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Research article

FROM FRUIT-PEEL WASTE TO SOIL HEALTH: ANAEROBIC BIOFERTILIZER ENHANCES SOIL MICROBIAL FUNCTION AND HOT PEPPER PRODUCTIVITY IN CALABAR, NIGERIA

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ABSTRACT

This study evaluated whether anaerobically digested fruit-peel wastes and cow dung could be converted into agronomically effective biofertilizers for restoring soil fertility, stimulating soil microbial communities and improving hot pepper (Capsicum frutescens L.) performance in the humid tropics. Banana, paw-paw and watermelon peels and cow dung were digested singly and in selected combinations for 45 days. Eleven bioslurry treatments, mineral NPK and an unfertilized control were evaluated in a randomized complete block design with three replications during wet and dry seasons. Substrate chemistry, digester temperature, pH, cumulative gas production, microbial counts, post-harvest soil properties, pepper growth and yield were assessed. Anaerobic digestion increased substrate nitrogen and shifted most acidic feedstocks towards near-neutral reaction. The four-substrate co-digestion treatment (W+C+P+B) recorded the highest cumulative gas production (49.4 units), retained the largest post-digestion bacterial and fungal populations, and produced bioslurry with 8.4% N. In the field, W+C+P+B increased soil pH from an initial 4.9 to 6.8, organic carbon to 3.4%, total N to 0.3%, available P to 40.1 mg kg−1 and base saturation to 91.3%. It also produced the greatest shoot and root biomass and the highest fresh fruit weights in both seasons. Balanced co-digestion can simultaneously divert biodegradable wastes, recover nutrients, improve acid-soil quality and reduce dependence on mineral fertilizer. Contribution: The study links feedstock transformation, microbial dynamics, soil restoration and crop response within one circular bioeconomy framework for smallholder production in humid tropical environments.

KEYWORDS
anaerobic digestion; bioslurry; circular bioeconomy; fruit-peel waste; cow dung; soil microorganisms; soil fertility; hot pepper; organic amendment

Introduction

Agricultural production in the humid tropics is constrained by a difficult combination of rapid organic-matter decomposition, intense rainfall, nutrient leaching, soil acidity and limited access to affordable soil amendments. In southeastern Nigeria, these constraints are especially important on strongly weathered soils, where low base status and exchangeable acidity restrict nutrient availability and weaken fertilizer-use efficiency. At the same time, urban markets and households generate large quantities of biodegradable residues, including banana, paw-paw and watermelon peels, while abattoirs and livestock enterprises produce animal manures. When these materials are unmanaged, they contribute to odour, vector proliferation, blocked drains and greenhouse-gas emissions. When they are biologically transformed, however, the same residues can become sources of renewable energy and nutrient-rich soil amendments.

The transition from waste disposal to nutrient recovery is central to circular agriculture. Anaerobic digestion provides a practical pathway because microorganisms decompose organic materials in oxygen-limited conditions and generate two useful products: biogas and digestate or bioslurry. The gaseous fraction can contribute to household or farm energy, whereas the residual slurry contains mineralised nutrients, microbial metabolites and partially stabilised organic matter. Its agricultural value depends on the biochemical quality of the feedstock, the balance between readily degradable carbon and nitrogen, digester pH and temperature, retention time and the interactions among hydrolytic, fermentative, acetogenic and methanogenic organisms. Thus, digestate should not be treated as a uniform product; its quality is a function of the materials and process from which it is derived.

Fruit peels are attractive feedstocks because they are abundant, moisture-rich and readily degradable. Yet single fruit wastes may contain an imbalanced carbon-to-nitrogen ratio, acidic compounds or insufficient buffering capacity. Cow dung can complement these materials by supplying nitrogen, alkalinity, active microbial consortia and micronutrients. Co-digestion may therefore improve process stability and create a bioslurry with a broader nutrient spectrum than single-substrate digestion. The agronomic question is whether this improved transformation is expressed after soil application through better chemical fertility, larger and more active microbial populations, enhanced crop growth and higher marketable yield.

Hot pepper (Capsicum frutescens L.) is a suitable test crop because it is economically important, nutrient demanding and widely cultivated in southern Nigeria. Pepper responds to nitrogen, phosphorus, potassium, calcium and magnesium, but its productivity may decline where soil acidity limits root development and nutrient uptake. Mineral fertilizers can provide immediately available nutrients, yet their cost, acidity effects and weak contribution to soil organic matter have encouraged interest in locally produced organic and biological inputs. A bioslurry that supplies nutrients while improving soil reaction and biological functioning could therefore address both short-term crop demand and longer-term soil quality.

Previous studies have established beneficial effects of biofertilizers, poultry manure, rhizobial inoculants and arbuscular mycorrhizal fungi on soil fertility and crop performance in Nigerian soils (Akpan et al., 2018; Uko et al., 2020; Omeke et al., 2022; Onnoghen et al., 2025). More recent work has highlighted the importance of decomposed organic residues for microbial biomass, enzyme activity and nutrient cycling in humid tropical plantations (Peter et al., 2026a, 2026b; Akpan et al., 2026a). However, fewer studies have followed the complete pathway from feedstock composition through anaerobic transformation, bioslurry microbiology, post-application soil change and crop response across contrasting seasons. Such an integrated assessment is necessary because a treatment that performs well in the digester may not necessarily produce the best field response, and a treatment that increases crop growth may not simultaneously improve soil biological quality.

This article therefore evaluates biofertilizers produced from watermelon, banana and paw-paw peels and cow dung, used singly and in combinations, as circular inputs for hot pepper production in Calabar, Nigeria. The specific objectives were to: (i) characterise the chemical and microbial transformation of the feedstocks during 45 days of anaerobic digestion; (ii) compare pH, temperature and cumulative gas-production dynamics; (iii) determine the effects of the resulting bioslurries on soil chemical and microbial properties; (iv) assess pepper growth, biomass and fruit production during wet and dry seasons; and (v) identify the feedstock combination that provides the most balanced agronomic and environmental performance.

Literature review

Biofertilizer, digestate and the circular nutrient economy

Biofertilizer is used in several related ways. In a narrow microbiological sense, it refers to formulations containing beneficial microorganisms that improve nutrient availability through biological nitrogen fixation, phosphate solubilisation, phytohormone production or enhanced root exploration. In an organic-resource context, the term may also include biologically transformed materials such as compost extracts and anaerobic digestates that carry nutrients, organic compounds and active microbial populations. The bioslurries evaluated in this study belong primarily to the second category, although their function is partly mediated by living organisms. Clear terminology is important because the agronomic action of a microbial inoculant cannot be assumed to be identical to that of a nutrient-bearing digestate.

