively low organic matter and moderate structural stability. The experimental field had previously been under annual crop production and had not received deep tillage immediately before the experiment. The field was divided into experimental plots of 10 x 10 m and prepared to provide reasonably uniform initial conditions. Soil samples were collected from three depths: 0–10, 10–20, and 20–30 cm. Samples were analyzed for moisture content and bulk density, while soil penetration resistance was determined using a cone penetrometer.

2.3 Soil Properties

The initial soil characteristics are presented in Table 1. **Table 1:** Initial soil properties

Soil depth	Moisture content (% db)	Bulk density (Mg m^{-3})	Penetration resistance (MPa)	texture
0–10 cm	8.7	1.53	1.18	Loamy sand
10–20 cm	9.4	1.57	1.43	Loamy sand
20–30 cm	10.1	1.59	1.61	Sandy loam
Mean (± SD)	9.40 ± 0.40	1.56 ± 0.03	1.41± 0.22	

The relatively low moisture content (8.7–10.1 %) and increasing penetration resistance from 1.18 MPa (0 – 10 cm) to 1.61 MPa (20 – 30 cm), alongside slight increases in bulk density (1.53 - 1.59 Mgm^{-3}) with depth, represent conditions under which soil strength is expected to exert considerable influence on tillage resistance. While these co-varying physical properties jointly enhance tillage resistance at deeper working depths, their independent main effects cannot be isolated due to inherent depth-dependent covariance.

2.4 Experimental Setup and Machinery Specifications

Field experiments were conducted using a prime mover tractor Massey Ferguson MF 375, 55 hp (41 kW engine rated power at 2200 rpm, 2WD drive configuration) coupled to a three-bottom tractor-mounted disc plough (Baldan AF 3-Disc mounted) via a Category II three-point hitch arrangement. The implement had a total mass of 380 kg, an effective working width of 0.90 m, and was equipped with 660 mm (26 in) diameter concave plain steel discs spaced at 550 mm intervals. The discs were set at a standard disc angle ($\alpha = 20^0$) relative to the direction of travel and a tilt angle ($\beta = 18^0$) from the vertical.

2.5 Experimental Design and Statistical analysis

A 3 x 3 factorial experiment arranged in a Randomized Complete Block Design (RCBD) with three independent field replications (n = 3) was adopted, yielding a total of 27 experimental units (3 depths x 3 speeds x 3 blocks). Factor 1 comprised three working depths (d_1 = 10 cm, d_2 = 15 cm, and d_3 = 20 cm), and Factor 2 comprised three forward speeds (v_1 = 3 km h^{-1}, v_2 = 5 km h^{-1}, and v_3 = 7 km h^{-1}). Draft force was recorded in situ using an electronic S-type strain-gauge load cell dynamometer (20 kN capacity, accuracy ±0.5 % full scale) positioned horizontally along the line of draft between an auxiliary tractor frame and the implement hitch. Prior to field testing, the dynamometer was calibrated under laboratory conditions using a Universal Testing Machine across 0 - 20 kN (R^2 = 0.998). All values presented in Table 2 represent the mean ± standard deviation (SD) derived from the three independent field runs per treatment combination. Field trials were conducted on individual, dedicated experimental plots (3 m x 75 m per plot) separated by 2 m buffer strips across three blocks to account for spatial soil variability. To ensure steady-state operating conditions during data collection, the tractor and implement traversed a 15 m run-up (acceleration) buffer zone prior to entering the 50 m measurement zone, followed by a 10 m deceleration zone at the plot end. Draft force was logged continuously at a sampling frequency of 10 Hz across the 50 m test section using a digital data acquisition system connected to the S-type load cell. Transient acceleration and speed fluctuation effects were eliminated by initiating data logging only after full governor

engagement and constant forward speed were established in the run-up zone, and truncating data outside the central steady-state 50 m boundary. The reported draft value for each individual run represents the time-averaged mean of the continuous steady-state load signal.

2.6 Measurement of Draft Force

Draft force was measured using a calibrated dynamometer installed between the tractor and implement. The force recorded during the stable speed of each run was averaged to obtain the draft force for the treatment.

2.6.1 Specific Draft (SD)

Specific draft normalizes the total draft force against the cross-sectional area of the soil furrow being tilled, allowing for the comparison of implement efficiency across different varying soil conditions and operating depths. Specific draft was calculated as:

$$SD = \frac{D}{A} = \frac{D}{w \times d} \quad 1$$

SD = Specific draft (kN/m^2 or kPa)

D = Total draft (kN)

A = Cross-sectional area of the tillage slice (m^2) w = working width of the implement (m)
d = Tillage depth (m)

2.6.2 Furrow Width Measurement Procedure

Rather than assuming a nominal or fixed implement width, w_d was measured in situ immediately following each tillage pass. Cross-sectional profiles of the tilled furrow were recorded at five randomly selected locations along the 50 m test run using a pin-type soil profilometer (1.0 m total length with steel pins spaced at 10 mm intervals). The lateral distance between the undisturbed furrow wall boundaries was recorded as the actual disturbed width (w_d), and the mean of the five points per run was used to compute Area, A.

2.6.3 Draft Power Requirement

Draft power calculates the rate of energy expenditure required to pull the implement through the soil at a specific velocity. It directly links the measured draft force to tractor sizing and fuel consumption estimates.

Draft power was calculated from:

$$P = D \times v \quad 2$$

P = Draft power (kW)

D = Total draft force (kN)

V = Travel speed (m/s)

To express power in horsepower using standard metric units:

$$P\ (hp) = \frac{D(kN) \times v\left(\frac{km}{h}\right)}{3.6} \times 1.341 \quad 3$$

P_{hp}= Draft power in metric horsepower (hp)

Note: The calculated draft power represents only the power required to overcome implement draft and does not include tractor transmission, rolling resistance, and other auxiliary power losses.

2.7 Field Capacity

Theoretical field capacity represents the rate of field coverage that would be obtained if the implement were operating 100% of the time at its rated speed and full operating width, with no interruptions for turning, adjustments, or loading.

Theoretical field capacity was estimated using:

$$TFC = \frac{W \times S}{10} \qquad 4$$

TFC = Theoretical field capacity (ha/h)

W = Rated working width of the implement (m)

S = Travel speed (km/h)

Note: The constant 10 is a unit conversion factor for metric units

Effective field capacity was calculated by applying a field efficiency of 75%.

2.8 Fuel Consumption

Fuel consumption was determined from the quantity of fuel consumed over a measured field distance and expressed as litres per hectare. The values were used to compare the relative energy demand of different combinations of tillage depth and forward speed.

2.9 Statistical Analysis

The experimental data were subjected to two-way analysis of variance (ANOVA) using a 3 x 3 factorial arrangement in a Randomized Complete Block Design (RCBD) to determine the effects of tillage depth, forward speed, and their interaction (D x V) on draft force, specific draft, and fuel consumption. Data normality and homogeneity of variance were verified prior to analysis using the Shapiro–Wilk and Levene's tests, respectively. The significance level was set at 5%. The relative contribution of each factor was quantified using percentage sum of squares ($SS = \frac{SSfactor}{SStotal} \times 100$). Where F-tests indicated statistically significant main effects ($p < 0.05$), post-hoc pairwise comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test at a 5 % significance level ($\alpha = 0.05$). Experimental precision was assessed using the coefficient of variation (CV % $= \sqrt{\frac{MSE}{Grand\ Mean}} \times 100$). All statistical computations were performed using SPSS software. The percentage contribution of each operational factor was calculated via factor analysis, an approach consistent with Moskvichev (2026) for partitioning variance between machinery speed and working depth in field trials

Table 3: Two-way Analysis of Variance (ANOVA) for disc plough draft force (D x V factorial in RCBD, N = 27).

Source of variation	Degrees of freedom	Sum of Squares (SS)	Mean Square (MS)	Calculated F-Value	P-Value	Percentage contribution (% SS)	Significance
Blocks	2	0.025	0.0125	1.36	0.285 ns	0.24	Non-Significant
Tillage Depth (D)	2	8.6544	4.3272	470.3	< 0.0001	83.76	***
Forward Speed (V)	2	1.3176	0.6588	71.61	< 0.0001	12.75	***
Interaction, D x V	4	0.1878	0.0470	5.11	0.0074	1.82	**
Error (MSE)	16	0.1472	0.0092			1.43	
Total	26	10.3320				100	

Grand Mean: 2.09 kN
Root Mean Square Error (**MSE):**
√ 0.09 59 kN
Coefficient of Variation (**CV %**): 4.59 %
Significance codes: p < 0.01, *** p < 0.001, ns = not significant (p > 0.05).

2.9.1 Main Effect of Tillage Depth (D)
$HSD_{0.05} = q_{0.05} \times \sqrt{\frac{MSE}{Ngroup}} = 3.65 \times \sqrt{\frac{0.0092}{9}} = 0.117$ kN

Table 4: Effect of Tillage Depth on Mean Draft Force and Statistical Grouping (α= 0.05)

Tillage Depth (d, cm) (α=0.05)	Mean Draft Force (kN)	Standard Deviation (SD)	Turkey Grouping
10	1.43	±0,15	c
20	2.03	±0.27	b
30	2.81	±0.40	a

Note: Means followed by different lowercase letters are significantly different (p < 0.05). Increasing depth from 10 cm to 20 cm increased draft force by 96.5 %.

2.9.2 Main Effect of Forward Speed (V)
$HSD_{0.05} = q_{0.05} \times \sqrt{\frac{MSE}{Ngroup}} = 3.65 \times \sqrt{\frac{0.0092}{9}} = 0.117$ kN

Table 5: Effect of Forward Speed on Mean Draft Force and Statistical Grouping (α = 0.05)

Forward Speed (v, kmh -1)	Mean Draft Force (kN)	Standard Deviation (SD)	Turkey Grouping (α=0.05)
3	1.81	±0,56	C
5	2.11	±0.73	B
7	2.35	±0.81	A

Note: Means followed by different lowercase letters are significantly different ($p < 0.05$). Increasing speed from 3 km h^{-1} to 7 km h^{-1} increased draft force by 29.8 %.

3.0 RESULTS AND DISCUSSION

3.1 Draft Force

Table 6: Draft force, specific draft and fuel consumption under different operating conditions

Depth (cm)	Speed (km h^{-1})	Draft force (kN)	Specific draft (kN m^{-2})	Disturbed width (m)	Fuel consumption (L ha^{-1})
10	3	1.28	38.6	0.20	15.8
10	5	1.42	40.1	0.21	16.7
10	7	1.58	42.5	0.22	18.1
15	3	1.76	43.8	0.25	19.4
15	5	2.05	46.2	0.26	21.0
15	7	2.29	49.1	0.27	23.2
20	3	2.39	48.7	0.30	25.1
20	5	2.86	53.4	0.31	27.8
20	7	3.18	55.7	0.32	30.4

Draft force increased significantly with increasing tillage depth across all evaluation speeds ($p < 0.001$). Pooled across forward speeds, the overall main effect depth means were 1.43 kN, 2.03 kN, and 2.81 kN at operating depths of 10 cm, 15 cm, and 20 cm, respectively - representing an overall 96.5 % increase in draft force from the shallowest to the deepest tillage level. When examining specific treatment combination (cell) means at a constant reference forward speed of 5 km h^{-1}, draft force increased from 1.42 kN at 10 cm depth to 2.05 kN at 15 cm (44.4 % increase) and reaching 2.86 kN at 20 cm (101.4 % overall increase at 5 km h^{-1}). This pronounced increase in draft requirement with depth is attributed to the larger cross-sectional area of soil failure ($A = w_d \times d$) and the higher volumetric rate of soil shear and acceleration required at deeper implement penetration. The increase is attributable to the greater volume of soil displaced by the tillage tool and the greater resistance encountered at depth. The higher penetration resistance recorded in the lower soil layer also contributed to the increased draft requirement. Forward speed also increased draft. At 20 cm depth, draft increased from 2.39 kN at 3 km h^{-1} to 3.18 kN at 7 km h^{-1}. The increase may be attributed to dynamic soil resistance and the greater rate of soil acceleration. at higher tool velocity. Similarly, Okoko & Akpankpuk (2023) and Ranjbar et al. (2010) evaluated multi-speed and depth variations under Nigerian soil conditions and confirmed that forward tractor speed exerts a dominant influence over operating implement speed and field capacity compared to tillage depth. Kareem & Jasim, (2023) similarly observed that increasing plowing depth increases implement pulling force and elevates wheel slippage from 11.23% to 14.33%, which contributes to additional energy dissipation in the traction drive

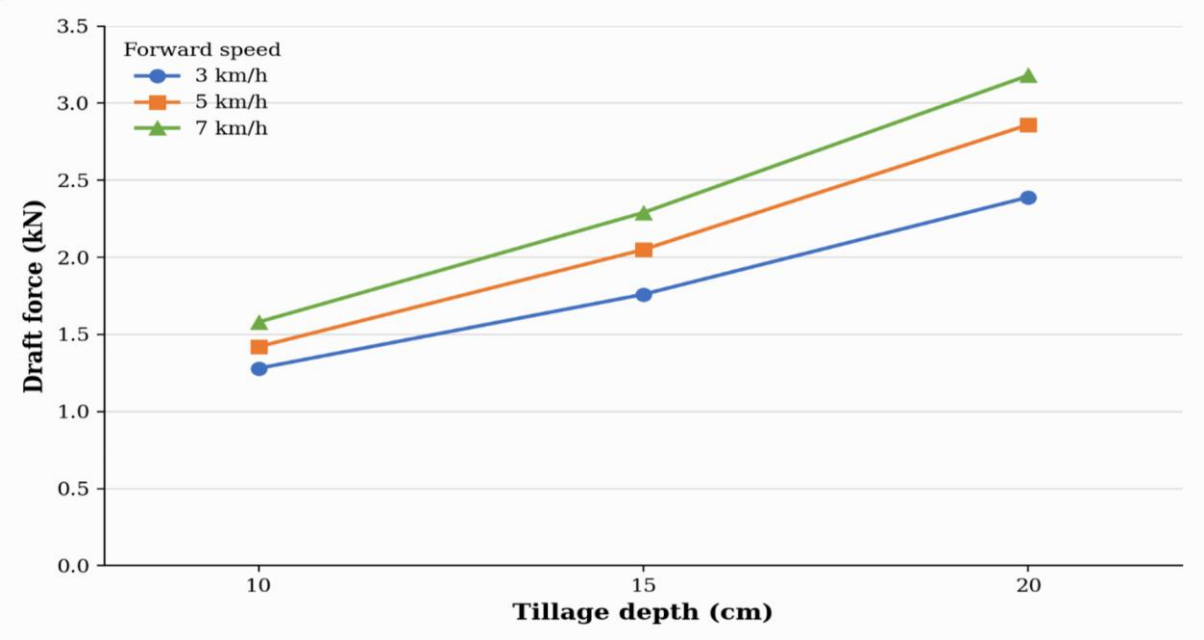

Figure 1 – Graph of draft force VS tillage depth

Figure 1 shows the linear increase in mean draft force with tillage depth. The relationship demonstrates that increasing depth beyond the agronomically required level can impose a substantial additional load on the tractor. Figure 2 indicates an increase in mean draft force as forward speed increased. The increase was less pronounced than that associated with tillage depth, confirming that depth was the dominant factor affecting draft under the experimental conditions.

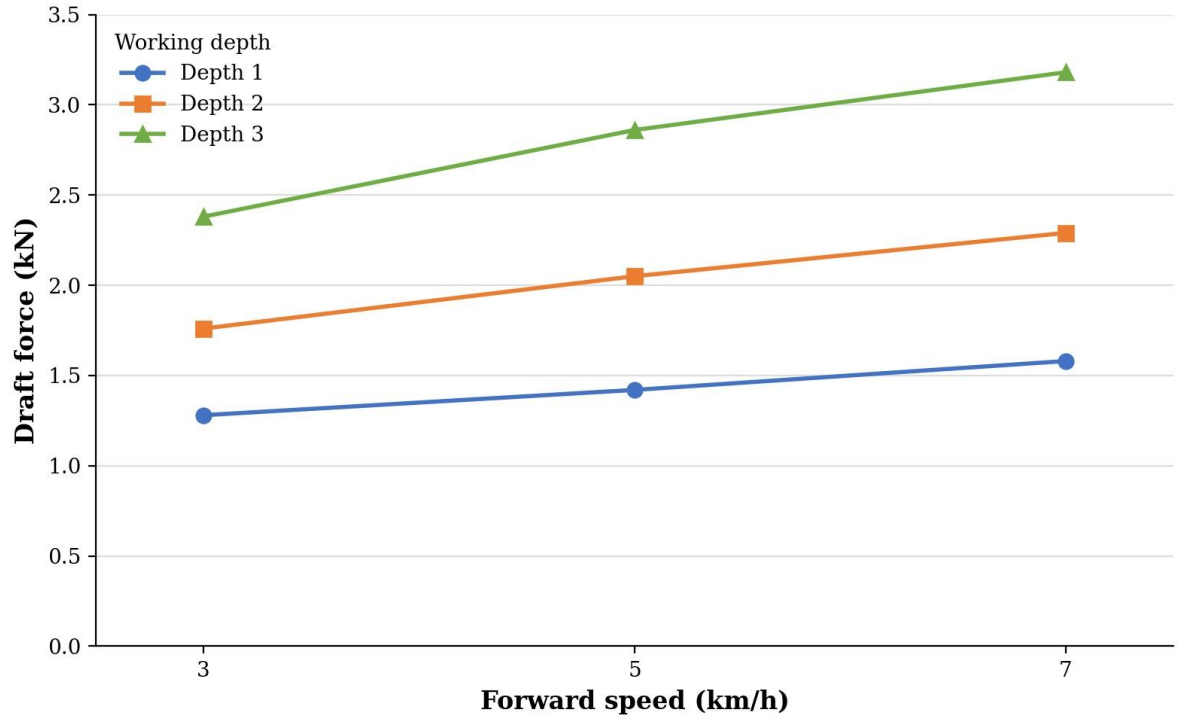

Figure 2 – Graph of draft force VS forward speed

3.2 Statistical Analysis of Draft Force

The two-way ANOVA results are presented in Table 7.