Anaerobic digestion creates value from residues that would otherwise be discarded. Hydrolytic microorganisms break complex carbohydrates, proteins and lipids into soluble compounds; fermentative organisms produce volatile fatty acids; acetogens convert intermediates into acetate, carbon dioxide and hydrogen; and methanogens generate methane under suitable redox, temperature and pH conditions. The process reduces the concentration of easily decomposable carbon while conserving a substantial fraction of feedstock nutrients in the slurry. Consequently, the carbon-to-nitrogen ratio often narrows and ammoniacal nitrogen becomes more available. This can accelerate crop response, although excessive ammonia or salts may create phytotoxicity if digestate is applied at inappropriate rates.

The circular-economy value of digestate extends beyond fertilizer substitution. It links urban organic-waste management with renewable energy, soil restoration and local food production. In regions where municipal waste separation and centralized treatment are limited, small or medium batch digesters can provide a decentralised option. Their success, however, requires attention to feedstock hygiene, loading rate, retention time, gas safety, digestate maturity and nutrient-based application. A technically simple digester can still produce an agronomically inconsistent slurry if feedstocks are poorly mixed or process conditions are not monitored.

Feedstock complementarity and co-digestion mechanisms

Feedstock selection determines both digestion performance and fertilizer quality. Fruit peels contain soluble sugars, pectin, cellulose, hemicellulose, potassium and several micronutrients. Their high moisture content supports microbial activity, but their acidity and readily fermentable carbon may cause rapid volatile-acid accumulation. Cow dung is comparatively buffered and supplies nitrogen, minerals and diverse anaerobic organisms. Blending fruit peels with dung can therefore improve nutrient balance, dilute inhibitory compounds and reduce abrupt pH decline. The interaction is not merely additive: one material may supply a limiting nutrient or microbial group that enables more complete conversion of another.

An appropriate carbon-to-nitrogen balance is necessary because microbial cells require carbon for energy and nitrogen for protein synthesis. Very high C:N ratios can slow decomposition as available nitrogen becomes limiting, whereas very low ratios may increase ammonia formation. In the present feedstocks, co-digestion was expected to moderate these extremes and produce a more stable process. The four-way blend was particularly important because it combined the soluble carbon of fruit residues with the buffering and nitrogen contribution of cow dung. The broad substrate diversity also increases the probability that one feedstock supplies compounds missing from another.

Co-digestion can improve gas production when complementary materials increase biodegradability and sustain methanogenic activity. Nevertheless, higher gas production is not the only criterion of success. A farm-scale system should also retain useful nutrients, produce a biologically safe slurry, improve soil properties and increase crop productivity. Evaluation must therefore include both the digester and the field. This systems perspective distinguishes circular nutrient recovery from a narrow energy-yield assessment.

Soil microbial processes and rhizosphere functioning

Soil microorganisms regulate organic-matter decomposition, nutrient mineralisation, aggregate formation and many plant-health processes. Bacteria and fungi occupy different but overlapping ecological roles. Bacteria often respond rapidly to labile carbon and nutrient inputs, whereas fungi can exploit more complex substrates and contribute to aggregate stability through hyphal networks. Changes in total viable counts do not describe the entire microbial community, but they provide useful evidence of whether an amendment creates a more biologically active soil environment.

The rhizosphere is particularly important because root exudates stimulate microbial growth and microbial metabolites can alter plant nutrition. Rhizobacteria may fix nitrogen, solubilise phosphorus, produce siderophores and synthesise auxins or other growth-promoting substances. Arbuscular mycorrhizal fungi extend the nutrient-absorbing zone beyond the root surface and improve uptake of phosphorus and some micronutrients. Nigerian studies have shown that mycorrhizal inoculation, rhizobial inoculants and organic amendments can improve chemical fertility, microbial populations and crop performance, although responses depend on soil acidity, host crop, inoculation method and nutrient status (Akpan et al., 2013; Akpan et al., 2018; Uko et al., 2020; Akpan et al., 2026b).

Digestate influences microbial communities through several pathways. It supplies mineral nutrients and soluble carbon, changes pH, introduces microorganisms from the digestion process and modifies soil moisture retention. A moderate rise in soil pH can be especially beneficial in acid soils because it reduces aluminium stress and expands the range of conditions suitable for bacterial growth. Conversely, very alkaline or saline digestates may suppress sensitive organisms. The direction and magnitude of response must therefore be measured rather than assumed.

Organic amendments, acid-soil restoration and nutrient availability

Acid soils commonly exhibit low exchangeable bases, high aluminium activity and strong phosphorus fixation. Organic amendments can alleviate these constraints by adding basic cations, complexing aluminium, increasing cation-exchange capacity and stimulating mineralisation. Their effects may be gradual, but digestates can act more rapidly than raw residues because a portion of their nutrients has already been mineralised. The increase in pH after digestion also means that bioslurry may have a greater liming effect than the fruit waste.

Soil organic carbon is a central indicator because it influences aggregation, water retention, nutrient buffering and microbial habitat. Repeated mineral-fertilizer use without sufficient organic input may sustain yield for a period while failing to rebuild carbon stocks. Integrated nutrient management seeks to combine immediate nutrient availability with organic matter and biological processes. Research in continuously cropped Ultisols and other Nigerian soils has shown that integrated organic and inorganic nutrient sources can reduce degradation and improve nutrient-use efficiency (Nwanyieze et al., 2019; Aberagi et al., 2025).

The quality of an amendment should be judged across a set of indicators rather than by one nutrient concentration. Soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable calcium, magnesium and potassium, cation-exchange capacity, effective cation-exchange capacity and base saturation together describe the chemical environment available to plant roots and microorganisms. Improvements in several indicators at the same time provide stronger evidence of soil restoration than a large increase in one variable accompanied by deterioration in others.

Pepper nutrition, seasonal response and yield formation

Pepper yield is the outcome of sequential growth processes. Early nutrient availability supports leaf initiation and canopy expansion; a larger photosynthetic surface increases assimilate production; root growth improves access to water and nutrients; and successful flowering and fruit set determine the number and mass of harvested fruits. Treatments that enhance plant height but do not improve leaf area, biomass or fruit weight may have limited commercial value. Comprehensive assessment should therefore include both vegetative and reproductive traits.

Season can modify amendment performance through differences in soil moisture, nutrient leaching, temperature and disease pressure. Wet-season conditions may increase nutrient movement and microbial activity but can also intensify leaching and reduce oxygen around roots. Dry-season production requires adequate water supply and may expose plants to greater evaporative demand, yet nutrients may remain longer in the root zone. Evaluating the same treatments in both seasons provides a more reliable indication of agronomic robustness than a single-season trial.

Organic inputs may not always maximise fruit number, because fruit size and dry-matter accumulation can respond differently. A mineral fertilizer may stimulate rapid flowering or a large number of fruits, while a balanced organic treatment may produce heavier fruits and greater total biomass. For farmers, marketable yield, input cost, soil improvement and consistency across seasons are all relevant. The most appropriate treatment is therefore the one that combines crop productivity with soil-health benefits and feasible local production.

Fruit-Peel Waste Valorisation, Soil Microbial Health, and Hot Pepper Productivity

The conversion of fruit-peel waste into anaerobic biofertilizer reflects a growing emphasis on environmentally sustainable approaches to resource use, waste reduction, and ecosystem management. Organic wastes that are poorly managed may contribute to environmental pollution, unpleasant odour, greenhouse gas emissions, and the deterioration of local environmental quality. Sustainable environmental management therefore requires strategies that transform biodegradable waste into useful agricultural inputs rather than allowing it to accumulate in open dumps or drainage systems. Existing studies in Nigeria have increasingly emphasized the need to balance human activities, livelihood improvement, and environmental conservation through locally appropriate sustainability practices (Eneyo, 2025a; Onnoghen et al., 2024, 2025; Onnoghen & Anabaraonye, 2024). Similarly, research on environmental degradation and resource conservation has shown that unsustainable resource use can weaken ecosystem quality and reduce the long-term productive capacity of natural resources (Agbor et al., 2026; Onnoghen et al., 2024, 2025; Unimtiang et al., 2025). Within this context, the anaerobic conversion of fruit-peel waste into biofertilizer provides a practical circular approach by reducing organic waste while producing nutrient-rich material that may support soil fertility and agricultural productivity.

Soil health is strongly influenced by biological activity, nutrient availability, organic matter content, and the capacity of soil microorganisms to support nutrient cycling. Environmental studies in Cross River State and other parts of Nigeria have highlighted the close relationship between environmental quality, ecological processes, and sustainable livelihood systems (Inah et al., 2022; Igelle et al., 2023; Onnoghen et al., 2025). Although these studies did not specifically investigate fruit-peel biofertilizer, they demonstrate the importance of maintaining environmental conditions that support ecosystem productivity and resilience. Anaerobic biofertilizers derived from fruit residues may improve the soil environment by supplying decomposed organic matter and nutrients that stimulate microbial activity. This is particularly important because soil microorganisms contribute to the decomposition of organic materials, nutrient mineralisation, and the availability of essential nutrients required for crop growth. Sustainable agricultural practices that enhance soil biological functions may also reduce dependence on inorganic fertilizers and contribute to environmentally responsible production systems. Such an approach is consistent with broader sustainability perspectives that promote resource recovery, ecological conservation, and the productive reuse of locally available materials (Eneyo, 2025a; Onnoghen et al., 2024; Onnoghen et al., 2025).

Hot pepper production is economically important to many urban and peri-urban farmers in Calabar, but productivity may be constrained by declining soil fertility, high fertilizer costs, and inadequate organic soil amendments. Previous studies in Cross River State have examined environmental sustainability, livelihood transitions, tourism development, natural resource use, and community resilience (Eneyo & Archibong, 2024; Eneyo et al., 2023; Eneyo et al., 2026; Eyo et al., 2026). However, limited attention has been given to the agricultural potential of fruit-peel waste, particularly its anaerobic conversion into biofertilizer and its effects on soil microbial function and hot pepper productivity. The available literature therefore reveals an important gap concerning the relationship between organic waste recovery, soil biological health, and crop performance under local environmental conditions in Calabar. Investigating the effects of anaerobic fruit-peel biofertilizer on soil microbial activity and hot pepper growth may provide evidence for a low-cost and environmentally sustainable agricultural practice. The study may also contribute to current efforts aimed at improving resource efficiency, reducing biodegradable waste, strengthening soil health, and supporting sustainable livelihood development in Nigeria (Agbor et al., 2026; Eneyo, 2025a; Onnoghen et al., 2025; Unimtiang et al., 2025).

Knowledge gap and analytical proposition

The literature supports the separate use of biofertilizers, manures, microbial inoculants and decomposed plant residues, but evidence is more fragmented on the entire waste-to-crop pathway. Studies frequently report either biogas production, digestate chemistry, soil properties or crop yield. Fewer integrate all four levels, and fewer still compare multiple fruit-peel and cow-dung combinations under humid tropical field conditions. This limits the ability to explain why one formulation performs better than another.

The present study addresses this gap through an integrated analytical proposition: feedstock complementarity improves digestion stability and nutrient mineralisation; improved bioslurry quality changes the chemical and microbial environment of an acid soil; and the restored root-zone environment supports greater pepper growth, biomass and fruit production. The proposition does not assume that the treatment with the highest nutrient concentration must produce the highest yield. Rather, it expects performance to emerge from the combined effects of nutrient balance, pH buffering, microbial activity, organic matter and seasonal conditions.

Conceptual and analytical framework

The framework used in this article connects four sequential but interacting domains: feedstock quality, anaerobic transformation, soil response and crop performance. Feedstock quality is represented by the identity and combination of watermelon peel, banana peel, paw-paw peel and cow dung, together with their initial moisture, solids, pH, carbon and nutrient content. Anaerobic transformation is represented by the 45-day trajectories of temperature, pH and gas production and by the chemical and microbial properties of the resulting bioslurry. Soil response includes changes in acidity, organic carbon, macronutrients, exchangeable bases, cation-exchange properties and culturable bacterial and fungal populations. Crop performance includes canopy development, biomass allocation, fruit number and fresh and dry fruit mass.

The framework recognises feedback and mediation. For example, feedstock composition can affect digester pH, which influences microbial succession and the degree of mineralisation. Bioslurry pH and nutrient composition can then alter soil reaction and nutrient availability. Soil chemical improvement may stimulate resident microorganisms, while microbial activity can further mineralise organic compounds and enhance nutrient acquisition. Crop roots contribute additional rhizodeposits, meaning that plant growth and microbial activity reinforce one another. The observed field response is therefore interpreted as the outcome of a soil-plant-microbe system rather than as a direct fertilizer effect alone.

For decision making, treatment performance was considered across five criteria: process stability, gas production, bioslurry nutrient quality, soil restoration and crop productivity. A treatment was judged superior when it performed consistently across several criteria and across both seasons. This multi-criterion interpretation avoids selecting a formulation solely because it produced the largest gas volume or the highest value for one soil variable.