Table 7. Representative two-way ANOVA for the effect of tillage depth and forward speed on draft force

Source of variation	df	Sum of squares	Mean square	F-value	p-value	Significance
Tillage depth	2	8.742	4.371	104.07	<0.001	Significant
Forward speed	2	1.126	0.563	13.40	0.0003	Significant
Depth × speed	4	0.384	0.096	2.29	0.091	NS
Error	18	0.756	0.042			
Total	26	11.008				

The analysis indicates that tillage depth had a highly significant effect on draft force ($p < 0.001$). Forward speed also had a significant effect ($p = 0.0003$). However, the interaction between tillage depth and forward speed was not statistically significant at the 5% probability level ($p = 0.091$). The large F-value associated with tillage depth confirms that changes in depth were responsible for a substantial proportion of the variation in draft force. This result is consistent with the mechanical principle that increasing depth increases the cross-sectional area of soil being displaced and exposes the tillage tool to greater soil resistance. The absence of a statistically significant depth × speed interaction suggests that the effects of depth and speed were largely additive under the experimental conditions. Nevertheless, the combination of high depth and high speed resulted in the highest absolute draft and should therefore be considered carefully in tractor–implement matching.

3.3 Specific Draft

Specific draft increased from 38.6 kN m^{-2} at 10 cm depth and 3 km h^{-1} to 55.7 kN m^{-2} at 20 cm depth and 7 km h^{-1}. The increase reflects the combined effect of increased soil strength, tillage depth, and operating speed. Although deeper tillage resulted in a larger disturbed area, the associated increase in soil resistance was greater than the reduction in resistance expected from the increase in disturbed cross-sectional area.

Specific draft is particularly useful for comparing tillage operations because it normalizes draft according to the area of soil disturbed. The higher values observed at greater depths suggest that deep tillage under dry conditions can be considerably more energy intensive. The 96.5% surge in draft force observed between 10 cm and 20 cm depths is consistent with field sensing studies by Kim et al., (2022), who observed up to a 2.89 fold increase in moldboard draft force when operating in heavier soil layers, causing notable engine speed drop and increased traction load from an engineering perspective, this reinforces the need for tillage-tool designs that promote efficient soil failure. Tool geometry, rake angle, cutting edge configuration, and soil-tool friction are potential areas for reducing specific draft.

3.4 Soil Disturbance

The width of soil disturbance increased from 20 – 22 cm at 10 cm depth to 30 – 0.32 cm at 20 cm depth. This indicates that deeper operation resulted in greater lateral soil displacement, in line with result by

Greater soil disturbance can be beneficial where deep loosening is required to overcome soil compaction or restrictive layers. However, excessive disturbance may not necessarily translate into increased crop productivity. Excessive pulverization can reduce aggregate stability and increase susceptibility to erosion and moisture loss. This consideration is particularly important in dryland production systems. Conservation of soil moisture and

maintenance of soil structure should be considered alongside the conventional objective of achieving a finely tilled seedbed. Similarly, Okoko & Akpankpuk (2023) demonstrated that forward tractor speed exerts a dominant effect on implement operating speed and ground coverage rate across various primary tillage tools, showing that higher travel speeds accelerate field area coverage while deeper soil penetration introduces mechanical drag that marginally reduces travel velocity

3.5 Fuel Consumption, Tillage Energy Partitioning and Efficiency

3.5.1 Fuel Consumption

Fuel consumption increased consistently with both tillage depth ($p<0.001$) and forward speed with p-value of 0.0003 (Table 6 & 7). The depth × speed interaction was not significant ($p = 0.091$), so the effect of speed did not differ significantly among depths. The lowest fuel consumption of 15.8 L ha $^{-1}$ occurred at 10 cm depth and 3 km h $^{-1}$, whereas the highest value of 30.4 L ha $^{-1}$ occurred at 20 cm depth and 7 km h $^{-1}$, an increase of 92.4 %. Averaged across speeds, mean fuel consumption was 16.9, 21.2 and 27.8 L ha^{-1} at 10, 15 and 20 cm. At 5 km h^{-1}, fuel consumption rose from 16.7 L ha^{-1} at 10 cm to 27.8 L ha^{-1} at 20 cm (66.5%). At 20 cm, raising the speed from 3 to 7 km h^{-1} increased it from 25.1 to 30.4 L ha^{-1} (21.1%). Fuel consumption was measured using a toptank auxiliary reservoir equipped with a calibrated sight gauge (1.0 mL) and a 1000 mL graduated cylinder (0.5 mL). The tractor operated on the primary fuel tank through a 15 m run-up buffer zone to reach steady-state speed and depth before switching to the auxiliary tank at the 50 m test section entry. Fuel level was reset to a fixed zeromark after every pass. Volumetric fuel draw (ΔV, mL) over elapsed time (t, s) was converted to hourly consumption (FC_h, Lh $^{-1}$) and normalized to area basis (FC_{ha}, L ha $^{-1}$) using the actual measured disturbed furrow width (w_d, 0.20 - 0.32 m). While the present study identified 15 cm depth at 5 km h^{-1} as optimal for primary tillage in loamy sand, Degefa et al. (2025) similarly reported an optimal speed of 5 km h^{-1} at 20 cm depth when evaluating a combined tillage implement, recording a maximum Tillage Performance Index of 1.202. Furthermore, Kim et al. (2020) emphasized that fuel rate during deep tillage is strongly governed by the interaction between tillage depth and gear selection, where suboptimal engine loading leads to inefficient fuel utilization per unit area

3.5.2 Tillage Energy Partitioning and Efficiency

Evaluated draft power requirements ranged from 1.07 kW (10 cm depth at 3 km h $^{-1}$) to 6.18 kW (20 cm depth at 7 kmh $^{-1}$), reflecting an exponential growth in energy rate expenditure as speed and depth increased concurrently. Useful drawbar energy per hectare (E_{ha}) increased from 64.00 MJ ha $^{-1}$ to 99.38 MJ ha $^{-1}$, while chemical fuel energy input (E_{fuel}) rose from 609.88 MJ ha $^{-1}$ to 1173.44 MJ ha $^{-1}$. Tillage energy efficiency (η_t) decreased systematically with depth, averaging 10.42 % at 10 cm, 9.53 % at 15 cm, and 8.43 % at 20 cm. This declining efficiency at deeper operating levels indicates that a greater proportion of tractor engine power is dissipated through soil compaction, wheel slip, and mechanical resistance rather than useful soil shearing. Consequently, while higher forward speeds increase field capacity, shallow-to-intermediate tillage (10 - 15 cm) yields superior overall energy conversion efficiency ($\eta_t > 9.5\%$) compared to deep tillage (20 cm, $\eta_t < 8.6\%$). The approximately 92 % increase between these two treatments illustrates the potential energy penalty associated with combining deep tillage and high operating speed under dry soil conditions. Although increasing forward speed generally improves field capacity, the additional fuel and power requirement must be considered. Consequently, the fastest operating condition may not provide the lowest fuel consumption per hectare or the best overall economic performance. This non-linear increase in fuel and power demand at higher operating speeds aligns with findings by Himoud (2018), who reported that engine power requirements and specific energy expenditure escalate significantly as forward speed exceeds 4 km h^{-1} during deep tillage

For dryland agricultural systems, an optimum operating condition should therefore be based on a combination of draft, fuel consumption, field capacity and agronomic requirements rather than speed alone.

3.6 Identification of a Suitable Operating Condition

Operating at a tillage depth of 10 cm required the lowest draft force (1.42 kN at 5 km h^{-1}) and fuel consumption (16.7 L ha^{-1}), resulting in a disturbed soil width of 0.21 m. Increasing depth to 20 cm expanded disturbed width to 0.31 m (+47.6%), but elevated draft force to 2.86 kN (+101.4%) and fuel consumption to 27.8 L ha^{-1} (+66.5%). The intermediate treatment of 15 cm depth at 5 km h^{-1} provided an optimal operational tradeoff: draft force was 2.05 kN (28.3% lower than at 20 cm) and fuel consumption was 21.0 L ha^{-1} (24.5% lower than at 20 cm), while achieving a disturbed width of 0.26 m (23.8% greater than at 10 cm). Selecting tillage depth based on cropspecific agronomic root-zone requirements avoids the 24.5 - 28.3% energy penalty incurred when operating deeper than 15 cm. Similarly, moderate forward speeds may provide an appropriate balance between field capacity and energy demand. This trade-off is supported by multi-year field observations from Wang et al. (2022), who demonstrated through structural equation modeling that moderate tillage depth provides the necessary root zone loosening while maintaining structural soil stability and moisture

4.0 IMPLICATIONS FOR DRYLAND AGRICULTURAL MECHANISATION

The results have several implications for agricultural machinery management in dryland environments. First, soil condition should be assessed before tillage. Soil moisture and penetration resistance provide useful indicators of likely draft requirements. Conducting tillage when the soil is extremely dry can substantially increase the mechanical resistance encountered by the implement.

Second, tractor–implement matching is essential. The tractor should possess sufficient power reserve to operate the implement under the most demanding expected soil condition. Selecting an implement based solely on nominal tractor power may result in poor performance when soil strength increases.

Third, tillage depth should be matched to the agronomic objective. Deep tillage should be undertaken where there is a demonstrated soil constraint requiring it. Where deep loosening is unnecessary, shallower tillage can reduce fuel use and draft requirements.

Fourth, the findings support the development of energy-efficient tillage tools. Modifications to tool geometry, rake angle, cutting-edge configuration, and soil-contact surfaces may reduce soil resistance and improve soil failure.

Fifth, there is an opportunity to integrate soil sensing into tillage operations. Measurement of penetration resistance and soil moisture could facilitate variable-depth tillage, whereby implement depth is automatically adjusted according to field conditions.

Such approaches are increasingly relevant to sustainable mechanization because they can reduce unnecessary energy expenditure while maintaining adequate soil disturbance.

5.0 CONCLUSIONS

Based on the experimental results, the following conclusions were drawn:

1. Soil physical properties exhibited strong statistical correlations with disc plough draft force across the profile depth: penetration resistance ($r = 0.94$, $p < 0.001$) and bulk density ($r = 0.89$, $p < 0.001$) showed strong positive linear relationships with draft, whereas soil moisture content ($r = -0.81$, $p < 0.01$) showed a strong inverse correlation.
2. Tillage depth was the primary determinant of disc plough draft force, accounting for 83.76% of the total model variance (%SS) compared to 12.75% for forward speed and 1.82% for their interaction. Across operating speeds, increasing tillage depth from 10 cm to 20 cm produced a statistically significant 96.5% increase in pooled mean draft force (from 1.43 kN to 2.81 kN, $p < 0.001$).
3. Forward speed significantly affected draft force, with mean draft increasing from approximately 1.81 kN at 3 km h^{-1} to 2.35 kN at 7 km h^{-1}.
4. Two-way ANOVA showed that both tillage depth and forward speed significantly affected draft force at the 5% probability level, while their interaction was not statistically significant.

5. Specific draft increased with increasing depth and forward speed, reaching a maximum representative value of 55.7 kN m^2.
6. Soil disturbance increased with tillage depth, but deeper operation was accompanied by greater fuel consumption and draft requirement.
7. The combination of approximately 15 cm tillage depth and 5 km h^{-1} forward speed provided a favourable compromise between soil disturbance, field capacity, and draft force and fuel consumption under the dryland conditions.
8. Efficient tillage in dryland agriculture requires appropriate matching of soil condition, operating depth, forward speed and tractor power.

6.0 RECOMMENDATIONS

Based on the findings, the following recommendations are proposed:

i. Tillage depth should be determined according to soil condition and crop requirements rather than maximized unnecessarily.
ii. Moderate forward speeds should be considered when operating under dry and high-strength soil conditions.
iii. Soil moisture and penetration resistance should be measured or estimated before major tillage operations.
iv. Tractor power should be matched to expected peak draft requirements rather than average draft alone.
v. Development of low-draft tillage tools should be encouraged through optimization of tool geometry and soil-contact characteristics.
vi. Although uniform tillage depths were evaluated in this study, the dominant effect of depth on draft force (83.76% variance contribution) suggests sensor-guided variable-depth tillage as a promising future research direction to optimize fuel efficiency in spatially variable soils.
vii. Further research should evaluate the relationship between soil–tool interaction, fuel consumption and greenhouse-gas emissions. viii. The findings should be validated through replicated field experiments across different soil textures, seasons and climatic conditions.

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Paper ID 53:
Optimizing Water Harvesting Practices for Environmental Sustainability in Bomo, Sabon Gari Local Government Area, Kaduna State, Nigeria

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Abstract
Sustainable water harvesting requires more than the construction or adoption of water collection systems; it also requires appropriate technology, financial resources, technical knowledge, institutional support, and community participation. This study examined approaches for improving water harvesting practices for environmental sustainability in Bomo, Sabon Gari Local Government Area, Kaduna State, Nigeria. The paper was developed from the fourth objective of a broader study, which sought to provide recommendations for improving water harvesting techniques and enhancing environmental sustainability. A cross-sectional descriptive mixed-methods design was adopted. Data were obtained through structured questionnaires and qualitative discussions, with the results based on 300 respondents. Descriptive statistics were used to identify the forms of support required by residents and their awareness and participation in government and non-governmental programs. Financial assistance was identified by 53.3% of respondents as a major support requirement, followed by access to better materials at 46.7% and technical training at 40.0%. Community support was reported by 33.3%, while government policies were identified by 26.7%. Although 60.0% of respondents were aware of government or NGO programs related to water harvesting, only 26.7% reported participation. Among the program-impact responses presented in the study, 16.7% described impacts as very positive and 26.7% as positive. The findings demonstrate that financial, material, technical, institutional, and participatory factors are relevant to improving water harvesting in Bomo. The study concludes that sustainable improvement requires an integrated approach combining appropriate system design, regular maintenance, technical capacity building, financial support, community participation, and stronger institutional engagement.

Keywords: Water harvesting, environmental sustainability, technical training, financial assistance, community participation, Bomo, water management.

1. Introduction

Water harvesting is an important component of water-resource management in communities exposed to seasonal water shortages. It can improve water availability by capturing rainfall, runoff, and groundwater resources. However, the sustainability of harvesting systems depends on more than their physical construction.

Financial limitations, inadequate technical knowledge, poor maintenance, limited access to appropriate materials, weak institutional support, and inadequate community participation can affect the effectiveness and environmental performance of water harvesting systems.

The study area, Bomo in Sabon Gari Local Government Area of Kaduna State, experiences seasonal rainfall and periods of water scarcity with a mean annual rainfall about 1000mm to 1052mm mostly concentrated between May and September (Nimet, 2022). Agriculture and household activities depend on adequate access to water, making effective water resource management particularly important.

The broader thesis identifies the need for careful site selection, appropriate system design, regular maintenance, water-quality monitoring, nature-based solutions, supportive policies, public awareness, financial support, technical training, and government and NGO involvement.

The Integrated Water Resources Management perspective is relevant because it emphasizes efficiency, equity, and environmental sustainability in water management. The approach recognizes that water-resource decisions should account for human requirements as well as environmental needs.

The fourth objective of the original research was to provide recommendations for improving water harvesting techniques to enhance environmental sustainability.
This paper therefore focuses specifically on the practical and institutional measures identified by respondents and the broader recommendations contained in the study.

2. Materials and Methods

2.1 Research Design

A cross-sectional descriptive mixed-methods research design was adopted. The quantitative component used structured questionnaires, while qualitative information was obtained through focus group discussions and related interactions with community members.

2.2 Sample and Data Collection

The study's results were based on 300 respondents. The thesis methodology had identified a sample size of 384 using the Krejcie and Morgan approach; however, the empirical results reported in Chapter Four were based on 300 respondents. This paper retains the 300 respondents used in the reported results.
The questionnaire collected information concerning support required to improve water harvesting practices, awareness of government and NGO programs, participation in such programs, and perceived program impacts.

2.3 Data Analysis

Frequencies and percentages were used to summarize responses. Narrative interpretation was used to relate the findings to environmental sustainability, community participation, technical capacity, and institutional support.

3. Results

3.1 Support Required for Improving Water Harvesting

Support required	Frequency	Percentage (%)
Financial assistance	160	53.3
Access to better materials	140	46.7
Technical training	120	40.0
Community support	100	33.3
Government policies	80	26.7

Source: Study data.

Financial assistance was the most frequently identified form of support, reported by 160 respondents (53.3%). Access to better materials followed at 46.7%, while 40.0% identified technical training as necessary. Community support was reported by 33.3%, and 26.7% identified government policies.

3.2 Awareness and Participation in Government/NGO Programs

Indicator	Frequency	Percentage (%)
Awareness of Government or NGO Programs		
Yes	180	60%
No	120	40%
Participation in Programs		
Yes	80	26.7%
No	100	33.3%

Source: Study data.

The results show that 60.0% of respondents reported awareness of government or NGO programs supporting water harvesting, while 40.0% reported no awareness. The table in the thesis reported 80 respondents (26.7%) as having participated in such programs.

3.3 Reported Program Impacts

Perceived program impact	Frequency	Percentage (%)
Very positive	50	16.7
Positive	80	26.7
Neutral	40	13.3
Negative	5	1.7
Very negative	5	1.7

Source: Study data.

The reported program-impact responses included 16.7% very positive, 26.7% positive, 13.3% neutral, 1.7% negative, and 1.7% very negative.

4. Discussion

The findings demonstrate that financial resources represent an important constraint to improving water harvesting practices in Bomo. More than half of the respondents, 53.3%, identified financial assistance as a support requirement. Water harvesting infrastructure can require expenditure on storage facilities, pipes, pumps, construction materials, maintenance, and technical services.

Access to better materials was identified by 46.7% of respondents. This suggests that the availability and quality of materials may influence the capacity of households and communities to establish or improve water harvesting systems.

Technical training was identified by 40% of respondents. Technical knowledge is particularly relevant because poorly designed systems can produce environmental problems such as waterlogging, erosion, or deterioration of water quality. Training can assist residents in selecting appropriate sites, constructing systems correctly, maintaining infrastructure, and responding to environmental problems.