Methodology

Study area and experimental materials

The study was conducted at the Teaching and Research Farm of the Faculty of Agriculture, University of Calabar, Cross River State, Nigeria. Calabar lies within the humid tropical rainforest belt at approximately 5°00′–5°40′ N and 8°04′–8°62′ E, about 39 m above sea level. The area has a bimodal rainfall regime of approximately 2,500–3,500 mm annually, mean annual temperatures of about 22.2–38.2 °C and relative humidity commonly between 75 and 90%. High rainfall encourages leaching, and the dominant soils are generally acidic, with low base status and appreciable exchangeable aluminium.

Watermelon (Citrullus lanatus), paw-paw (Carica papaya) and banana (Musa acuminata) peels were collected from fruit vendors within Calabar metropolis. Fresh cow dung was obtained from the abattoir along Atimbo Road. Approximately 40 kg of each material was collected. Hot pepper (Capsicum frutescens L.) cv. Angel F1 served as the test crop.

Digester design and feedstock formulation

Locally fabricated 60-L batch anaerobic digesters were used. Each unit had a feed inlet, a sampling outlet and a gasometric assembly connected through tubing to a 100-mL graduated burette and a paraffin-oil displacement system. Gas volume was estimated from the volume of paraffin oil displaced. The batch configuration enabled the same feedstock to remain in the digester throughout the 45-day retention period.

Four single feedstocks, six two-material combinations and one four-material combination were prepared. Fruit peels were reduced to pulp before loading. For a single-feedstock treatment, 13 kg of substrate was mixed with water at a 1:3 substrate-to-water ratio. For two-material combinations, 6.5 kg of each component was used; for the four-material treatment, 3.25 kg of each component was combined to maintain a total substrate mass of 13 kg. Temperature, pH and gas production were monitored at five-day intervals.

Table 1. Feedstock and field-treatment structure

Treatment	Code	Description
T1	W	Watermelon peel
T2	C	Cow dung
T3	P	Paw-paw peel
T4	B	Banana peel
T5	W+C	Watermelon peel + cow dung
T6	W+P	Watermelon peel + paw-paw peel
T7	W+B	Watermelon peel + banana peel
T8	C+P	Cow dung + paw-paw peel
T9	C+B	Cow dung + banana peel
T10	P+B	Paw-paw peel + banana peel
T11	W+C+P+B	All four feedstocks
T12	NPK	NPK 15:15:15
T13	Control	No nutrient input

Note. W = watermelon peel; C = cow dung; P = paw-paw peel; B = banana peel.

Bioslurry analysis, field design and crop management

Before loading and after 45 days of digestion, samples were analysed for pH, total nitrogen, available phosphorus, organic carbon and exchangeable potassium, sodium, calcium and magnesium using standard soil and plant analytical procedures. Total viable bacterial and fungal populations were enumerated by culture-based methods. Isolates were characterised using colony morphology, microscopy and conventional biochemical tests. The microbial assessment was designed to compare broad culturable population changes rather than to resolve community composition by molecular methods.

The field experiment consisted of the eleven bioslurry treatments, an NPK 15:15:15 treatment and an unfertilized control. Treatments were arranged in a randomized complete block design with three replications, giving 39 experimental plots. The field measured approximately 34 m × 14 m. Each plot measured 2 m × 3 m and was separated by a 0.5-m alley; blocks were separated by 1 m. Bioslurry application volumes were adjusted according to nitrogen concentration to supply a theoretical nitrogen rate of approximately 80 kg N ha−1. NPK 15:15:15 was applied at 533 kg ha−1.

Pepper seedlings were raised for approximately five weeks in a sterilised soil-poultry-manure nursery medium and transplanted at 60 cm between rows and 40 cm within rows, equivalent to approximately 41,667 plants ha−1. Bioslurries were applied in split doses at 2, 4, 6, 8 and 10 weeks after planting. The trial was conducted during dry and wet seasons using comparable field procedures.

Soil, microbial and plant measurements

Composite soil samples were collected before treatment application and after the experiment from the 0–15 cm depth. Particle-size distribution, pH, organic carbon, organic matter, total nitrogen, available phosphorus, exchangeable bases, exchangeable acidity, cation-exchange capacity, effective cation-exchange capacity and base saturation were determined. Soil bacterial and fungal populations were assessed before and after treatment application.

Plant height, leaf length, leaf width, number of leaves, total leaf area and leaf-area index were measured at 4, 6, 8 and 10 weeks after planting. Leaf area was estimated from leaf length and width using an appropriate correction factor. At maturity, fresh and dry shoot weights, fresh and dry root weights, number of fruits and fresh and dry fruit weights were determined from sampled plants. Measurements were taken from the net plot to reduce border effects.

Data were subjected to analysis of variance appropriate for the randomized complete block design. Treatment means were separated using Duncan's multiple range test at the 5% probability level. Because this article synthesises a large experimental dataset, emphasis is placed on treatment direction, magnitude, seasonal consistency and agronomic interpretation. Letter groupings in the analysis indicate statistical differences among means within the same measurement occasion.

Quality assurance and limitations

The study used equal total substrate masses and a common dilution ratio to improve comparability among digesters. A uniform retention period and repeated monitoring schedule were maintained. In the field, blocking, replication and nutrient-based bioslurry application reduced the influence of spatial variability and unequal nitrogen supply. The inclusion of both NPK and unfertilized controls allowed the biofertilizers to be compared with conventional fertilizer and baseline soil productivity.

Several limitations should guide interpretation. Culture-based counts represent only the cultivable fraction of the microbial community. Gas values are reported in the units recorded by the gasometric system and should be treated comparatively rather than as industrial methane yields. The work was conducted at one location and on one pepper cultivar. Nutrient-release patterns, pathogen reduction, heavy metals and greenhouse-gas balances were not fully quantified. Multi-location trials, molecular microbial profiling and economic analysis are therefore required before broad recommendation.

Results and discussion

Initial feedstock characteristics and moisture status

The feedstocks were characterised by high moisture content, ranging from 82% in cow dung to 93% in watermelon peel and the watermelon-containing blends. Total solids ranged from 7% to 18%. These values confirm that the materials were suitable for wet anaerobic digestion and required only moderate dilution. The relatively higher solids content of cow dung increased the structural and nutrient density of mixtures containing dung, while the fruit peels supplied rapidly degradable carbohydrates and water.

Moisture-rich feedstocks support hydrolysis and microbial transport, but an excessively dilute slurry can reduce volumetric productivity. The common 1:3 substrate-to-water ratio created comparable hydraulic conditions across treatments. Differences in later gas production and bioslurry quality can therefore be interpreted primarily in relation to feedstock composition and microbial interactions rather than large differences in initial water availability.

Table 2. Moisture content and total solids of the digestion feedstocks

Feedstock	Moisture content (%)	Total solids (%)
B	89	11
P	92	8
C	82	18
W	93	7
W+B	93	7
W+P	93	7
C+P	85	15
W+C	89	11
C+B	86	14
P+B	91	9
W+C+P+B	91	9

Chemical transformation during anaerobic digestion

Anaerobic digestion substantially increased the measured nitrogen concentration of all feedstocks. Banana peel increased from 0.3% to 1.7% N, paw-paw from 0.6% to 3.4%, watermelon from 0.3% to 1.7% and cow dung from 0.7% to 5.6%. The greatest final nitrogen concentration, 8.4%, occurred in the four-substrate blend. The increase should be interpreted as concentration and transformation rather than creation of nitrogen: loss of carbon as biogas and mineralisation of organic nitrogen increased the proportion measured in the residual slurry. This concentration effect is one of the principal agronomic advantages of digestion.

Most initially acidic fruit-based feedstocks moved towards near-neutral reaction by day 45. Banana peel increased from pH 4.9 to 6.0, paw-paw from 3.0 to 5.9, watermelon from 4.3 to 6.0 and the four-way blend from 3.6 to 6.8. Cow dung remained alkaline, changing from pH 7.3 to 8.3 in the chemical dataset. The general rise indicates consumption of organic acids, generation of bicarbonate alkalinity and increasing ammoniacal buffering as digestion progressed. A near-neutral bioslurry is advantageous on the acid soils of Calabar because it is less likely than raw fruit waste to intensify acidity.

Phosphorus and exchangeable cations showed treatment-specific responses. The four-way blend retained 5.1 mg kg−1 P and contained 1.6, 0.8, 1.3 and 1.3 cmol kg−1 of K, Na, Ca and Mg, respectively. Although the absolute values differ among feedstocks, the mixed treatment provided the most balanced nutrient profile. Single wastes sometimes supplied one nutrient well but lacked others. Agronomic performance is therefore better explained by nutrient balance and soil interaction than by the maximum value of a single element.

Table 3. Selected chemical properties before and after 45 days of digestion

Feedstock	Initial N (%)	Final N (%)	Initial pH	Final pH	Initial P	Final P
B	0.3	1.7	4.9	6.0	3.1	3.1
P	0.6	3.4	3.0	5.9	2.1	3.1
W	0.3	1.7	4.3	6.0	3.2	4.3
C	0.7	5.6	7.3	8.3	5.2	5.4
W+B	0.3	1.1	4.0	6.4	3.8	6.3
W+P	0.4	1.7	3.0	6.5	3.7	3.2
C+P	0.5	4.5	3.5	6.2	3.7	3.2
W+C	0.6	1.8	4.8	6.6	4.2	3.1
P+B	0.6	3.4	3.4	5.8	3.8	6.9
C+B	0.6	6.7	6.2	7.6	4.6	4.4
W+C+P+B	0.6	8.4	3.6	6.8	6.3	5.1

Temperature, pH trajectory and cumulative gas production

Digester temperatures remained predominantly within the mesophilic range. Most treatments fluctuated between 28 and 31 °C, conditions suitable for the growth and metabolic activity of many anaerobic bacteria. The four-substrate treatment rose to 35 °C by day 40 and ended at 34 °C, suggesting greater metabolic heat associated with more active degradation. The relatively narrow temperature range across the experiment reduced the likelihood that abrupt thermal inhibition determined treatment differences.

pH changed more markedly than temperature. Acidic fruit substrates generally increased towards pH 6–7 during the first ten days, although temporary fluctuations occurred as fermentative acids accumulated and were subsequently consumed. The four-way treatment rose from pH 3.6 to 7.0 by day 5, reached 8.3 at day 15, then stabilised near 7.1 by day 45. This pattern is consistent with a transition from rapid acidogenesis to stronger acetogenic and methanogenic activity. Stable pH near neutrality is important because methanogens are more sensitive to acidification than many hydrolytic and fermentative organisms.

Cumulative gas production differed strongly among feedstocks. The four-way blend generated the largest cumulative volume, reaching 49.4 by day 45. Watermelon + cow dung ranked second at 24.0, closely followed by watermelon + banana at 23.4. Paw-paw + banana produced 18.4, cow dung + banana 12.6 and paw-paw alone 12.4. Watermelon alone, cow dung alone and watermelon + paw-paw recorded no measurable gas in the source dataset. The high output from the four-way mixture supports the feedstock-complementarity hypothesis: diverse carbon sources, additional nitrogen, buffering and a broader inoculum likely reduced nutritional limitations and sustained methanogenesis.

The result also demonstrates why co-digestion should not be designed solely by adding similar fruit wastes. Some two-fruit combinations performed weakly, whereas mixtures containing cow dung or banana often improved output. Cow dung alone did not generate measurable gas under the test conditions but enhanced several mixtures, indicating that its role may have been primarily as a buffer, nutrient source and microbial inoculum. The four-way blend integrated these functions more effectively than any single material.

Table 4. Cumulative gas production during the 45-day digestion period

Feedstock	Day 5	Day 15	Day 25	Day 35	Day 45
B	0	0	0	0	2.2
P	1.2	4.2	8.8	11.8	12.4
W	0	0	0	0	0
C	0	0	0	0	0
W+B	2	11	15.7	18.6	23.4
W+P	0	0	0	0	0
C+P	0	0	3.3	6.0	7.6
W+C	2	9	14.1	20.8	24.0
P+B	2	6.4	11.8	16.9	18.4
C+B	2	5.2	7.2	11.0	12.6
W+C+P+B	7	30	36.8	43	49.4

Note. Values are cumulative gas readings in the units recorded by the gasometric apparatus.

Microbial dynamics in the digesters

Total viable bacterial and fungal populations declined between the first day and day 45 in every feedstock, but substantial populations remained in the stabilised bioslurries. The decline is expected in a closed batch process because readily available substrates are progressively depleted and environmental conditions become more selective. It may also reflect the inability of the culture media and aerobic enumeration conditions to recover strict anaerobes that became important during digestion. Therefore, lower final plate counts should not be interpreted as absence of microbial activity.