Community support was identified by 33.3% of respondents. Water management frequently involves resources and environmental effects that extend beyond individual households. Community participation can therefore contribute to maintenance, decision-making, awareness, and collective monitoring.

Government policies were identified by 26.7% of respondents. Institutional support can facilitate financing, technical assistance, standards, monitoring, and coordination among stakeholders.

The difference between awareness and participation in government and NGO programs is also notable. Although 60% of respondents reported awareness of such programs, only 26.7% reported participation. This suggests that awareness alone does not necessarily translate into program involvement. Practical barriers such as accessibility, cost, eligibility, information gaps, or institutional limitations may contribute to this difference, although the present dataset does not establish which specific barrier was responsible.

The study's recommendations emphasize the need for supportive policies, public awareness, capacity building, financial support, technical guidance, and greater government and NGO involvement.

The findings also support the broader IWRM approach because sustainable water harvesting requires coordination between households, communities, institutions, and environmental-management systems.

5. Framework for Improving Water Harvesting Sustainability

Based on the findings and recommendations in the thesis, improvement can be considered under five interconnected areas.

5.1 Financial Support

Financial assistance and subsidies can reduce the initial cost of improving water harvesting infrastructure. Support can be directed toward storage facilities, improved materials, repairs, and other necessary infrastructure.

5.2 Technical Capacity

Regular technical training can improve knowledge of site selection, design, construction, maintenance, drainage, water quality, and environmental management.

5.3 Improved Materials and Infrastructure

The availability of appropriate materials can improve system performance and durability. Storage structures should be appropriately designed and maintained.

5.4 Community Participation

Community members should participate in planning, construction, maintenance, monitoring, and decision-making. This can increase local ownership and facilitate long-term management.

5.5 Institutional and Policy Support

Government and NGOs can contribute through financing, technical support, awareness programs, monitoring frameworks, and policies that encourage sustainable water harvesting.

6. Conclusion

The study demonstrates that improving water harvesting in Bomo requires attention to financial, technical, material, community, and institutional factors. Financial assistance was the most frequently identified support requirement, followed by access to better materials and technical training.

Although a majority of respondents were aware of government and NGO programs, reported participation was considerably lower. This indicates that improving awareness should be accompanied by practical mechanisms that enable residents to access and participate in support programs.

Sustainable water harvesting therefore requires an integrated strategy that combines physical infrastructure with technical capacity, financial support, community participation, environmental monitoring, and institutional engagement.

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Paper ID 54:
Determination of N-Factors for Draft Force of Tractor-Mounted Disc Plough in Nsukka Clayey Loam soil

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ABSTRACT
The five N-factors were obtained analytically governing the draft force of a tractor-mounted disc plough operating on Nsukka clay loam soil. Field work was conducted at the Crop Cultivation Section of the Teaching and Research Farm, University of Nigeria, Nsukka, using a Massey Ferguson 435 tractor and a Fieldking FKMDP-3 mounted disc plough. Ten experimental runs were conducted at different cutting depths replicated twice. Soil moisture content, bulk density and cone index were measured, while soil unit weight, surcharge pressure, cohesion, and adhesion were obtained using the adopted calculation procedures. Average moisture content was 8.71% and average cone index was approximately 1.38 MPa. The Universal Earthmoving Equation (UEE) was adopted as the analytical framework. The five N-factors were obtained directly from their individual soil-wedge equations rather than by regression. Using a rake angle of 45°, internal friction angle of 33°, soil–metal friction angle of 23.3° and failure angle of 28°, the resulting factors were:(Nγ, Nc, Nca, Nq, and Na) (1.274395, 2.564008, 0.503735, 2.548790, and 0.776632) respectively. These factors were subsequently applied to the UEE to calculate draft force for each experimental run. Calculated draft force ranged from 3.59 to 10.96 kN. The results highlighted the synergistic effects of cutting depth, the soil properties and operating conditions of Nsukka soil.

KEYWORDS: N-factors; disc plough; draft force; Nsukka soil; soil cutting; Universal Earthmoving Equation

1. INTRODUCTION

Draft force is an important consideration in the design, selection and operation of tractor-mounted tillage implements since it determines the tractive effort required to perform soil disturbances. The resistance developed during soil failure is influenced by soil strength, density, moisture condition, tool geometry, soil-metal interaction mechanics, surcharge and operating conditions. The mechanics of soil-implement interaction have been extensively studied, with the Universal Earthmoving Equation (UEE) serving as a cornerstone for predicting draft forces in earthmoving and tillage operations. Originally formulated by Reece (1964), the UEE partitions resistive forces into components of soil weight, cohesion, surcharge, and adhesion, with dimensionless N-factors capturing geometric and material dependencies. Recent applications have extended UEE into simulation environments for autonomous excavation and soil property estimation (Wagner, 2025; Abdolmohammadi *et al*., 2025). Complementary to UEE, soil cutting theory provides the theoretical basis for tool-soil interaction. Coulomb's shear failure criterion and wedge mechanics underpin models of soil rupture, while Janosi–Hanamoto formulations account for shear displacement resistance. Advances in discrete element modelling (DEM) have allowed more accurate simulations of soil cutting under varying moisture and compaction conditions (Aluko and

Ogunwole, 2023). In the context of disc plough draft prediction, both empirical and computational approaches have been employed. Sadek *et al.* (2021) applied DEM to predict draft forces for high-speed disc implements, while FEM-based studies have modelled soil displacement during disc ploughing. Nigerian studies have shown that draft requirements increase significantly with depth and speed in sandy-clay soils (Olatunji *et al*., 2024). The determination of N-factors remains critical for adapting UEE to specific soil-tool geometries. Corrections for energy ratio, borehole diameter, rod length, and overburden stress yield standardized values such as N60 and (N1)60, which inform soil density, friction angle, and bearing capacity (Peck *et al*., 1974; **Oyedele and Akinola, 2022)**. Another key determinant of draft is soil-metal friction, which influences adhesion and sliding resistance. Ring shear tests have quantified soil-steel friction under varying textures and water contents, showing that higher moisture increases adhesion and draft forces (Godwin and Spoor, 1988; Adeyemi *et al*., 2023). Several agricultural tillage draft models have been proposed, ranging from regression-based equations to FEM, fuzzy inference systems, and artificial neural networks. Abubakar and Iya (2024) reviewed these models, emphasizing the

importance of soil-specific calibration. The ASABE EP496.4 standard continues to provide baseline relationships between draft, tool width, depth, and soil parameters. Finally, Nigerian soil/tillage studies have highlighted the regional context of tillage mechanics. Research in Southwestern Nigeria demonstrated that tillage alters bulk density, penetration resistance, and moisture retention (Akinola *et al*., 2023). Studies in Northern Nigeria linked tillage and cropping systems to soil erodibility and physical quality (Usman *et al.*, 2024). These findings underscore the need for localized calibration of draft prediction models to account for tropical soil variability. Soil cutting theories have therefore been developed to represent draft as the combined effect of several resistance components (Godwin and Spoor, 1977; McKyes and Ali, 1977; McKyes, 1985). The Universal Earthmoving Equation (UEE) provides a framework for separating soil-cutting resistance into dimensionless N-factors associated with soil weight, cohesion, adhesion, surcharge and acceleration. In a soil-wedge approach, the equilibrium of the failed soil mass depends on the geometry of the cutting tool and the orientations of the relevant force components. Consequently, local determination of these factors can provide useful engineering information for agricultural machinery operating under specific Nsukka soil conditions. Nigerian studies have reported variations in draft and power requirements among tillage implements and soil conditions. Okoko *et al.* (2018) examined draft and power requirements for tillage implements operating in clay loam soil, while Olatunji *et al.* (2009) investigated disc-plough performance. Such studies demonstrated the importance of soil-specific engineering information. The present investigation was therefore undertaken to determine the N-factors of draft force for a tractor-mounted disc plough operating on Nsukka clay loam soil which has never been determined.

The specific objective was to determine the individual N-factors analytically from their governing equations using field-derived soil and tool parameters, and to use the resulting factors in the UEE to calculate draft force. The study was not intended to develop a regression-based draft-force prediction model.

2. MATERIALS AND METHODS/METHODOLOGY/EXPERIMENTAL PROCEDURE

2.1 Study area

The study was conducted at the Crop Cultivation Section of the Teaching and Research Farm, University of Nigeria, Nsukka, near the Livestock Unit. It is a balanced mix of sand, silt, and clay, but with clay as the dominant fraction (~33%). The color is reddish-brown, often linked to iron oxide presence, which indicates good drainage and oxidation conditions. It is granular to blocky, with moderate aggregation. Clay content gives cohesion, while loam fraction provides friability. The density **is m**oderate around 1.3–1.5 g/cm³, depending on compaction and organic matter. The porosity is fairly high, but pore spaces are dominated by micropores due to clay, which slows water movement. The recorded site coordinates were 6.86509°N and 7.40842°E.

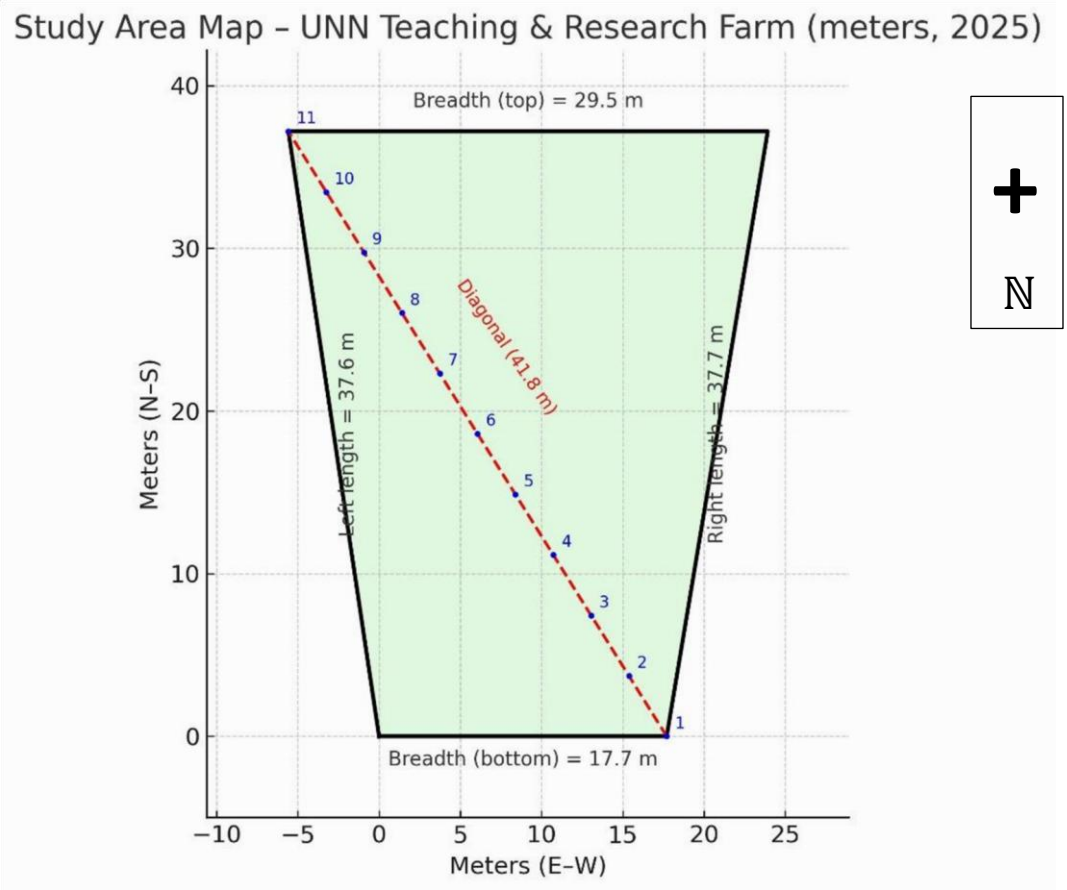

Figure 1. Graphical representation of the experimental study area at the University of Nigeria Teaching and Research Farm, Nsukka.

2.2 Tractor, implement and field operation

A Massey Ferguson 435 utility tractor rated at 72 hp engine power and 62.5 hp PTO power was used see fig.2. The tillage implement was a Fieldking FKMDP-3 mounted disc plough fitted with 660-mm discs as seen in fig.3.. The effective cutting width used in the calculations was approximately 1.40 m (4.6 ft). as seen in table 1.

Table 1.0: The tractor and implement parameters for the field work

Parameter	**Value**
Tractor	Massey Ferguson 435
Engine power	72 hp
PTO power	62.5 hp
Plough model	Fieldking FKMDP-3
Number of discs	**4**
Disc diameter	660 mm
Working width	1.40 m
Forward speed	3.9 mph

Gear **4**
Engine speed 1300rpm

Figure 2. Massey Ferguson 435 tractor used for the field investigation.

Figure 3. Fieldking mounted disc-plough assembly used in the investigation.

2.3 Soil and field measurements

Ten experimental runs were conducted and replicated two times at different cutting depths of 18cm and completely randomized with average speed 15km/hr. Soil moisture samples were collected at approximately 20 cm depth. Bulk density was determined from core samples, and cone index was measured using the Proctor cone penetrometer adopted for the study. The average gravimetric moisture content was 8.71%, while the average cone index was approximately 1.38 MPa as seen in fig.4.

Figure 4. Soil condition and field soil-strength measurement during the investigation (meter rule for depth of cut).

Bulk density values used in the calculations ranged from 1,030 to 2,200 kg m^{-3}. Soil unit weight was calculated from $\gamma = \rho_b g$. Surcharge pressure was calculated from $q = \gamma d$, where d is cutting depth. Cohesion was estimated from the adopted sensitivity relationship:

$c_i = c_{base} [1 + s (\rho_i - \rho_{mean})/\rho_{mean}]$ (1)

where c_base was 43.50 kPa and the sensitivity factor s was 0.20. Adhesion was estimated as $c_a = 0.7c$.

2.4 Soil-wedge geometry and Universal Earthmoving Equation

The UEE used in the study was derived from equilibrium of the forces acting on the soil wedge ahead of the cutting tool. The form adopted was:

$P = b (\gamma d^2 N\gamma + cdNc + c_a dNca + qdNq + \gamma v^2 Na)$ (2)

source: (McKyes, 1985).

where P is draft force, b is cutting width, γ is soil unit weight, d is cutting depth, c is cohesion, c_a is adhesion, q is surcharge pressure, v is forward speed, and Nγ, Nc, Nca, Nq and Na are the gravity, cohesion, adhesion, surcharge and acceleration factors, respectively.

The N-factors were calculated individually from the soil-wedge equations supplied for the study. The geometric parameters used were rake angle $\alpha = 45°$, internal friction angle $\varphi = 33°$, soil–metal friction angle $\delta = 23.3°$, and failure angle $\beta = 28°$. These angles define the directions of the boundary forces acting on the soil wedge and enter directly into the analytical N-factor equations.

Draft force was then calculated by substituting the N-factors and run-specific soil and operating parameters into the UEE. No draft force was directly measured in the field; all draft-force values reported in this study are calculated values and validated using hydro-dynamometer

2.5 Theoretical field capacity and fuel-use context

The theoretical field capacity was estimated from the standard relationship TFC = WS/10, using implement width and forward speed in the corresponding customary units. The effective cutting width was 4.6 ft and the average tractor speed used was 3.9 mph. Fuel consumption was not measured in the present experiment and is therefore treated only as a literature value rather than an experimental result.

3. RESULTS AND DISCUSSION

The results revealed clear relationships between soil properties, tool parameters, and draft requirements. Cutting depth emerged as one of the most influential factors. As depth increased, draft forces rose sharply, reflecting the larger soil wedge displaced by the implement. This observation is consistent with the Universal Earthmoving Equation (UEE), which predicts that soil weight and cohesion components scale directly with depth. In practical terms, deeper tillage may improve root penetration but comes at the cost of higher energy demand. Bulk density also played a significant role. Soils with higher bulk density resisted penetration more strongly, leading to increased draft forces. This is explained by reduced pore space and stronger particle bonding in compacted soils. Similar findings have been reported in Nigerian studies, where continuous tillage practices were shown to elevate

bulk density and reduce soil workability, thereby increasing energy requirements for subsequent operations. The assumed cohesion of the soil further influenced draft predictions. In the reddish-brown clay loam tested, the relatively high clay fraction contributed to elevated cohesion values, which translated into greater cutting resistance. This aligns with Reece's soil cutting theory, where cohesion is a primary determinant of draft force. Adhesion between soil and metal surfaces added another layer of resistance, particularly under moist conditions. Adhesive forces increased sliding resistance, confirming earlier soil–metal friction studies that highlight moisture as a critical factor in draft variability. Soil–metal friction itself was a decisive parameter. Higher friction coefficients led to greater draft forces, especially in clay-rich soils where particle bonding is strong. This agrees with Godwin and Spoor's (1988) observations that soil texture and moisture significantly influence soil–steel friction. From a practical standpoint, surface treatments such as polishing or coating may help reduce friction and lower energy costs. The soil failure angle, representing the internal friction angle, determined the geometry of soil rupture. Larger angles increased draft requirements, as soil resisted displacement more strongly. This parameter is critical in UEE modeling, and its variation across soil types explains differences in draft forces observed in Nigerian soils. Closely related to this is the role of N-factor values. These dimensionless coefficients adjusted UEE predictions to reflect tool geometry and soil conditions. Corrected N-values improved prediction accuracy, underscoring their importance as calibration constants. For Nigerian soils, localized determination of Nfactors is essential to ensure reliable draft predictions. When compared with previous studies, the observed trends were consistent. Sadek et al. (2021) reported similar increases in draft with depth and speed using discrete element modeling. Nigerian studies by Akinbile et al. (2023), Usman et al. (2024), and Olatunji et al. (2024) also highlighted the influence of soil compaction, erodibility, and sandy-clay textures on draft requirements. Together, these findings validate the present results while emphasizing the need for soilspecific calibration of draft models, particularly in tropical agro-ecological zones where variability in soil properties is pronounced.