The four-way mixture retained the largest final counts: 6.3×10^6 cfu g−1 bacteria and 3.9×10^5 cfu g−1 fungi. Paw-paw + banana retained 6.0×10^6 bacterial cfu g−1, while watermelon + cow dung retained 5.9×10^6. The same mixed treatment also had the highest initial fungal count and remained highest after digestion. The persistence of a diverse cultivable population may increase the biological value of the bioslurry after soil application, although field establishment depends on soil conditions and competition with resident organisms.

The microbial transformation observed here agrees with the principle that organic amendments can act as both nutrient sources and biological stimulants. Previous studies in Calabar and related humid tropical soils reported larger microbial populations following biofertilizer, poultry-manure and decomposed-litter application (Akpan et al., 2017; Akpan et al., 2018; Peter et al., 2026a). The present results extend that evidence by showing how microbial abundance is shaped before application by the digestion formulation itself.

Table 5. Total viable bacterial and fungal populations before and after digestion

Feedstock	Bacteria, day 1	Bacteria, day 45	Fungi, day 1	Fungi, day 45
B	4.2×10^6	3.1×10^6	2.3×10^5	1.5×10^5
P	5.6×10^6	3.9×10^6	3.6×10^5	2.8×10^5
W	3.8×10^6	2.4×10^6	2.7×10^5	2.0×10^5
C	6.6×10^6	5.4×10^6	4.1×10^5	3.2×10^5

Feedstock	Bacteria, day 1	Bacteria, day 45	Fungi, day 1	Fungi, day 45
W+B	5.5×10^6	3.7×10^6	3.6×10^5	1.9×10^5
W+P	5.7×10^6	4.1×10^6	3.4×10^5	1.6×10^5
C+P	7.4×10^6	5.8×10^6	4.2×10^5	2.8×10^5
W+C	7.9×10^6	5.9×10^6	3.9×10^5	2.5×10^5
P+B	8.3×10^6	6.0×10^6	4.0×10^5	2.7×10^5
C+B	7.3×10^6	5.7×10^6	3.4×10^5	1.8×10^5
W+C+P+B	8.1×10^6	6.3×10^6	4.7×10^5	3.9×10^5

Post-harvest soil chemical restoration

The experimental soil was initially acidic (pH 4.9), with 1.5% organic carbon, 0.1% total nitrogen, 38.3 mg kg−1 available phosphorus and low exchangeable magnesium, potassium and sodium. These properties are typical of highly weathered humid tropical soils in which intense rainfall and leaching reduce base status. The unfertilised control declined to pH 4.7 and available P of 28.1 mg kg−1, confirming that cropping without nutrient replacement can further deplete fertility.

All bioslurry treatments increased soil pH relative to the control, although the magnitude varied. The four-way blend produced pH 6.8, while cow dung and cow dung + banana produced pH 8.2 and 7.8, respectively. The NPK treatment remained acidic at pH 4.8. This contrast is agronomically important: mineral fertilizer supplied nutrients but did not correct the underlying acidity, whereas most bioslurries improved the root-zone chemical environment. A moderate increase towards pH 6–7 can reduce aluminium toxicity and improve the availability of phosphorus, calcium and magnesium.

The largest organic-carbon value, 3.4%, occurred under W+C+P+B, more than double the initial concentration. Several binary mixtures recorded 2.7–2.9%, whereas NPK and the control recorded 1.2%. The four-way treatment also increased total nitrogen to 0.3%, available phosphorus to 40.1 mg kg−1, exchangeable calcium to 5.8 cmol kg−1, potassium to 0.9 cmol kg−1, effective CEC to 9.2 cmol kg−1 and base saturation to 91.3%. These simultaneous improvements indicate broad soil restoration rather than isolated nutrient enrichment.

The increase in organic carbon likely reflects addition of partially stabilised organic compounds and greater rhizosphere biomass. Increased exchangeable bases can arise from direct nutrient supply, reduced leaching during the cropping period and pH-dependent changes in exchange sites. Higher effective CEC and base saturation improve the soil's capacity to retain nutrient cations. The response agrees with reports that integrated organic amendments and microbial inputs improve chemical fertility in Ultisols and other acid soils (Uko et al., 2020; Aberagi et al., 2025).

Cow dung alone raised pH strongly but did not produce the largest organic carbon or available phosphorus. Conversely, some fruit combinations increased carbon but supplied a less balanced suite of bases. The four-way formulation appears to have combined the liming and nutrient contribution of dung with the carbon and mineral diversity of fruit peels. This result illustrates the value of multi-feedstock design for soil amendment quality.

Table 6. Selected soil chemical properties before treatment and after harvest

Treatment	pH	Org. C (%)	T.N (%)	Avail. P	Ca	Mg	K	ECEC	BS (%)
Initial soil	4.9	1.5	0.1	38.3	4.2	0.2	0.1	5.4	85.2
B	6.1	1.6	0.2	38.3	5.1	0.4	0.1	6.7	88.1
P	6.0	1.6	0.2	37.4	4.3	0.4	0.3	6.1	86.9
W	6.1	1.4	0.3	38.1	4.6	1.0	0.3	7.1	90.1
C	8.2	1.5	0.2	34.4	4.0	1.1	0.4	6.7	88.1
W+B	6.5	2.8	0.2	37.7	5.8	1.2	0.6	8.9	93.3
W+P	6.7	2.4	0.2	40.1	5.0	1.2	0.6	8.3	89.2
C+P	6.2	2.9	0.3	38.2	4.6	1.1	0.6	8.0	86.3

Treatment	pH	Org. C (%)	T.N (%)	Avail. P	Ca	Mg	K	ECEC	BS (%)
C+B	7.8	2.9	0.3	38.3	5.6	1.1	0.6	9.0	87.3
W+C+P+B	6.8	3.4	0.3	40.1	5.8	1.1	0.9	9.2	91.3
NPK	4.8	1.2	0.2	30.1	3.2	0.3	0.6	4.9	87.8
Control	4.7	1.2	0.1	28.1	2.7	0.2	0.3	4.2	78.6

Note. Exchangeable bases and ECEC are in cmol kg−1; available P is in mg kg−1.

Soil bacterial and fungal response

Treatment application increased culturable bacterial and fungal populations above the initial soil values in most cases, although response differed by season and feedstock. During the wet season, cow dung + banana produced one of the largest bacterial populations, while watermelon + paw-paw produced the largest reported fungal population. The four-way treatment supported high populations of both groups and provided a more balanced biological response than treatments that favoured only one group.

The microbial response can be attributed to increased carbon substrates, improved pH and a greater supply of nitrogen and phosphorus. In acid soils, pH correction may be as important as organic carbon because many bacterial groups are constrained by strong acidity. Fungi often tolerate acidity more readily, but their abundance also responds to the type and complexity of added carbon. The differing responses among formulations indicate that bioslurry quality influenced the ecological niches available after application.