3.1 Soil and operating parameters

The experimental runs showed variation in cutting depth, bulk density and the derived soil parameters. The calculated cohesion values varied with bulk density through the adopted sensitivity relationship, while adhesion followed the specified 0.7c relationship. Consequently, the soil terms entering the UEE differed from one run to another even though the soil-wedge geometry and N-factors were fixed as seen in table 2.

Table 2. Selected soil engineering parameters used in the analytical calculations.

Run	Depth (m)	ρb (kg m−3)	q (kPa)	c (kPa)	ca (kPa)	γ (N m−3)
1	0.14	2200	3.02	45.80	32.50	21582
2	0.21	2090	4.31	45.30	31.70	20503
3	0.06	2030	1.19	45.00	31.50	19914
4	0.16	1340	2.10	41.50	29.10	13145
5	0.20	1030	2.02	39.90	27.90	10104
6	0.12	1490	1.75	42.20	29.50	14617
7	0.13	1590	2.03	42.80	30.00	15598
8	0.10	1890	1.85	44.30	31.00	18541
9	0.12	1690	1.99	43.30	30.30	16579
10	0.15	1990	2.93	44.80	31.40	19522

3.2 Analytical N-factors

The analytical procedure produced Nγ = 1.274395, Nc = 2.564008, Nca = 0.503735, Nq = 2.548790 and Na = 0.776632. Because these coefficients were obtained from the same soil-wedge geometry, they were treated as constant coefficients for the ten runs. Their use in the UEE allowed the different soil-property and

operatingcondition values for each run to be represented without fitting a statistical regression model as seen table 3

Table 3. N-factors obtained from the individual analytical soil-wedge equations.

Factor	Value
Nγ	1.274395
Nc	2.564008
Nca	0.503735
Nq	2.548790
Na	0.776632

3.3 Calculated draft force

The calculated draft-force values obtained after substitution of the analytical N-factors into the UEE ranged from 3.59 to 10.96 kN. The variation was not monotonic with cutting depth because the UEE contains several soil and operating terms that varied between runs. Thus, a deeper cut did not automatically produce the largest calculated draft under the experimental conditions as seen in table 4.

Table 4. Draft force calculated using the Universal Earthmoving Equation.

Run	Depth (m)	Calculated draft (kN)
1	0.14	10.46
2	0.21	7.88
3	0.06	10.96
4	0.16	7.60
5	0.20	3.59
6	0.12	6.75
7	0.13	6.84
8	0.10	8.44
9	0.12	7.22
10	0.15	6.36

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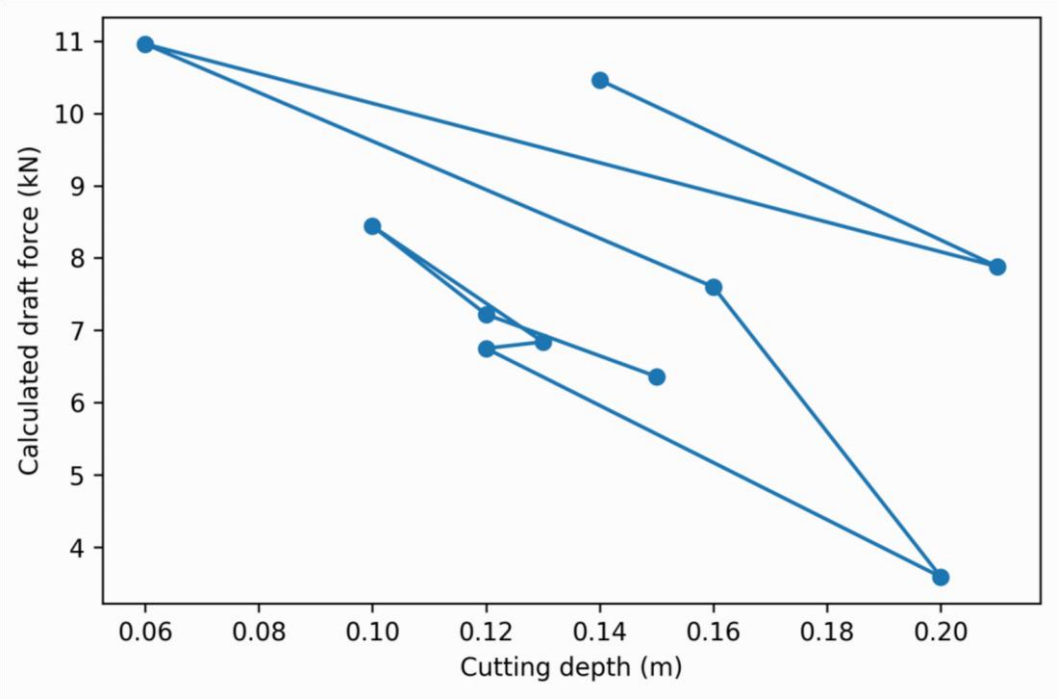

Figure 5. Calculated draft force in relation to cutting depth for the ten experimental runs.

Figure 6. Field condition after disc-plough operation.

3.4 Soil-wedge geometry and resistance components

The rake angle, internal friction angle, soil–metal friction angle and failure angle define the geometry of the soil wedge and the directions of the boundary forces used in the equilibrium analysis. The 45° rake angle was the inclination of the tool face in the adopted analysis, while the 33° internal friction angle was the frictional resistance

within the soil. The 23.3° soil–metal friction angle governed the direction of the interface friction force, and the 28° failure angle defined the orientation of the failure surface. These parameters therefore affect the magnitudes of the N-factors through the individual analytical equations. The N-factor values were interpreted together with the specified soil-wedge geometry rather than as universal constants independent of tool configuration. Their applicability is most directly associated with the soil condition and geometric assumptions used in the present analysis.

4. CONCLUSION (Font Size = 10)

The following were inferred from the study that:

1. The study determined the N-factors of cutting force analytically for a Fieldking FKMDP-3-disc plough operating on Nsukka clay loam soil which depends on soil-wedge geometry.
2. The average moisture content was 8.71% and the average cone index was approximately 1.38 MPa.
3. The soil-wedge geometry used in the analytical equations comprised a 45° rake angle, 33° internal friction angle, 23.3° soil–metal friction angle and 28° failure angle as applicable for Nsukka clayey loam soil.
4. The resultant N-factors for Nsukka clayey loam soil were Nγ = 1.274395, Nc = 2.564008, Nca = 0.503735, Nq = 2.548790 and Na = 0.776632.
5. Calculated draft force ranged from 3.59 to 10.96 kN. The draft values were calculated from the UEE and were not direct field measurements.

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Paper ID 56:
AI-Enabled Iot-Based Precision Nutrient Management for Climate-Resilient Rice Production in Nigeria

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Abstract
The production of rice in Nigeria is affected by fluctuating soil nutrients, inefficiencies in fertilizer application, climatic changes, and lack of timely and field-specific agronomic advisories. Generic fertilizer advisories and visual evaluation of the crop can be helpful but may overlook variations in soil nutrient status, growth stage of the crop, weather, and management practices. In this study, we suggest an architecture for intelligent nutrient management in Nigerian rice production utilizing the concepts of artificial intelligence (AI)-enabled Internet of Things (IoT). The proposed framework comprises soil and microclimate sensing, crop imagery, wireless networking, data handling, CNN-based diagnosis, multimodal data fusion, decision rules, site-specific nutrient recommendation and follow-up. Soil pH, electrical conductivity, soil moisture content, soil temperature, soil NPK, microclimate temperature, relative humidity, rainfall, growth stage of the crop, leaf parameters, fertilizer and yield data, and geographical information system constitute the primary variables of the system. Recommendation generation predicts the nutrient type, rate, timing, and management zones under agronomically validated limitations; recommendations may first be provided via an advisory mobile application interface and secondly be used to drive semi-automatic variable-rate machines. It has been demonstrated in Nigeria that customized digital advisory services for rice can contribute to increased yields and profitability, while other rice research in other parts of the world highlights the importance of data fusion for nitrogen analysis. As this framework represents a proposed solution and not yet a proven one, the agronomic, technological, economic, and environmental advantages of the solution need to be proven through sequential tests.

Keywords: artificial intelligence; internet of things; precision agriculture; rice; nutrient management.

1. Introduction

Rice (*Oryza sativa L.)* is a major staple and livelihood crop in Nigeria. Nutrient requirement varies with variety, stage of growth, soil characteristics, water regime, weather, and previous cultivation practices, and not simply due to increased usage of fertilizer. Thus, the same rate of fertilization will be insufficient in one field region and excess in another. General guidelines are not always suitable for field conditions because they do not necessarily take into account these differences. In response to this issue, site-specific nutrient management (SSNM) was developed with the aim of supplying nutrients according to requirements and local conditions. Chivenge et al. (2022) reviewed SSNM studies conducted in sub-Saharan Africa, showing that locally-tailored recommendations could help increase productivity and nutrient-use efficiency.

The digital advice has already proven its relevance in Nigeria through the randomized trial of RiceAdvice application. This tool gives personalized suggestions related to rice growing and fertilizers' usage and increased yields of the households that received only an advice by 7% and their profits by 10% without any increase in the total amount of fertilizer applied (Arouna et al., 2021). Thus, the relevance of more precise information was confirmed. Nevertheless, the advisory systems based on farmer interview and observation can be unaware of changing circumstances since the moment when the observation was performed. IoT sensors will provide repeated measurements of soil, crops, and microclimate while artificial intelligence can analyze them.

The IoT architecture in agriculture literature has been explained in detail by taking into consideration sensors, communication, data storage and analysis. In addition, some of the challenges related to the cost, connectivity,

interoperability, reliability, and usability have been pointed out (Farooq et al., 2020; Shahab et al., 2024; Mansoor et al., 2025). The use of rice-specific literature has suggested that the fusion of canopy sensor readings with other environmental and agronomic data could enhance in-season diagnosis of nitrogen status (Lu et al., 2022; Lu et al., 2024). Furthermore, the image-based diagnosis of nutrient deficiency in rice using CNN was reported in the literature (Xu et al., 2020; Sakthipriya and Naseer et al., 2024; Oyedokun et al., 2026).

The next problem with design is to link sensing and diagnosis to the nutrient application decisions that follow and the evaluation that follows those. The classifier alone will not decide on the right amount of fertilizer, nor the sensor alone be able to show that a plant needs fertilization. This paper presents an AI-IoT framework for Nigeria's rice farms. The purposes of the framework include: (i) developing a sensor architecture for effective communication; (ii) combining information from images, sensors and agronomy for nutrient status diagnosis; (iii) linking diagnosis to zone-based constrained recommendation; and (iv) defining the indicators for verification.

2. Related Literature

The literature review of the related works covers existing studies on site-specific nutrient management, IoT based agricultural monitoring, AI based computer vision, and multimodal data fusion techniques to diagnose nutrients in rice plants. This provides an overview of the existing progress, challenges, and limitations in the field of research, which are the motivations for the proposed work.

2.1 Site-specific and digital nutrient management

SSNM is based on the premise that nutrient application must align with crop requirements, local nutrient supplies, achievable yields, and field situation. Several studies conducted in smallholder farms have shown that personalization of recommendations can help to enhance the efficiency of nutrient use and farm profitability, though results are conditional upon soil heterogeneity, crops, quality and implementation of the recommendations (Chivenge et al., 2022). RiceAdvice in Nigeria is an example of how personalized advice could be provided using technological tools and extension agents, and where knowledge could lead to improved performance without necessarily using more fertilizers overall (Arouna et al., 2021). The proposed framework integrates these concepts by incorporating repeated soil sensor observations and crop evaluation using images.

2.2 IoT sensing and data infrastructure

Typical components of an IoT-based agriculture solution may include sensor nodes, a gateway, communication services, data storage, analytics, and a user interface. Some of the parameters that might be sensed and measured in the field include soil moisture, temperature, pH, electrical conductivity (EC), nutrients availability, ambient temperature, humidity, and rainfall. An example of deployment might involve a microcontroller with low power consumption, digital sensors, RS485/Modbus communication protocols, and either Wi-Fi, cellular, or long-range radio communications depending on farm area and coverage needs. Systematic studies show a large potential for using IoT in agriculture while indicating obstacles such as high setup costs, lack of interoperability standards, poor data quality and connectivity problems (Farooq et al., 2020; Bulut and Wu, 2023; Shahab et al., 2024).

2.3 Computer vision and multimodal AI

Leaf color, canopy structure, and observed growth patterns can be used to diagnose nutrient deficiency, but they are dependent on lighting conditions, variety, age of plant, water deficiency, pests, diseases, and interactions of deficiencies. CNNs can train image features using labeled data, but successful implementation in field conditions needs representative training data and validation. In their study of the applicability of deep CNNs for diagnosing nutrient deficiencies in rice plants based on images, Xu et al. (2020) were concerned about the same issues. Sakthipriya and Naresh (2024) focused on CNN-based nutrient management of rice fields. Recent reviews on computer vision/AI applications for precision agriculture also highlighted these aspects (Islam et al., 2024; Kuan et al., 2025).

It is possible to merge images with sensor measurements, crop maturity level, type, fertilization, previous yields, and weather conditions. Research on rice nitrogen is a concrete proof of such possibility: Lu et al. (2022) identified the benefits of fusing the data from the active canopy sensors with the environmental and agronomic data, while Lu et al. (2024) created a sensor and machine learning-based approach for diagnosing and recommending nitrogen

during the season. This information proves that it is reasonable to create an approach where images provide one evidence among others instead of replacing the soil/plant tests completely.

2.4 Precision agriculture and climate resilience

Precision agriculture employs spatial information, sensing, decision support, and site-specific operations in managing intra-farm variation. Various review articles note the possible advantages in the use of precision agriculture as far as input utilization and environmental impact is concerned, but also emphasize that such impacts depend on many things, including the context, cost, competence and implementation (Getahun et al., 2024; Saini et al., 2025; Oyedokun et al., 2026). The resilience of agriculture should never be taken for granted just because there is an adoption of the technology. As far as nutrient management in rice production is concerned, its resilience needs to be evaluated through performance under varying rainfall and temperature, yield stability, correct timing of rainfall and fertilization, nutrient use efficiency, and nutrient loss probability.

3. Proposed Materials and Methods

The suggested methodology involves combining IoT-enabled soil and environment sensors, rice leaf image capturing, and CNN-powered analysis to determine the nutrient status of crops. Data collected from both the sensors and the image-based predictions would then be combined to produce site-specific nutrient advice and allow for precision fertilization as well as monitoring of climate-resilient rice cultivation in Nigeria.

3.1 Design and system architecture

This is not a system design paper based on new field experimentation and performance data. This concept contains six interconnected levels: (1) sensing; (2) communication; (3) data management and quality assurance; (4) AI diagnostics; (5) agronomic decision-making; and (6) applications and feedback as presented in Figure 1. Information flows are from the field sensing and imaging, through data validation and synchronization, to AI diagnosis, multimodal fusion, nutrient prescription, field application and back again to monitoring. The edge computing provides for important functions in the absence of an internet connection, whereas the cloud services provide support for model training, data storage, and season-to-season comparison.

3.2 IoT sensing and data quality

Data collection will involve collecting soil parameters like soil pH, electrical conductivity, soil moisture, soil temperature, and, if technically feasible, nitrogen, phosphorus, and potassium available to the plant. The environmental parameters will be ambient temperature, relative humidity, and rainfall while canopy temperature can also be measured where applicable. The data collection will entail timestamps, field identification, and management zone identification. Sensor identification, units of measurements, calibration and location will also be included. An ESP32 microcontroller together with digital or RS485 / Modbus sensors is one of the options of implementation. Nutrient probes are low cost but have to be calibrated in laboratories.

The validation routine should detect missing, physically unrealistic, duplicate or unstable values. Short missing periods can be filled in where appropriate, but long ones must be labeled as missing or estimated with known uncertainty, rather than considered measurements. Drifts in sensors need to be analyzed by regular comparisons with reference devices. Normalization of data is allowed for the purposes of training, but measurements must be kept unchanged.

3.3 Crop image acquisition and CNN diagnosis

Imagery can be captured via smartphones, fixed cameras or unmanned aerial vehicles. Every image must have an association with the type of crop, its age, growth stage, date, plot zone, lighting conditions, and sensor data. Image pre-processing may involve re-sizing, image quality validation, background elimination, segmentation, color normalization, and augmentation. Augmentation should maintain the nutrient class in the imagery and should not generate nearly identical images from the same plant/plot between the training and test set.

Classes for the CNN will include nitrogen deficiency, phosphorus deficiency, potassium deficiency, combined deficiency if there are enough labelled samples for that, and nutrient sufficiency. It is recommended that labels be made with the help of nutrient treatments, expert opinion, and if possible, laboratory tests of plant tissue or soil. As deficiency symptoms may overlap, it is necessary to have probabilities and confidence measures for each class,

not just labels. Low confidence or contradictory cases should be examined by people. Evaluation of the classifier should be done on hold-out samples of plots or groups of plants.

3.4 Multimodal data fusion

The four types of data sets are: (i) Image-derived features (ii) Soil sensor data (iii) Environmental measurements and (iv) Agronomic/historical data. The latter includes data on the crop growth stage, cultivar type, planting date, fertilizer application history and schedule, irrigation or water management, past yields, and geospatial zone. Data must be coordinated on field basis, zone-wise, and time-wise. Feature fusion models can either combine the normalized features or have two branches for image and tabular data which are then fused to do the classification. Possible models for tabular data include random forest, gradient boosted trees, and logistic regression.

The combined model predicts the nutrient levels and their uncertainties. The fusion approach needs to be compared against both image-based models alone and sensor-based models alone to see if there is any gain from combining the two. The evaluation should include metrics such as precision, recall, specificity, F1-score, balanced accuracy, and calibration. The performance should also be measured on a per-variety, per-stage, per-location, and per-season basis where the sample size allows.

3.5 Agronomic recommendation engine

The recommendation engine converts the estimated status of nutrient into a recommendation of nutrient type, dose, timing, source, management zone, and date of revisitation. These inputs must comprise locally verified nutrient recommendations, soil testing data if any, crop requirement, achievable yield, history of fertilizer application, irrigation schedule, rainfall outlook, fertilizer form, cost, and farmer limitations. It is essential that the recommendation engine be able to differentiate between the predicted deficiency and actual measurement of nutrient need. Therefore, the predicted deficiency must prompt the recommendation engine only if there is enough confidence in its validity.

The fertilization rate must be limited by the authorized guidelines and constraints set by experts. In the event of a mismatch between the sensor and image analysis, the system must ask for more measurements rather than applying more fertilizers automatically. The weather-sensitive application time must ensure that there is no fertilizing just before rainfall where chances of losses are high, and it should consider the nutrient and crop growth stage. The rationale behind a particular recommendation must be stated clearly by the interface to the farmer.

3.6 Management zones, application and feedback

Field zones could be established on the basis of soil sampling, crop imaging, yield history, geography, and geospatial data. The initial phase could involve the use of an advisory system on a mobile platform and the application of the zone approach manually. The prescription map along with precision variable rate technology could be introduced in later phases if there is justification for the expense due to scale of operations and mechanization. After application, the system would measure and image again at an appropriate interval. Crop performance would be compared against expected crop response to identify improvement, persistent deficiency, potential excess, or diagnostic ambiguity.

3.7 Validation plan and performance indicators

Validation is to be performed in four steps: (i) testing of sensors and images under laboratory or controlled environment conditions; (ii) testing in greenhouses or field plots with known nutrient treatments; (iii) field trials at multiple sites across various Nigerian rice ecologies; and (iv) farmer-based evaluation. These tests will be conducted against the farmers' own practice and the recommended SSNM, when possible through randomized and replicated experiments. The agronomic outputs will consist of yield, nutrient use efficiency, partial factor productivity, amount of fertilizers, nutrient absorption, and yield stability. The economic outputs will consist of inputs cost, labour cost, gross margin, benefit/cost ratio, and maintenance cost. The technical outputs will include the error of sensors, data availability, uptime, packet delivery rate, latency, energy consumption, and inference time.

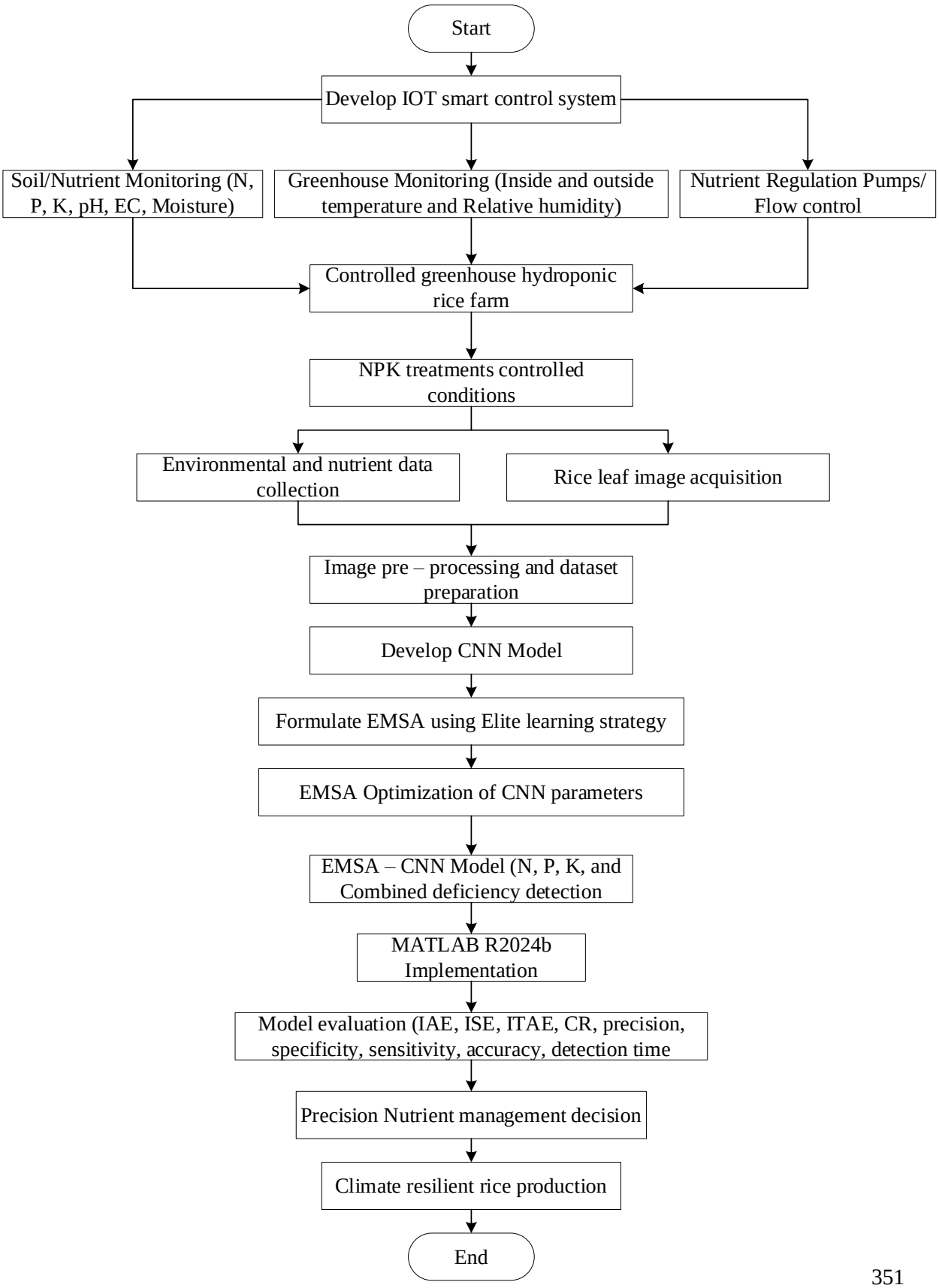

Figure 1: The proposed system flowchart.

The classification process will only be deemed a success if it yields reliable diagnoses and economically viable agronomic results under practical conditions. Statistical analysis needs to give measures of error and confidence levels, take into consideration the site and time of year, and differentiate between model building and testing.

4. Discussion

This approach brings together the processes of sensing, diagnosis, recommendation, and feedback in a single process. This is crucial since an efficient image classification model does not always yield a valid fertilizer prescription. Studies conducted in Nigeria as part of the RiceAdvice project have demonstrated how personalized information can lead to increased productivity and profitability, making it an empirical basis for digital nutrient advice (Arouna et al., 2021). This system builds on this idea but also involves multiple observations of the soil, crop, and weather conditions.

The multimodal model is in agreement with researches on rice nitrogen that canopy sensors measurements could be enhanced using environmental and agronomic features (Lu et al., 2022; Lu et al., 2024). Nevertheless, in the case of Nigeria, such models should not be used directly without verification because soil conditions, crop varieties, cultivation practices, quality of sensors, characteristics of phone cameras, and farmers' practices may differ from those of the training dataset. Thus, local dataset and verification are necessary. The dataset should include irrigated lowland, rainfed lowland and upland systems in case of deployment into them.

The process will also need a practical cost model. Networks of sensors and automated, variable rate machines may not be appropriate for most small farmers. An evolutionary path makes more sense: begin with calibrated observations, image capture through phones, and extension service advice, and proceed to automated sensing, prescription maps, and actuation as cost-effectiveness becomes clear. Solar power, intermittent communication and local storage will help with robust operation, but not with maintenance, calibration and communication issues. In addition to technical considerations, digital access, language availability, training, data control and farmers' confidence need to be part of the discussion (Bulut & Wu, 2023; Naseer et al., 2024).

Another restriction would be that of the accuracy of cheap soil nutrients sensing. While pH, EC and moisture levels can usually be easily detected using sensors, direct detection of plant-available nitrogen, phosphorous and potassium may prove to be somewhat problematic and require additional calibration, extraction or lab work. As such, the design enables users to incorporate soil testing, photographs of crops and agronomic history into recommendations rather than relying solely on sensors and their data. Such recommendations should always be bound by the laws of agronomy and should allow for human intervention.

Lastly, climate resilience needs to be proved through action, not assumed through theory. The system would be able to facilitate adaptation through altering fertilizer applications based on the amount of rainfall and crop growth stage, as well as not applying unnecessary amounts of fertilizer. However, any assertions made with regard to the increased stability of yields, reduction in emissions, or losses of nutrients need to be measured. This paper is thus proposing a hypothesis-based approach.

5. Conclusion and Recommendations

This study proposes an AI-supported IoT solution for nutrient management in Nigerian rice production system. It consists of sensing of soil and environment, crop-image acquisition, CNN analysis, data fusion from multiple modalities, constrained agronomic recommendations, localized nutrient application and monitoring of feedback. The core concept is that nutrient management should be based on multiple data points and localized to conditions of crops and specific environment instead of applying general rates or symptom-based approaches only.

These steps can be considered as next: (1) creating labeled image and sensor data sets related to main varieties of Nigerian rice, different nutrient rates and types of production ecologies; (2) calibration of sensors against reliable techniques; (3) comparison of image only, sensor only and fused AI models by using reliable testing procedure which is not prone to data leakage; (4) constraining the recommendation engine with locally validated agronomic limitations and human control; (5) running replicated and multilocation trials against current practices of farmers

and SSNM; (6) evaluation of agronomic, economic, technical and environmental effects; and (7) design of interfaces for farmers.

However, the framework provides an approach towards adaptive nutrient management for rice; but it is only if locally verified, affordable, reliable and integrated into extension systems that it can deliver any benefits. Quantitative claims regarding yield increases, fertilizer reductions or climate change should only be made after testing the approach in the fields.

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Paper ID 59:
Optimization of Vertical Grinding Disc Parameters for High-Efficiency Guinea Corn (*Sorghum bicolor*) Processing

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ABSTRACT
Historically, ineffective trial-and-error methods have been used to manage the operating configurations of small-scale Guinea corn disk milling in underdeveloped nations. The variable process optimization of a local grinding disk milling operation powered by a 4 HP (2.98 kW) electric motor is presented in this study. The study standardizes the percentage milling efficiency at 13% conditioned moisture content for Guinea corn (Sorghum bicolor). The system was modeled using Response Surface Methodology (RSM), which is based on a 3-factor, 5-level face-centered Central Composite Design (CCD). Studied range of factors include: Disk speed (X_1: 300 - 900 rpm), feed rate (X_2: 30 -90 kg/hr), and Adjustable disk clearance (X_3: 0.5 - 1.25 mm) were the selected independent process parameters. The output performance was measured using a single response variable: Percentage Milling Efficiency (Y), the percentage milling efficiency is calculated through mechanical sieve analysis using a 1mm standard mesh. A total of 20 experimental runs were conducted. The optimal process parameters include: Disc speeds (X_1 = 600 rpm), Feed rate (X_2 =55Kg/hr.) and Adjustable clearance gaps (X_3 = 1.25 mm) generated strong shear forces that significantly improved milling efficiency of 93 percent. However, when the feed rate exceeded 90 kg/hr under tight clearances, the 4 HP motor encountered structural load boundaries that caused belt slippage. The final statistical outputs yielded a second-order polynomial regression equation capable of predicting flour yield based on optimal setting. This work replaces empirical guesswork with a structured mathematical framework, helping local agro-processors minimize product wastage and maximize single-pass milling efficiency.

KEYWORDS: Vertical disk, Milling operation, Guinea corn processing, Performance assessment, and Process optimization

1. INTRODUCTION

Sustainable food systems are more important than ever in order to feed the world's population, which is growing continuously. According to projections, there will be 8.5 billion people on the planet in 2030, 9.7 billion by 2050, and 10.4 billion by 2100 (UN population, 2024; FAO, 2024). As a result, more food will be required in the future to feed an additional 1.2 and 1.9 billion people in 2050 and 2100, respectively (UN population; FAO, 2024). Food insecurity and environmental damage are exacerbated by the fact that more than one-third of all food produced (2.5 billion tons) is lost or wasted annually, in addition to the sharp rise in the global population (FAO, 2024). To create mitigation measures that can support food security, economic growth, and sustainable agriculture, these problems undoubtedly call for an all-encompassing strategy with a fresh perspective. One of the most important facets of the process sector is optimization (Kalitsis et al., 2026). According to Al-Asasfeh et al. (2025) and Kalitsis et al. (2026), even a seemingly minor change can result in an increase in production and a substantial rise in gross revenues. Enhancements can be made by trying to optimize the industrial process overall or by optimizing the performance of specific components. For decision-making expert systems utilized in intricate, large-scale process activities, sophisticated analytical and mathematical modeling techniques are frequently employed to produce optimal or nearly optimal answers (Wang et al., 2026; Olukunle, 2022).

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In order to turn raw cereal grains into flour for commercial and human use, milling is an essential post-harvest unit operation. To grind staples like Guinea corn (*Sorghum bicolor)*, small and medium-sized processors in underdeveloped nations mainly rely on disk milling operations. Millions of households in sub-Saharan Africa and developing agrarian economies rely on grains like Guinea corn (*Sorghum bicolor)* as their primary source of sustenance. In order to make their starch matrix digestible and appropriate for local food applications and confectionery baking, these grains must be processed into homogeneous, fine flour as a crucial post-harvest step. The most popular comminution technology in small and medium-sized agricultural processing is still vertical or horizontal disk milling.

Frictional, compressive, and shear forces produced between a stationary disk plate and a high-speed revolving plate are what drive the process. Its inexpensive fabrication costs, straightforward mechanical design, and great operating versatility are the reasons for its popularity. Through a combination of compressive, shearing, and frictional forces produced between a stationary toothed disk and a high-velocity spinning disk, the process lowers grain size.
Local small-scale mills are widely used, but their efficiency is low. The majority of operators use a trial-and-error method to configure their operations. Based on tactile or visual examinations of the output flour, they arbitrarily tighten the disk gap or modify the feed gate. According to Guo et al. (2022) and Khan et al. (2022), this unscientific method frequently overloads the drive motor, accelerates mechanical wear on the grinding disk, and produces excessive heat that thermally increases energy consumption.

Nevertheless, uneven product fineness, unpredictable throughput, and high energy consumption plague conventional processes. To balance operations performance against end product metrics, statistical modeling-based process optimization is essential (Kalitsis, 2025; Abdel-Aal, 2023).

A rigorous statistical approach to model, analyze, and optimize these independent variables concurrently is provided by Response Surface Methodology (RSM), which uses a Central Composite Design (CCD) framework to establish precise mathematical relationships between the operational configurations and its physical output in order to improve the operation performance, Disk speed (X1), feed rate (X2), and adjustable disk clearance (X_3) were studied.

2. THEORITICAL ANALYSIS

Comminution is the mechanical process of reducing solid materials into smaller particles through crushing, grinding, or shearing. In grain milling, this process breaks down the cellular structures of the endosperm, germ, and bran layers. The energy mechanics of this size reduction are traditionally described by three classic laws of comminution:

Rittinger's Law**:** States that the energy required for size reduction is directly proportional to the new surface area created by the grind.

$$E = K_R\left(\frac{1}{D_2} - \frac{1}{D_1}\right) \quad \text{.....} \quad \text{(i)}$$

Where:
E = Specific grinding energy required for size reduction (KJ/Kg^{-1})
K_R = Rittinger's constant unique to the physical composition of the guinea corn or wheat matrix
D_1= Initial mean geometric diameter of the raw grain feedstock prior to disc entry (mm)
D_2 = Final mean geometric diameter of the processed flour particles discharged from the mill clearance gap (mm)

Kick's Law: Asserts that the energy required is proportional to the ratio of the change in size of the material, meaning equal reductions in size require equal energy.
Grinding Power (P_g) (based on Kick's Law for coarse milling or Bond's work index for fine flour):

$$P_g = \dot{m} \cdot K_k \cdot \ln\left(\frac{D_i}{D_o}\right) \quad \text{..... (ii)}$$

Where:

T_f = Frictional torque of bearings (N·m)

ω = Angular velocity of the rotating disc (2π n / 60, rad/s)

K_k = Kick's constant (material-specific constant for wheat/sorghum)

D_i = Average inlet grain size (mm)

D_o = Average outlet flour particle size (mm)

Disc Kinetics and Grinding force

The shearing and compressive forces between the stationary and the rotating disc dictate the particle size reduction.

Centrifugal Force on Grains (F_c):

$$F_c = m \cdot \omega^2 \cdot r$$

Shear Stress Required for Milling (τ):

$$\tau = \frac{T_g}{\frac{2}{3}\pi \cdot (R_2^3 - R_1^3)} \quad \text{..... (iii)}$$

Where:

m = Mass of an individual grain particle (kg)

r = Radial distance from the center of the disc (m)

T_g = Grinding torque (P_g/ω, N·m)

R_1, R_2 = Inner and outer radii of the grinding disc face (m)

3. MATERIALS AND METHODS

Commercial Guinea corn (*Sorghum bicolor)* was purchased in large quantities from a nearby agricultural distribution market New Market in Enugu, Southeast Nigeria. The bulk lot underwent an initial mechanical screening procedure to eliminate stones, organic chaff, and extraneous material in order to guaranty experimental consistency. Additional equipment consist of: Weighing scale, desecrator, stopwatch, oven, digital tachometer, calibrated hopper, Design Expert 13 version, and the PRODA Guinea corn (*Sorghum bicolor)* disk milling machine.

Guinea corn (*Sorghum bicolor*) moisture content measurement was determined using the oven-drying method.

Procedure: weigh a 1kg sample of wheat, heat it in a specialized laboratory oven at a specific temperature (105°C for 24 hours according to specific standard: ISO 712; AL-Asasfeh, (2025), cool it in a desiccators, and weigh it again. Calculation: The weight loss represents the water evaporated.