Greater microbial abundance does not automatically imply improved function, but it is consistent with stronger nutrient cycling and residue decomposition. Recent work in Ibiae oil-palm soils showed that decomposed leaf litter can increase microbial biomass, enzyme activity and fertility indices across landscape positions and depths (Peter et al., 2026a, 2026b). Together with the present findings, this suggests that locally available organic residues can be managed as biological resources rather than treated as waste.

Vegetative growth and canopy development

Bioslurry application significantly affected pepper height, leaf dimensions, leaf number, total leaf area and leaf-area index. Treatment differences became more pronounced as plants developed, indicating cumulative effects of nutrient release and rhizosphere improvement. The four-way treatment consistently ranked among the best treatments in both seasons and produced the tallest plants at 10 weeks after planting: approximately 45.3 cm in the wet season and 39.7 cm in the dry season. The unfertilised control remained much shorter.

Cow-dung-containing combinations generally performed better than many single fruit wastes, especially at later growth stages. Cow dung + paw-paw and cow dung + banana supported large leaf numbers, while W+C+P+B produced 147.7 leaves per plant in the wet season and 183.3 in the dry season at 10 weeks. The response reflects both nutrient supply and improved soil conditions. Nitrogen supports chlorophyll and vegetative growth, phosphorus supports root development and energy transfer, and potassium contributes to stomatal regulation and assimilate movement.

Total leaf area and leaf-area index provided stronger evidence of canopy productivity than plant height alone. In the dry season, the four-way blend produced a total leaf area of 2,473.6 cm^2 and a leaf-area index of 1.03 at 10 weeks, compared with 454.1 cm^2 and 0.19 in the control. In the wet season, W+C+P+B produced 3,414.3 cm^2 and a leaf-area index of 1.42, comparable with the strongest cow-dung-based treatments. A larger photosynthetic surface increases the capacity to intercept radiation and supply assimilates for flowering and fruit filling.

Nevertheless, the treatment ranking and associated leaf-area-index values consistently indicate a strong advantage for the mixed bioslurry. This transparent qualification is important because agronomic interpretation should not overstate precision where transcription or unit inconsistencies may exist.

Table 7. Selected pepper growth indicators at 10 weeks after planting

Season	Treatment	Height (cm)	Leaf length (cm)	Leaves plant−1	Total leaf area	LAI
Wet	W+C+P+B	45.3	5.87	147.67	3414.33	1.42
Wet	C+P	41.7	4.33	148.0	2236.7	0.93
Wet	C	36.8	6.87	136.33	3432.57	1.43
Wet	NPK	39.7	4.43	59.67	800.87	0.33
Wet	Control	24.53	2.77	81.67	327.9	0.14
Dry	W+C+P+B	39.73	5.27	183.3	2473.57	1.03
Dry	C+B	25.2	5.9	111.0	1656.47	0.68
Dry	C+P	32.7	3.53	154.3	1048.2	0.44
Dry	NPK	20.3	3.83	107.3	710.1	0.3
Dry	Control	15.87	3.13	84.0	454.07	0.19

Shoot and root biomass

The four-substrate bioslurry produced the greatest fresh shoot mass in both seasons: 27.90 g in the wet season and 23.43 g in the dry season. It also produced the highest fresh root mass, 3.50 g and 3.10 g, respectively. Dry shoot and root weights were among the highest treatment values. The response indicates that improved canopy growth was supported by a larger root system rather than by excessive shoot elongation alone.

Root biomass is particularly relevant in acid, highly leached soils because a larger root system explores a greater volume of soil and can improve water and nutrient acquisition. Organic amendments may support root growth by reducing aluminium stress, supplying calcium and phosphorus, improving aggregation and stimulating rhizosphere organisms. The combination of a near-neutral soil reaction and higher effective CEC under W+C+P+B likely created a more favourable root environment than the untreated or mineral-fertilized soil.

NPK produced moderate biomass but did not match the best bioslurry combinations. This suggests that nutrient availability alone did not explain performance. The organic treatments also altered pH, carbon status and microbial habitat. These complementary effects are consistent with the concept of integrated soil fertility management, in which productivity emerges from interactions among nutrient inputs, soil organic matter and biological processes.

Table 8. Pepper shoot and root biomass at harvest

Season	Treatment	Fresh shoot (g)	Dry shoot (g)	Fresh root (g)	Dry root (g)
Wet	W+C+P+B	27.9	6.9	3.5	1.57
Wet	C+B	24.17	6.83	3.1	1.43
Wet	C+P	23.3	7.13	3.17	1.27
Wet	NPK	21.57	5.3	2.4	1.2
Wet	Control	11.93	4.9	2.43	1.17
Dry	W+C+P+B	23.43	6.57	3.1	1.1
Dry	C+B	22.17	6.43	2.87	1.03
Dry	C+P	21.87	6.53	2.87	0.97
Dry	NPK	19.43	5.03	2.8	0.93
Dry	Control	17.13	3.87	2.23	1.17

Fruit production and agronomic effectiveness

Fruit number, fresh fruit mass and dry fruit mass responded significantly to treatment. In the wet season, NPK produced the largest fruit number (130.7), but its fresh fruit mass was only 47.0 g and dry fruit mass 4.43 g. The four-way bioslurry produced a statistically comparable high fruit number (124.7) and the greatest fresh and dry fruit masses, 113.3 g and 30.13 g. Thus, the mixed bioslurry supported not only fruit set but substantially greater fruit filling and dry-matter accumulation.

The same pattern was evident in the dry season. W+C+P+B produced the highest fruit number (35.3), fresh fruit mass (35.5 g) and dry fruit mass (8.4 g). The control produced 14.3 fruits, 14.3 g fresh mass and 3.73 g dry mass. The response was therefore robust across contrasting moisture regimes. Cow dung + watermelon and cow dung + paw-paw also performed well, confirming the benefit of formulations that combine animal manure with fruit residues.

The contrast between fruit number and fruit weight is agronomically meaningful. Mineral fertilizer may have promoted a larger number of wet-season reproductive sites, but the organic treatment sustained assimilate supply and nutrient availability during fruit development. Greater leaf area, root biomass and improved soil chemical properties under the four-way treatment provide a plausible mechanism. The larger dry fruit mass also indicates that the fresh-weight advantage was not merely a water-content effect.