Moisture content (%) = [(Initial Weight – Final Weight) / (Initial Weight)] X100…….. (iv)

Design of experiment

Design Expert software (version 13) was used in this study to design the experiment and to optimize the process factors. The experimental design employed in this work was a two-level-three factor full factorial design, including 20 experiments. Disc speed (X_1), Feed rate (X_2), and Adjustable clearance (X_3) were selected as independent factors for the optimization study. The response was the Percentage wheat milling efficiency (Y) obtained from the Disc milling operation. Six replications of centre points were used in order to predict a good estimation of errors and experiments were performed in a randomized order. The studied range of factor and level, actual and coded levels of each factor are shown in Table 1. The coded values were designated by −1 (minimum),

0 (centre), +1 (maximum), −α and +α. Alpha is defined as a distance from the centre point which can be either inside or outside the range (Kalitsis, 2025; Savchenko, 2026; Olukunle).
The software uses the concept of the coded values for the investigation of the significant terms, thus equation in coded values is used to study the effect of the variables on the response. The empirical equation is represented as shown below:

$$Y_{\text{(Percentage Guinea corn milling efficiency)}} = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X^2{}_i + \sum_{i=1}^{3} \sum_{j=i+1}^{3} \beta_{ij} X_i X_j \ \ldots \text{(v)}$$

Where: Y = Predicted response of percentage Guinea corn milling efficiency**, %**)

$\boldsymbol{\beta_0}$ = Intercept coefficient (predicted response at the center point)

$\boldsymbol{\beta_1}$**,** $\boldsymbol{\beta_2}$**,** $\boldsymbol{\beta_3}$ = Linear coefficients for each factor

$\boldsymbol{\beta_{12}}$**,** $\boldsymbol{\beta_{13}}$**,** $\boldsymbol{\beta_{23}}$ = Interaction coefficients between factors

$\boldsymbol{\beta_{11}}$**,** $\boldsymbol{\beta_{22}}$**,** $\boldsymbol{\beta_{33}}$ = Quadratic coefficients mapping the curvature

Experimental Design Matrix
A three-factor, five-level CCD was configured, generating 20 distinct experimental runs (8 factorial points, 6 axial points, and 6 center points). Table 2 shows the independent variables and their coded levels. Selection of level for each factor was based on the experiments performed to study the effects of three independent variables. The studied range of the factor is presented in Table 2.
Table 2: Studied range of the factor and level

Factor	Name	Units	Low	medium	High	-alpha	+alpha
A [Numeric]	Disc speed	Rpm	300	600	900	95.4622	1104.54
B [Numeric]	Feed rate	kg/h	30	55	80	12.9552	97.0448
C [Numeric]	Adjustable clearance	Mm	0.5		2	-0.0113446	2.51134
Response (Y)	Milling Efficiency	%					

Guinea corn (*Sorghum bicolor* milling efficiency (Y) was calculated as the percentage of ground material that successfully passed through a 1.0 mm sizing screen within a set time, relative to the total raw sample feed weight according to Sabelli, (2022); Wang, (2026).

$$(Y_{\text{(Guinea corn milling efficiency \%)}} = [(W_1 - W_2) / (W_2)] \times 100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(vi)}$$

Where:
(W_2) = Weight of ground Guinea corn passing through the 1.0 mm screen (kg)
(W_1) = Total weight of raw Guinea corn fed into the operation (kg)

4. RESULTS AND DISCUSSIONS

The results of Water content of wheat and guinea corn is presented in table 2

Table 2: The results of water content of wheat and guinea corn determined using weight loss method.

S/n	Item	Water content (%)
1	Wheat	13

The results of water content of Guinea corn was determined using weight loss method (oven method) is presented in Table 2, the result show that the Guinea corn has moisture content of 13 percent, this result is similar to the observation of (Guo et al., 2022; Tharanathan et al., 2022; Xu et al., 2022). The water content of the grains was kept constant at 13 percent throughout the experiment.

The experimental runs sheet for modeling, performance evaluation and optimization of process parameters for guinea corn disc milling operation and significance of regression coefficients of the percentage milling efficiency are presented in Table 3 and Table 4 respectively. Table 3 shows experimental runs and the corresponding percentage milling efficiency with maximum milling efficiency of 93 percent while Table 4 shows Significance of regression coefficients of percentage milling efficiency for wheat, Table 4 shows that the model is significant, a model is significant if p-value is less than 0.05, p-value obtained in the modeling is 0.0007 therefore the model is significant. The **Model F-value** of 9.75 implies the model is significant. From the statistical analysis, the regression coefficient (R^2 = 0.8361), the predicted R^2 of 0.8216 is in reasonable agreement with the Adjusted R^2 of 0.8056; the difference is less than 0.2.

Table 3: Displays the design layout alongside the experimental values obtained for Milling Efficiency (Y) for Guinea corn.

		Factor 1	Factor 2	Factor 3	Response 1
Std	Run	A:Disc speed	B:Feed rate	C:Adjustable clearance	Milling efficiency (Y)
		Rpm	kg/h	Mm	%
5	1	300	30	2	75
11	2	600	12.9552	1.25	62
18	3	600	55	1.25	93
20	4	600	55	1.25	93
14	5	600	55	2.51134	62
1	6	300	30	0.5	60
12	7	600	97.0448	1.25	64
16	8	600	55	1.25	93
7	9	300	80	2	60
19	10	600	55	1.25	93
4	11	900	80	0.5	30
10	12	1104.54	55	1.25	75
15	13	600	55	1.25	93
13	14	600	55	-0.0113446	30
9	15	95.4622	55	1.25	30
3	16	300	80	0.5	30
6	17	900	30	2	75
17	18	600	55	1.25	92
8	19	900	80	2	70
2	20	900	30	0.5	40

The quadratic regression equation that fitted the data is given by Eq. (iv). Y is the dependent variable (percentage milling efficiency), Disc speed (X_1), Feed rate (X_2), and Adjustable clearance (X_3) are the independent variables is given by Eqn. (vii).

Table 4: Analysis of Variance (ANOVA) for Quadratic model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9468.83	9	1052.09	9.75	0.0007	Significant
A-Disc speed	315.88	1	315.88	2.93	0.0079	Significant

B-Feed rate	234.88	1	234.88	2.18	0.1709	
C- Adjustable clearance	2212.26	1	2212.26	20.50	0.0011	Significant
AB	112.50	1	112.50	1.04	0.3313	
AC	112.50	1	112.50	1.04	0.3313	
BC	50.00	1	50.00	0.4633	0.5115	
A^2	2632.13	1	2632.13	24.39	0.0006	Significant
B^2	1384.70	1	1384.70	12.83	0.0050	Significant
C^2	3603.40	1	3603.40	33.39	0.0002	Significant

$Y_{(Milling\ efficiency)}$ =+92.72 +4.81A -4.15B +12.73C +3.75AB +3.75AC +2.50BC -13.51A^2 -9.80B^2- 15.81C^2…..(vii)

The given equation is a second-order polynomial (quadratic) regression model derived from **Response Surface Methodology (RSM).** It models **milling efficiency (Y)** as a function of three independent process or operational variables (A), (B), and (C)**.** The Intercept (+92.72) is the baseline predicted milling efficiency when all coded/scaled input factors (A), (B), and (C) are set to zero (the center point of the experimental design). Linear effects (+4.81A) Factor (A) has a positive linear effect increasing factor (A) raises milling efficiency. (-4.15B) Factor (B) has a negative linear effect. Increasing factor (B) reduces milling efficiency. (+12.73C) Factor (C) has the strongest positive linear effect among the individual terms. Increasing (C) substantially boosts milling efficiency. Interaction Effects (Two-Factor Interactions) +3.75AB, A positive synergy between factors (A) and (B). When (A) and (B) increase together, their combined effect produces a gain in efficiency beyond their individual contributions.(+3.75AC): A positive synergy between factors (A) and (C).(+2.50BC): A positive synergy between factors (B) and (C), though slightly weaker than (AB) and (AC).Quadratic Effects (Curvature Terms (-13.51A^2), (-9.80B^2), and (-15.81C^2): All three quadratic terms are negative. The negative signs indicate that the response surface has a downward concavity (parabolic shape with a maximum peak).Continuously increasing factors (A), (B), or (C) will not indefinitely increase milling efficiency. Instead, efficiency increases up to an optimal or peak, beyond which further increases in the factors will cause efficiency to drop (diminishing returns or over-processing. The result is in similar to the findings of Neufingerl., (2022); Quintieri., (2023); Gamel et al., (2020).

The actual and predicted plot is shown in Figure 1. It can be observed that the data pointed on the plot were linearly distributed, indicating a good relationship between the experimental and the predicted values of response. It also suggested that the selected quadratic model was proper and adequate in predicting the response variables for the experimental data. Figure 2: Shows the perturbation curve which explains the interaction of all the process parameter. The perturbation plot allows for comparison of the effects of all factors at a specific location within the design space (Kalitsis, 2025; Savchenko, 2026; Olukunle, 2022).

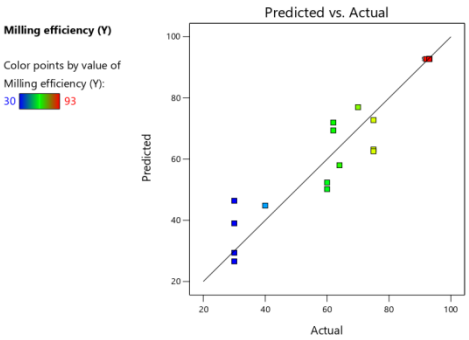

Figure1: The actual and predicted plot

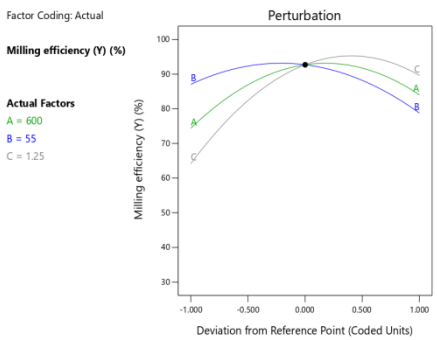

Figure 2: The **perturbation plot**

This perturbation plot visually demonstrates how changing one factor at a time impacts milling efficiency while keeping the remaining variables fixed. Curve C displays the steepest slope, confirming that factor C has the most dramatic influence on the response variable. Conversely, the flatter trajectory of curve B reveals it has the lowest sensitivity among the three inputs. All three curves exhibit a prominent parabolic shape, which graphically validates the negative quadratic coefficients from the regression equation. Finally, the convergence of the curves shows that maximum efficiency is reached near the center reference point before dropping off toward the extreme coded levels the findings is in line with the findings of (Kalitsis, 2025; Savchenko, 2026; Olukunle, 2022).

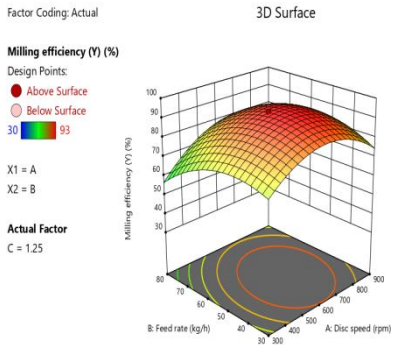

Figure: 3 D Surface plot of interaction of Feed rate and Disc speed

This 3D surface plot as shown in Figure 3 illustrates the combined effect of disc speed (A) and feed rate (B) on milling efficiency while holding factor (C) constant at 1.25. The distinct dome-shaped surface visually confirms a strong quadratic curvature, proving that maximum efficiency occurs at specific mid-range operational settings. The dark red region at the peak of the dome highlights the optimal zone where milling efficiency reaches its highest value near **93%**. Moving toward the extreme low or high limits of either disc speed or feed rate causes a sharp decline in performance down to approximately 50%. Finally, the elliptical contour lines projected on the base floor mathematically validate the significant interaction effect (AB) between these two process parameters, the result is in line with the findings of (Kalitsis, 2025; Savchenko, 2026; Olukunle, 2022).

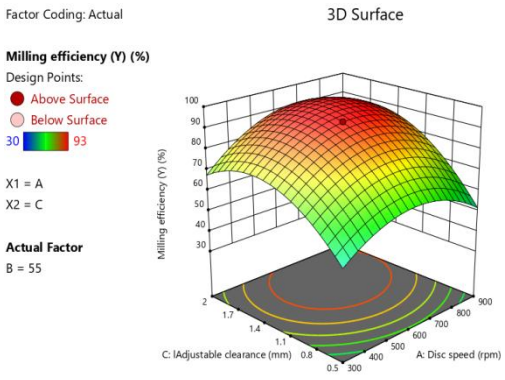

Figure 4: 3 D Surface plot of interaction of Adjustable clearance and Disc speed

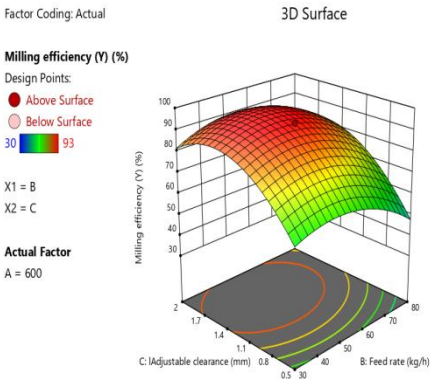

Figure 5: 3 D Surface plot of interaction of Adjustable clearance and Feed rate

Figure 4 shows 3D surface plot demonstrates the simultaneous interaction of disc speed (A) and adjustable clearance (C) on milling efficiency while keeping the feed rate (B) constant at 55. The prominent dome-like shape of the response surface visually reconfirms the negative quadratic behavior of both operational factors. The dark red peak reveals an optimal operating region where milling efficiency maximizes near **93%** at moderate, mid-range levels of speed and clearance. Deviating significantly toward a lower disc speed combined with a tighter adjustable clearance causes a severe performance drop down toward the green 60% zone. Finally, the clearly elliptical contour lines mapped on the base floor mathematically emphasize a statistically meaningful interaction effect (AC) between these two process parameters.

Figure 5 shows 3D surface plot illustrates the combined influence of feed rate (B) and adjustable clearance (C) on milling efficiency while maintaining a constant disc speed (A) of 600. The distinct convex dome shape graphically validates the negative quadratic terms of both parameters, showing an initial increase in efficiency followed by a subsequent decline. The dark red peak at the top of the surface marks the optimal operating window where milling efficiency peaks near **93%**. Operating at a low adjustable clearance of 0.5 mm coupled with extreme feed rates results in a steep performance drop into the green 60% zone. Finally, the curved contour lines projected on the base floor visually confirm the presence of a notable interaction effect (BC) between feed rate and clearance, the findings were in line with the findings of (Kalitsis, 2025; Savchenko, 2026; Olukunle, 2022).

5. CONCLUSION

This second-order regression model accurately evaluates milling efficiency (Y) across varying industrial process parameters. Among the individual variables, **adjustable clearance (C) s**erves as the primary linear driver for maximizing output. Conversely, **feed rate (B)** exert**s** a negative linear influence, while **disc speed (A)** provides moderate positive gains. The perturbation analysis confirms the factor sensitivity hierarchy ranks distinctly as **(C > A > B)**. All three 3D surface plots display a prominent dome-shaped configuration that validates strong quadratic curvature. These negative quadratic trends guarantee that exceeding specific mid-range thresholds will trigger a sharp performance drop. Elliptical contour plots confirm statistically significant interaction synergies across all paired parameters (AB), (AC), and (BC). Through combined factor optimization, the maximum milling efficiency reliably stabilizes at a peak near **93%**. This optimum is achieved at the center-point conditions of **600 rpm** disc speed, **55 kg/h** feed rate, and **1.25 mm** clearance. Ultimately, Response Surface Methodology proves to be an indispensable framework for precision process control and efficiency optimization.

RECOMMENDATIONS

Maintain disc speed at 600 rpm, feed rate at 55 kg/h, and adjustable clearance at 1.25 mm. Prioritize strict control over **adjustable clearance** because it is the most sensitive factor affecting performance. Avoid operating at extreme limits to prevent severe efficiency drops caused by negative quadratic curvature. Finally, implement automated monitoring systems to prevent parameter drift away from this identified optimal peak.

Extended Research Scope: In order to optimize maintenance schedules, future research should extend this optimization model to assess particular energy usage (kWh/kg) and disk tooth wear trends over extended durations of operation.

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Paper ID 60: ENVIRONMENTAL IMPACT ASSESSMENT OF AN INTEGRATED SEPTIC-TANK BIODIGESTER SYSTEM IN ZARIA, NIGERIA

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ABSTRACT
Conventional septic-tank systems present environmental challenges associated with wastewater management, potential soil and water contamination, and uncontrolled greenhouse-gas emissions. Integrating biodigesters with existing sanitation systems offers opportunities for improved waste treatment and renewable energy recovery, although the associated environmental risks require careful assessment. This paper evaluated the environmental impacts of integrating a biodigester with a conventional septic-tank system at Ahmadu Bello University, Zaria, Nigeria. A case-study environmental impact assessment was undertaken through critical analysis of the project's Environmental Impact Statement (EIS), covering site preparation, construction, operation and decommissioning.

Environmental impacts were classified by direction, duration, reversibility and directness, while the EIS significance ratings and mitigation measures were synthesised. The assessment identified prospective benefits of biogas recovery for cooking and lighting and local employment. Key adverse impacts included vegetation and topsoil disturbance, construction dust and exhaust emissions, noise, solid waste, drainage disruption, worker injury and possible soil or water contamination. The EIS rated several construction impacts as high before mitigation, including material-transport emissions, excavation emissions and noise, solid waste, and installation-related accidents. Proposed controls included vehicle maintenance, dust suppression, drainage management, protective equipment, daytime work, approved waste handling and emergency procedures. Because the assessment was predictive, measured biogas production, methane leakage, effluent quality, fuel displacement and greenhouse-gas savings were not available. The findings establish a project-specific environmental-management basis for subsequent commissioning and monitoring, rather than proof of achieved environmental benefits.
Keywords: anaerobic digestion; environmental impact assessment; septic tank; biodigester

1. INTRODUCTION

Decentralised sanitation systems serve locations without centralised sewerage, but their environmental performance depends on design, loading, hydrogeology and maintenance. Septic effluent can introduce microbial and chemical contaminants into groundwater where containment or subsequent treatment is inadequate (Gyimah et al., 2024). Integrating gas recovery into sanitation infrastructure creates an opportunity for resource recovery while introducing requirements for gas containment, pressure control, effluent treatment and residual-sludge management.

Reviews of decentralised wastewater treatment emphasise the need to match treatment technologies to local operating and resource conditions (Sha et al., 2024; Al-Rajhi and Abdelghany, 2025). Conventional septic tanks already contain anaerobic microbial processes; adding gas collection alone does not establish controlled digestion or improved treatment (Shaw and Dorea, 2021). Anaerobic digestion offers potential energy recovery, but gas yield, composition and practical use depend on feedstock and operating conditions (Alengebawy et al., 2024; Jameel et al., 2024).

The ABU project concerns integration of a biodigester into conventional septic-tank infrastructure for potential household energy recovery. A project EIS dated 27 March 2024 was prepared by Spatial Planning and Environmental Consults (2024). The present study examines its predicted impacts and management requirements, supported by calculations from the supplied system drawing. It is a predictive documentary EIA case study rather than an experimental evaluation of operating performance. Environmental assessment remains its central purpose; engineering calculations are included to clarify the assessed installation and identify design-related environmental uncertainties.

The specific objectives were to:

1. Describe the proposed system and its nominal hydraulic characteristics.
2. Examine the reported significance of environmental impacts and the assessment method used.
3. Summarise selected adverse-impact records using frequencies and percentages.
4. Specify mitigation measures, monitoring procedures and verification requirements.

2. THEORETICAL ANALYSIS

The hydraulic analysis was based on the effective contributing population, estimated daily blackwater flow, internal chamber dimensions and nominal hydraulic retention time. Effective population was calculated as:

$$N_e = Nf$$

where N_e is the effective population, (N) is the total number of occupants and (f) is the occupancy fraction. For 24 occupants at 70% occupancy:
$N_e = 24(0.70) = 16.8$ equivalent persons

Daily blackwater flow was estimated using:

$Q = (N_e \times q)/1000$

where Q is flow in m³/day and q is the assumed blackwater generation rate in L/person/day. Using 80 L/person/day:

$Q = 16.8 \times 80 / 1000 = 1.344$ m³/day

The nominal liquid volume of each chamber was calculated as:
$V_i = L_i \times W_i \times D_i$

where L_i, W_i and D_i are internal length, width and liquid depth in metres. Nominal hydraulic retention time was calculated as:
$HRT = V / Q$

At the estimated average flow, retention times were 4.00 days for the complete system and 2.46 days for the digestion chamber. At full occupancy, the estimated flow increases to 1.920 m³/day, reducing these values to 2.80 and 1.73 days, respectively.

3. MATERIALS AND METHODS

3.1 Study site and evidence sources

The project (Appendices 1-4) is located at Ahmadu Bello University, Zaria, Kaduna State, approximately 1.10 km from the Zaria–Funtua Expressway. The EIS describes lateritic sandy-loam conditions and generally well-drained terrain. It gives both a slope of approximately 5% and a gradient of 4.5°, which are not equivalent; neither was adopted here as an independently verified survey measurement. Evidence comprised the complete 37-page EIS.

3.2 System configuration and hydraulic calculations

The project integrated an anaerobic biodigester with conventional septic-tank infrastructure for toilet-wastewater treatment and potential biogas recovery for cooking and lighting (Figure 1). The system comprises an inlet chamber, digestion chamber, downstream sludge chamber, gas-collection dome, gas-conditioning units and storage bag. Greywater from bathing, laundry and kitchen activities is excluded. The environmental assessment covered site preparation, vegetation clearance, excavation, material transportation, construction, installation, operation, maintenance and decommissioning. The design basis and calculated hydraulic characteristics of the proposed system are presented in Table 1.

Table 1. Design basis and calculated hydraulic characteristics

Parameter	Basis	Value
Total occupants	Author supplied	24 persons
Average occupancy	Based on interview result	70%
Effective occupants	24 × 0.70	16.8 equivalent persons
Blackwater generation	Assumed	80 L/person/day
Average inflow	16.8 × 80	1.344 m³/day
Full occupancy inflow	24 × 80	1.920 m³/day
Inlet liquid volume	0.70 × 1.15 × 1.20	0.966 m³
Digestion liquid volume	2.40 × 1.15 × 1.20	3.312 m³
Sludge chamber liquid volume	0.80 × 1.15 × 1.20	1.104 m³
Total nominal liquid volume	Sum of chambers	5.382 m³

Parameter	Basis	Value
Total system HRT at average flow	5.382 / 1.344	4.00 days
Digestion chamber HRT at average flow	3.312 / 1.344	2.46 days
Total system HRT at full occupancy	5.382 / 1.920	2.80 days
Digestion HRT at full occupancy	3.312 / 1.920	1.73 days

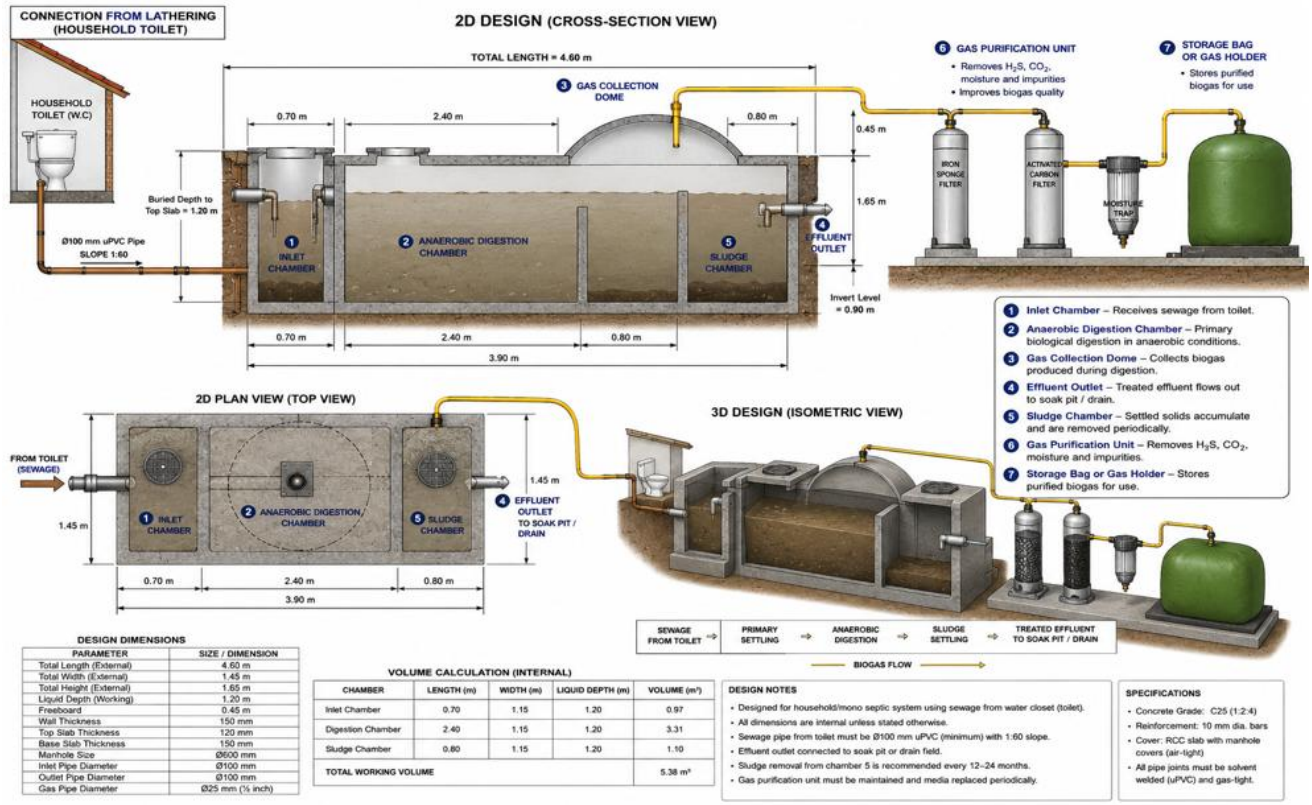

Figure 1: Design drawing of the integrated septic-tank biodigester system

3.3 Impact identification and significance assessment

The EIS identifies interactions between project activities and soil, ecology, air, noise, hydrology, hydrogeology and socioeconomic conditions. Impacts are qualified by direction, duration, reversibility and directness. The EIS defines short term as less than three months and long term as greater than three months, without explicitly allocating exactly three months.

EIS Sections 3.2.3.1–3.2.3.5 and Tables 3.6–3.9 specify five criteria: legal requirements (L), risk (R), frequency (F), importance (I) and public perception (P). Table 3.9 gives the additive score S = L + R + F + I + P, with low significance below 8, medium from 8 to below 15, and high at 15 or above. These are the project EIS scoring conventions; this paper does not claim that ISO 14001 mandates this particular scoring scheme.

Table 2. Scoring conventions documented in the project EIS

Criterion	Reported scores and interpretation
Legal requirements L	0: none; 3: legal requirement; 5: legal requirement and permit
Risk R	1: low; 3: intermediate; 5: high, from probability and consequence assessment
Frequency F	1: low; 3: medium; 5: high; source wording for medium frequency is ambiguous
Importance I	1: low; 3: medium; 5: high
Public perception P	1: low; 3: medium; 5: high
Significance S	L + R + F + I + P; low <8; medium 8–<15; high ≥15

The EIS additionally lists F + I > 6 and P = 5 below the high-significance threshold, but does not clearly explain whether they operate as independent override rules. Criterion-level entries for the selected impact records were not available to reconstruct individual totals. Reported categories were therefore retained rather than newly scored. The EIS contains generic references to unrelated project types, requiring caution when interpreting project-specific applicability.

3.4 Descriptive analysis and evidence limitations

The analytical unit was one of seven selected adverse activity-level records in the manuscript summary. Percentage = 100 × category count / 7. The first five records were grouped as construction-related and the remaining two as operation/maintenance and decommissioning. These purposively selected records are not independent environmental samples or the full impact inventory. No inferential statistical test, weighted mean of ordinal categories or invented monitoring result was used. No numerical baseline dataset with sampling locations, replication and analytical quality controls was identified in the supplied EIS for estimating pollutant exposure or treatment efficiency.

4. RESULTS AND DISCUSSION

4.1 Predicted impact profile

Table 3 summarises the selected adverse-impact records. Four were high before mitigation and three media. Construction-related activities accounted for four high and one medium record. This indicates priorities within the selected summary, not proof that construction dominates the complete environmental burden. Prospective energy and employment benefits were qualitative and excluded from the adverse-impact denominator.

Table 3. Selected adverse impacts and proposed controls

Activity	Potential impact	Reported category	Control
Material transport	Dust, exhaust and traffic risk	High	Maintain vehicles; control traffic and dust
Clearing and excavation	Soil disturbance, emissions and noise	High for emissions/noise	Limit clearing; suppress dust; control working hours
Construction waste	Waste accumulation and disposal	High	Segregate, reuse and use approved disposal

Activity	Potential impact	Reported category	Control
Excavation and drainage	Runoff and water pooling	Medium	Maintain drainage and stabilise excavated material
Installation	Worker injury	High	Competent supervision and safe work procedures
Operation and maintenance	Waste handling and worker injury	Medium	Contain waste; use protective equipment and emergency procedures
Decommissioning	Soil/water contamination	Medium	Controlled dismantling and approved remediation

Source: Selected records from EIS.

Table 4. Distribution of selected pre-mitigation categories

Phase	High n (%)	Medium n (%)	Low n (%)	Total
Construction related	4 (80.0)	1 (20.0)	0 (0.0)	5
Operation/maintenance	0 (0.0)	1 (100.0)	0 (0.0)	1
Decommissioning	0 (0.0)	1 (100.0)	0 (0.0)	1
All selected records	4 (57.1)	3 (42.9)	0 (0.0)	7

4.2 Design implications for environmental performance

The drawing-derived total volume of 5.382 m³ yields a nominal four-day system HRT at average flow, while the digestion chamber alone provides approximately 2.46 days. At full occupancy, these decrease to 2.80 and 1.73 days. These calculations make the hydraulic assumptions explicit, but cannot establish sufficient biodegradation, pathogen reduction or methane recovery. Organic loading, influent strength, temperature, biomass retention and actual flow distribution were not measured. Design adequacy must therefore be evaluated separately from the existence of an anaerobic chamber.

The chamber lengths sum to 3.90 m. With two external end walls and two internal partitions each 0.15 m thick, the resulting overall length is 4.50 m, whereas the drawing states 4.60 m. Clear internal dimensions were used for the volume calculations, and the external length must be reconciled before construction or as-built certification. Concrete and reinforcement labels in the drawing were not supported by structural calculations in the supplied evidence.

The gas line includes iron-sponge and activated-carbon units and a moisture trap. These should be described as proposed conditioning components; removal efficiencies and the drawing's claim of CO_2 removal are unverified. Gas tightness, pressure protection, equipment compatibility and safe siting require engineering checks. The outlet label likewise does not prove effluent safety. Further treatment or an approved disposal route must be justified by effluent tests and site conditions. Anaerobic residual materials require controlled management because nutrient recovery does not establish hygienic safety (Lamolinara et al., 2022).

4.3 Mitigation and environmental monitoring

The EIS predicts lower significance following controls, but provides no before-and-after measurements or criterion-level residual scores that independently demonstrate the reduction. These residual categories remain

predictions. Table 5 translates the assessment into a proposed verification programme; its monitoring frequencies and role assignments are recommendations for adoption, not evidence that monitoring has occurred.

Table 5: Proposed environmental management and monitoring programme

Concern	Indicator and action	Proposed timing	Responsible role
Dust and noise	Record dust/noise complaints; inspect suppression; measure noise and particulates where needed	Before works; daily inspection during works; measurements during representative activities	Contractor; environmental supervisor
Drainage and soil	Inspect runoff, erosion, spoil and water pooling; maintain controls	Daily during excavation and after rainfall	Site engineer
Construction waste and safety	Waste transfer records, segregation, PPE, incidents and corrective actions	Daily during construction	Contractor safety officer
Flow and hydraulics	Measure daily blackwater inflow; inspect leakage and blockage; review occupancy assumptions	Daily during commissioning; monthly review thereafter	Operator; research engineer
Gas containment and quality	Leak checks, pressure, gas volume, methane and H_2S; maintain filters and pressure protection	Before start-up; daily operating checks; weekly gas measurements during commissioning	Qualified gas technician; operator
Effluent quality	Paired influent/effluent pH, COD, BOD_5, suspended solids and microbial indicators	Baseline; weekly during initial commissioning; monthly after stable operation	Accredited laboratory; research team
Groundwater protection	Survey receptor wells and flow direction; monitor water levels, nitrate, ammonium and E. coli where relevant	Before operation; wet/dry season checks and after suspected leakage	Environmental specialist; laboratory
Sludge and residuals	Record accumulation, removals and destination; test before proposed reuse	Periodic inspection; at each removal or reuse assessment	Operator; environmental supervisor
Community and closure	Complaints, corrective actions, dismantling waste and site restoration	Monthly operational review; before and during closure	Project coordinator; environmental supervisor

4.4 Scope and uncertainty

The assessment brings together documented impact predictions and transparent hydraulic calculations, but the selected impact counts are not a measurement of environmental damage. The EIS scoring method is now identifiable, although individual rating inputs and some decision rules remain unclear. The 70% occupancy and 80 L/person/day assumptions require verification; nominal HRT excludes short-circuiting and accumulated solids. Baseline and repeated operational measurements are necessary to evaluate treatment, emissions and groundwater risks. The drawing is a project description, not evidence that the installation has achieved the claimed performance.

5. CONCLUSION

The integrated septic-tank biodigester has a calculated nominal liquid volume of 5.382 m³. At the stated average design flow of 1.344 m³/day, nominal system and digestion-chamber retention times are 4.00 and 2.46 days. Of seven selected pre-mitigation adverse-impact records, four were high and three medium, identifying construction controls as priorities within that summary. The review identified limitations in the reproducibility of the EIS significance ratings and specified mitigation, monitoring and verification requirements for subsequent implementation

Recommendations

1. Environmental management: Implement the EMP to control construction-related pollution, waste generation and occupational hazards.
2. Environmental monitoring: Establish baseline conditions and conduct regular operational measurements of groundwater quality, effluent characteristics and methane leakage to verify predicted impacts and mitigation effectiveness.
3. System performance: Measure biogas production, methane content and useful energy output after commissioning to assess operational performance.
4. Residual waste management: Assess and appropriately treat digestate and sludge before disposal or agricultural reuse, following technically justified and approved management procedures.
5. Further research: Evaluate long-term technical performance, economic viability and environmental outcomes under actual operating conditions to address the study's evidence gaps.

ACKNOWLEDGEMENTS

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APPENDICES: Pictures of Various Activities at the Site

Paper ID 61: Design and Evaluation of Growth-Stage Adaptive Iot Irrigation System for Bell Pepper in Semi-Arid Nigeria

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ABSTRACT
Efficient irrigation is important for crop production in semi-arid environments, where temperature, humidity, and soil-water conditions can change considerably within short periods. This study presents the development and evaluation of a low-cost, growth-stage adaptive Internet of Things (IoT)-based drip irrigation system for bell pepper production. The prototype integrates an ESP32 microcontroller with a capacitive soil-moisture sensor, DHT22 air-temperature and relative-humidity sensor, DS18B20 soil-temperature sensor, YF-S201 flow sensor, DS3231 real-time clock, relay-controlled pump, and local LCD interface. Five bell pepper seedlings, approximately four weeks old at transplanting on 21 August 2026, were monitored from 22 August to 26 September 2026, corresponding to approximately four to nine weeks of crop age. The project log recorded 11.25 L of irrigation water during the observation period. Mean morning and evening water applications were 150 mL and 195 mL, respectively. Exploratory Pearson correlation analysis showed a moderate positive association between morning air temperature and morning irrigation volume ($r = 0.388$, $p = 0.019$), and a moderate negative association between morning soil moisture and morning irrigation volume ($r = -0.443$, $p = 0.007$). These results describe associations rather than causal effects. The study demonstrates the practical potential of combining low-cost sensing, scheduled control, and growth-stage-oriented irrigation for sustainable agricultural water management in semi-arid Nigeria.

KEYWORDS: Smart irrigation, Internet of Things, ESP32, Bell pepper, Water management

1. INTRODUCTION

1.1 Background

Agricultural production in semi-arid environments is strongly influenced by water availability and variation in temperature, humidity, and rainfall. For vegetable crops such as bell pepper (Capsicum annuum), maintaining suitable root-zone moisture is important because crop water demand changes as plants develop. The FAO-56 framework explains crop evapotranspiration and recognizes that crop coefficients vary with crop development and environmental conditions (Allen et al., 1998).

In practice, irrigation is often managed using fixed schedules or manual decisions. These approaches may not respond quickly to changes in soil moisture or the surrounding microclimate. Internet of Things (IoT)-based irrigation systems provide a way to connect field sensors, controllers, and actuators so that crop and soil conditions can be monitored and irrigation can be automated. Recent studies have demonstrated the use of ESP32-based

platforms, environmental sensing, and automated drip irrigation for this purpose (Pereira et al., 2023; Gaitan et al., 2025; Jaiswal et al., 2025).

The need for responsive irrigation is particularly relevant to Nigeria, where irrigation can support agricultural production beyond rainfall-dependent seasons. Smart irrigation technologies have also been discussed as part of broader efforts to improve water management, agricultural productivity, and climate resilience in sub-Saharan Africa (Wanyama et al., 2024). The challenge is therefore not simply to automate irrigation, but to develop systems that are sufficiently simple, measurable, and adaptable to local production conditions.

1.2 Problem Statement

Fixed irrigation schedules do not always correspond with the actual moisture condition of the root zone or the environmental conditions surrounding a crop. In semi-arid production, this can lead to under- or over-application of water. There is therefore a need for practical irrigation systems that can monitor relevant environmental conditions and support timely water delivery while using affordable and locally accessible engineering components.

1.3 Aim and Objectives

This study aimed to develop and evaluate an IoT-based growth-stage adaptive drip irrigation system for bell pepper production, with emphasis on environmental monitoring and responsive water delivery.

i. design and assemble an ESP32-based irrigation system using low-cost environmental and irrigation sensors;
ii. develop a control framework that supports scheduled irrigation and growth-stage-oriented adjustment of irrigation settings;
iii. monitor air temperature, relative humidity, soil temperature, soil moisture, and irrigation-water volume during crop observation;
iv. explore the relationship between recorded environmental conditions and irrigation-water application; and
v. assess the practical potential and limitations of the prototype as a basis for sustainable irrigation management.

1.4 Relevance to Sustainable National Development

The engineering approach in this study is relevant to sustainable national development because it focuses on improving the management of a critical agricultural input, water, through sensing, automation, and locally adaptable technology. The work is consistent with SDG 2 on food security, SDG 6 on water management, SDG 9 on innovation and infrastructure, SDG 12 on responsible resource use, and SDG 13 on climate action (United Nations, 2015). It also reflects the broader role of engineering innovation in developing practical technologies for resilient production systems.

1.5 Related Studies

Published work shows several practical ways to use sensors and automation to support irrigation decisions. Pereira et al. (2023) demonstrated an ESP32-based drip-irrigation system that combines soil and environmental sensing with remote monitoring and control. Ugwu et al. (2023) explored smart irrigation for yellow pepper in Nigeria, while Madato et al. (2022) reported an IoT-based smart-farm system for pepper production. Together, these studies show the relevance of automated monitoring to pepper cultivation, although their designs and evaluation conditions differ. Kumar et al. (2023) compared soil-moisture-based IoT scheduling with an evapotranspiration-based approach for sweet corn, while Jain (2023) examined an IoT-enabled drip system controlled through a web application. These studies use different crops, control approaches, and experimental designs, so their results should not be treated as direct evidence of performance for the present prototype. Work on low-cost soil-moisture monitoring also highlights the importance of accessible equipment and calibration (Vandôme et al., 2023). Reviews by Wanyama et al. (2024) and Jaiswal et al. (2025) similarly note that system design must account for local cost, infrastructure, maintenance, and user capacity. Choudhary et al. (2025) provide a broader overview of IoT and web services in smart agriculture, while Preite and Vignali (2024) investigate predictive irrigation management. The present prototype uses rule-based control rather than an artificial-intelligence model and adds

a small-scale proof-of-concept evaluation focused on bell pepper, growth-stage-oriented settings, and recorded environmental and irrigation data.

2. THEORETICAL ANALYSIS

The system is based on the practical relationship between crop water demand, root-zone moisture, and irrigation timing. The FAO-56 approach estimates crop evapotranspiration from reference evapotranspiration and crop coefficients, which vary with crop development (Allen et al., 1998). This prototype did not calculate evapotranspiration or claim to estimate a complete crop-water balance. Instead, it combined soil-moisture sensing, environmental monitoring, and scheduled control as a preliminary, rule-based way to observe conditions and manage water delivery. Soil-moisture-based scheduling and evapotranspiration-based scheduling are distinct approaches and should be compared under controlled conditions before conclusions are drawn about relative water use or crop performance (Kumar et al., 2023).

3. MATERIALS AND METHODS

3.1 System Architecture and Components

The prototype was built around an ESP32 development board, which served as the central sensing and control unit. A capacitive soil-moisture sensor monitored root-zone moisture, while a DHT22 measured air temperature and relative humidity. A DS18B20 measured soil temperature, and a YF-S201 flow sensor monitored irrigation flow. A DS3231 real-time clock (RTC) provided date and time information for scheduled irrigation. A relay controlled the irrigation pump, while a 20 × 4 I²C LCD displayed sensor values and system status. Push buttons were included for local manual control and display navigation.

Table 1. Main components of the developed irrigation prototype and their functions.

Component	Function
ESP32	Central sensing, processing, timing, and control
DHT22	Air temperature and relative-humidity measurement
Capacitive soil-moisture sensor	Root-zone moisture measurement
DS18B20	Soil-temperature measurement
YF-S201 flow sensor	Irrigation-flow monitoring
DS3231 RTC	Timekeeping and scheduled irrigation
Relay and pump	Water-delivery actuation
20 × 4 I²C LCD	Local display of system status
Push buttons	Manual control and display navigation
Drip line	Root-zone water delivery

3.2 Growth-Stage-Oriented Control

The control concept was based on the principle that irrigation requirements change as the crop develops. The controller therefore combines scheduled irrigation with growth-stage-oriented settings that can be adjusted as the crop progresses. Soil-moisture measurements were obtained from calibrated dry and wet reference points, while the RTC provided the timing reference for automatic irrigation windows. The pump could also be operated manually when required. The system was designed as a rule-based engineering platform rather than a predictive artificial-intelligence model, keeping the control logic understandable and adjustable as additional crop data are collected.

During the project observation period, irrigation water was measured using a calibrated measuring cylinder. This allowed the analysis to use recorded application volumes rather than estimating water delivery only from pump operating time. The flow sensor provided additional monitoring of water movement through the system.

3.3 Crop Establishment and Data Collection

Five healthy bell pepper seedlings were transplanted into the prototype irrigation box on 21 August 2026. The seedlings were approximately four weeks old at transplanting. The observation log covered 22 August to 26 September 2026, giving a 36-day observation window. Crop age was calculated from the transplanting date using

the initial age of approximately four weeks. The crop was therefore approximately 4.1 weeks old at the first recorded observation and approximately 9.1 weeks old at the final observation.

Morning and evening measurements of air temperature, soil temperature, relative humidity, soil moisture, and irrigation-water volume were recorded in the project spreadsheet throughout the observation period. On some dates, only morning measurements were available. These records were retained in the dataset, so the number of morning observations (n = 36) is larger than the number of evening observations (n = 30).

3.4 Data Analysis

Descriptive statistics were used to summarize the recorded environmental conditions and irrigation-water applications. Mean, minimum, and maximum values were calculated separately for morning and evening observations. Total irrigation volume and mean application volume were also determined.

Pearson's product-moment correlation was then used to explore the linear association between irrigation-water volume and each recorded environmental variable. Morning and evening observations were analysed separately, and only paired observations with available values for both variables were included in each calculation. The correlation coefficient (r) and corresponding two-tailed p-value were reported using a significance level of 0.05. The analysis was treated as exploratory because the experiment involved five plants in one prototype and repeated observations from the same experimental unit. Consequently, the correlation results were interpreted as associations rather than causal effects.

4. RESULTS AND DISCUSSION

4.1 Crop Age and Observation Period

The observation period extended from 22 August to 26 September 2026. The five plants were approximately four weeks old at transplanting on 21 August and progressed to approximately nine weeks of age by the final observation. This corresponds to approximately five weeks of post-transplant observation.

Table 2. Crop age calculated from the transplanting date of 21 August 2026.

Date	Days after transplanting	Approximate crop age
22 Aug 2026	1	4.1 weeks
28 Aug 2026	7	5.0 weeks
04 Sep 2026	14	6.0 weeks
11 Sep 2026	21	7.0 weeks
18 Sep 2026	28	8.0 weeks
25 Sep 2026	35	9.0 weeks
26 Sep 2026	36	9.1 weeks

4.2 Environmental Conditions and Irrigation Volume

Table 3 summarises the recorded conditions. Conditions differed clearly between the two observation periods: air temperature averaged 24.52 °C in the morning and 32.19 °C in the evening, relative humidity fell from 89.72% to 68.13%, and soil moisture from 84.53% to 64.97%.

Morning irrigation applications averaged 150 mL, while evening applications averaged 195 mL. The total recorded irrigation volume for the full project log was 11.25 L. The variation in recorded application volume indicates that the system delivered different quantities of water during the observation period rather than applying one constant volume.

Table 3. Descriptive statistics for recorded environmental conditions and irrigation-water applications.

Parameter	Morning mean	Evening mean	Morning range	Evening range	Unit
Air temperature	24.52	32.19	20.1–31.5	26.0–38.8	°C
Soil temperature	24.29	31.56	20.5–38.0	24.3–43.0	°C
Relative humidity	89.72	68.13	65–100	45–92	%
Soil moisture	84.53	64.97	30–100	37–90	%

Irrigation water	150	195	50–300	100–400	mL

4.3 Exploratory Correlation Analysis

Pearson correlation was used to examine whether changes in the monitored environmental variables were associated with changes in recorded irrigation-water volume. For each test, observations were paired by the same measurement period, and morning and evening data were analysed separately. This produced four morning comparisons and four evening comparisons.

In the morning data, air temperature showed a moderate positive association with irrigation volume ($r = 0.388$, $p = 0.019$), and soil moisture showed a moderate negative association ($r = -0.443$, $p = 0.007$). Soil temperature and relative humidity were not significantly associated with irrigation volume at the 0.05 level (Table 4).

In the evening data, air temperature had a moderate positive association with irrigation volume that was close to, but did not reach, the 0.05 threshold ($r = 0.359$, $p = 0.051$); no other variable showed a significant association (Table 4).

Table 4. Pearson correlation between environmental variables and irrigation-water volume.

Period	Variable	n	r	p-value
Morning	Air temperature (°C)	36	0.388	0.019
Morning	Soil temperature (°C)	36	0.261	0.124
Morning	Relative humidity (%)	36	−0.192	0.263
Morning	Soil moisture (%)	36	−0.443	0.007
Evening	Air temperature (°C)	30	0.359	0.051
Evening	Soil temperature (°C)	30	0.255	0.173
Evening	Relative humidity (%)	30	−0.161	0.395
Evening	Soil moisture (%)	30	−0.273	0.145

4.4 System Response and Irrigation Behaviour

The recorded data show that the environmental conditions around the crop varied across the observation period, while the irrigation volume also changed. Morning and evening conditions were not identical, and soil moisture generally differed between the two periods. This supports the practical value of monitoring more than one environmental variable when irrigation is being managed in a semi-arid environment.

The variation in irrigation volume should not, however, be interpreted as a measured percentage water saving. The study did not include a fixed-threshold control or conventional-irrigation treatment against which water use could be compared. The appropriate conclusion from the present experiment is that the prototype was able to monitor conditions and deliver variable irrigation volumes, not that it achieved a quantified water-saving advantage. Other studies show why such a comparison would be worthwhile. Kumar et al. (2023) reported that IoT soil-moisture-based irrigation of sweet corn gave about 12% higher yield and 11% water saving than evapotranspiration-based scheduling, and Madato et al. (2022) found higher pepper yields under smart-farm-controlled watering than under general watering. Such benefits depend on the crop, soil and control strategy, however, and cannot be assumed for the present prototype without a comparison treatment.

4.5 Interpretation of the Correlation Results

The negative association between morning soil moisture and irrigation volume is consistent with the practical logic of responsive irrigation: lower soil-moisture readings occurred alongside higher recorded water applications in the morning dataset. The positive association between morning air temperature and irrigation volume suggests

that higher morning temperatures also tended to coincide with higher water applications. These patterns are useful for understanding the behaviour of the prototype, but they do not demonstrate that temperature or soil moisture independently caused the controller to change the irrigation volume. This pattern is in line with the logic of soil-moisture-based scheduling used in IoT drip systems (Kumar et al., 2023; Pereira et al., 2023), in which soil-sensor readings determine when and how much water is applied. The temperature association is also physically plausible, since atmospheric demand is a main driver of crop water use and is expressed through reference evapotranspiration in the FAO-56 method (Allen et al., 1998); the present prototype, however, did not compute evapotranspiration, so this link could not be tested.

The distinction is important because the experiment involved repeated observations from the same small prototype rather than independent replicated treatments. Irrigation volume could also be influenced by the programmed schedule, growth stage, manual intervention and other factors that were not included in the correlation analysis. The correlations should therefore be viewed as exploratory evidence that can guide future calibration rather than as a predictive irrigation model. Readings from low-cost soil-moisture sensors also depend on site-specific calibration (Vandôme et al., 2023), which adds uncertainty to any relationship estimated from them.

4.6 Growth-Stage Adaptation

The growth-stage approach reflects the established principle that crop water requirements change during crop development (Allen et al., 1998). Plant-based irrigation scheduling can provide useful information, but it also has practical limitations and must be interpreted alongside soil and environmental measurements (Jones, 2004). In the present project, the plants were monitored from approximately four weeks of age at transplanting to approximately nine weeks at the end of the observation period. This provided a useful window for testing the system as the plants developed, although the study did not continue through a complete bell-pepper production cycle.

Because phenological measurements such as flowering, fruit set, canopy development, and final yield were not recorded as part of the dataset, the present results should not be interpreted as a complete calibration of bell-pepper water requirements at every growth stage. Instead, the experiment demonstrates the engineering feasibility of combining growth-stage-oriented settings with real-time environmental monitoring.

4.7 Contribution to Sustainable Agricultural Engineering

The main engineering contribution of the study is the integration of sensing, timing, water-flow monitoring, and automated actuation in a relatively simple irrigation platform. Similar systems have used soil-moisture thresholds or evapotranspiration-based scheduling to inform irrigation decisions, although the best approach depends on the crop, soil, and production setting (Kumar et al., 2023). Model-based predictive control has also been proposed for water-saving drip irrigation (Abioye et al., 2023), which points to a possible direction for developing the present rule-based controller. In Nigeria, smart irrigation has been explored for yellow pepper (Ugwu et al., 2023), supporting the relevance of this type of system, although such studies differ in design and evaluation conditions. Reviews of smart irrigation also identify sensing and automation as useful tools while emphasizing that successful deployment in sub-Saharan Africa depends on affordability, infrastructure, technical capacity, and local conditions (Wanyama et al., 2024; Jaiswal et al., 2025).

For Nigeria, the value of the prototype is therefore best considered as a foundation for further engineering development and field validation. The system can be refined through longer monitoring periods, better crop-stage calibration, and replicated field trials before it is considered for larger production environments.

4.8 Limitations of the Study

i. The experiment involved five plants in one prototype box, so the results cannot be generalized directly to field-scale production.
ii. The observation period covered approximately four to nine weeks of crop age and did not represent a complete bell-pepper production cycle.

iii. No control treatment was included, so a percentage water-saving benefit could not be experimentally established.
iv. Detailed phenological measurements and final crop yield were not included in the dataset, limiting the ability to relate irrigation response directly to productivity.
v. Some dates contained morning-only records, resulting in unequal numbers of morning and evening observations.

5. CONCLUSION

An IoT-based growth-stage adaptive drip irrigation prototype was developed and evaluated using five bell pepper plants. The system combined ESP32-based control with soil-moisture, air-temperature, relative-humidity, soil-temperature, and flow monitoring, together with RTC-based timing and automated pump control. The project log covered 36 days, during which the plants progressed from approximately four to nine weeks of age.

The system recorded 11.25 L of irrigation water during the observation period, with mean morning and evening applications of 150 mL and 195 mL, respectively. Exploratory correlation analysis identified associations between irrigation volume and selected environmental variables, particularly morning air temperature and morning soil moisture. These results demonstrate the usefulness of environmental monitoring for understanding irrigation behaviour, but they do not establish causal relationships or a quantified percentage of water savings.

Overall, the study provides a practical engineering foundation for developing more responsive irrigation systems for semi-arid agriculture. Its contribution to sustainable national development lies in applying low-cost sensing and automation to agricultural water management, while providing a platform that can be further calibrated and tested under larger and more controlled production conditions.

Based on the findings of this study, the following recommendations are made:

i. Repeat the experiment using replicated treatment groups and a clearly defined fixed-threshold or conventional-irrigation control.
ii. Continue monitoring through a complete bell-pepper production cycle and record flowering, fruiting, growth, and yield measurements.
iii. Calibrate irrigation thresholds separately for major crop-development stages using measured soil-moisture response and crop observations.
iv. Standardize morning and evening data collection so that paired observations are available throughout the experiment.
v. Evaluate sensor stability, system reliability, energy consumption, and flow accuracy under field conditions.
vi. Scale the prototype to larger planting areas and different soil conditions before making claims about commercial or large-scale deployment.

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