From a farmer perspective, the best treatment should combine yield with input accessibility, soil improvement and waste-management benefits. The four-way formulation requires segregation and mixing of several residues, which may increase labour, but all components are locally available. Its superior and consistent performance suggests that the additional handling could be justified where organised collection systems exist. Simpler cow-dung-based binary mixtures may remain practical alternatives where one or more fruit wastes are unavailable.

Table 9. Pepper fruit production under selected treatments

Season	Treatment	Fruits plant−1	Fresh fruit weight (g)	Dry fruit weight (g)
Wet	W+C+P+B	124.67	113.3	30.13
Wet	NPK	130.67	47.03	4.43
Wet	C+P	115.33	99.92	18.53
Wet	C+B	106.33	93.37	18.27
Wet	Control	66.0	26.27	3.63
Dry	W+C+P+B	35.33	35.53	8.4
Dry	W+C	33.33	33.57	6.5
Dry	C+P	29.33	29.77	6.6
Dry	NPK	15.67	21.17	5.07
Dry	Control	14.33	14.27	3.73

Integrated treatment ranking and mechanistic interpretation

Across the complete evidence chain, W+C+P+B was the most consistently effective treatment. It produced the largest cumulative gas output, the highest final nitrogen concentration, high residual bacterial and fungal populations, broad improvement in soil fertility, the greatest shoot and root biomass and the largest fresh and dry fruit weights. No other treatment combined process, soil and crop performance as consistently. Its advantage supports the idea that functional diversity among feedstocks can improve both digestion and agronomic value.

The treatment effect can be interpreted through three linked mechanisms. First, co-digestion improved substrate conversion by balancing readily degradable fruit carbon with cow-dung nitrogen, minerals, buffering and inoculum. Second, the resulting bioslurry supplied a broader nutrient spectrum and increased soil pH and organic carbon, thereby improving nutrient retention and reducing acid-soil constraints. Third, the improved root-zone environment supported microbial activity, root growth and canopy development, which increased assimilate production and fruit filling.

The evidence also indicates that gas production and fertilizer value are related but not identical. Paw-paw alone produced moderate gas yet was not a top field treatment. Cow dung alone produced no measurable gas in the source system but substantially altered soil pH. Therefore, a formulation intended for a farm should be optimised according to the desired combination of energy recovery and crop response. Multi-objective optimisation may recommend a different blend from energy-only optimisation.

The strong performance of organic combinations relative to NPK should not be interpreted as evidence that mineral fertilizers are universally inferior. Mineral fertilizer provides concentrated nutrients and can be effective when soil acidity, organic matter and water are adequately managed. The present results show that, under the tested acid soil, the bioslurries provided functions beyond nutrient supply. Integrated use of digestate and carefully calibrated mineral fertilizer may further improve productivity, but such combinations require separate testing to avoid nutrient excess.

Table 10. Multi-criterion interpretation of leading treatments

Treatment	Gas response	Bioslurry quality	Soil response	Crop response	Overall interpretation
W+C+P+B	Highest	Highest final N; balanced bases	Strongest overall improvement	Highest biomass and fruit mass	Best integrated option
W+C	High	Moderate N; good buffering	Improved pH and bases	Strong fruit response	Promising binary option
C+P	Low-moderate	High final N	Good C, N and bases	High biomass and fruit mass	Strong soil-crop option
C+B	Moderate	High final N; alkaline	High C and ECEC	High biomass and fruit mass	Effective dung-based blend
NPK	Not applicable	Concentrated mineral nutrients	Did not correct acidity	High wet-season fruit number but lower mass	Useful comparator; soil constraints remain
Control	None	No nutrient addition	Further depletion	Lowest or near-lowest response	Unsustainable baseline

Discussion

Why the four-feedstock blend outperformed the single substrates

The superiority of the four-feedstock blend can be understood as an emergent property of substrate diversity. Watermelon and paw-paw peels provide readily fermentable carbohydrates and high moisture, banana peel contributes fibrous carbon and potassium-rich ash constituents, and cow dung supplies nitrogen, buffering compounds and a dense inoculum of organisms already adapted to anaerobic environments. When these materials were combined, no single feedstock characteristic dominated the process. Instead, the mixture reduced the likelihood that carbon, nitrogen, alkalinity, trace nutrients or microbial inoculum became limiting at the same time. The resulting balance is consistent with the higher gas output, stronger nitrogen concentration and broad field response observed for W+C+P+B.

Single-substrate digestion exposed the limitations of using one waste stream in isolation. Watermelon peel contained abundant moisture and soluble carbon but produced no measurable gas in the source system, possibly because rapid acidification or a shortage of buffering and methanogenic inoculum restricted conversion. Cow dung was alkaline and nutrient rich but also produced no measurable gas when used alone, perhaps because its degradable carbon fraction was insufficient under the loading and retention conditions. Banana and paw-paw produced some gas, but their final nutrient profiles were less balanced than the mixed treatment. These contrasts show that feedstock abundance alone is not an adequate basis for formulation.

The binary combinations demonstrate that complementarity depends on the identity of the partners. Watermelon + cow dung and watermelon + banana generated relatively high gas volumes, whereas watermelon + paw-paw did not. The first pair combined a rapidly degradable fruit waste with buffering, nitrogen and inoculum; the second combined a very moist feedstock with a more fibrous peel. By contrast, two acidic fruit wastes may have lacked sufficient buffering or microbial diversity. The practical implication is that co-digestion should be guided by functional characteristics rather than by convenience alone. A useful formulation deliberately combines carbon quality, nitrogen supply, alkalinity, moisture and inoculum.

The four-way treatment also reduced dependence on the variable composition of any one waste. Fruit residues change with cultivar, maturity, storage and market practices, while dung quality varies with animal diet and handling. A mixed formulation can buffer these fluctuations because a deficiency in one component may be compensated by another. This is particularly relevant for smallholder or market-based systems, where laboratory characterisation of every batch is unlikely. A standardised recipe based on several locally available residues may therefore produce more reliable output than a single-feedstock system, provided that the mixture is kept within an acceptable solids and loading range.

Interpreting nutrient concentration after digestion

The increase in measured nitrogen after digestion should be interpreted carefully. Anaerobic digestion does not add nitrogen to a closed system; rather, it changes nitrogen form and concentrates nutrients as carbon is converted to methane and carbon dioxide. Organic nitrogen in proteins and other compounds is hydrolysed and ammonified, increasing the fraction that can be extracted by analytical procedures and potentially increasing plant availability. At the same time, some nitrogen may be lost through ammonia volatilisation if pH and temperature are high. The large final nitrogen value in W+C+P+B therefore indicates efficient concentration and mineralisation, but a complete nitrogen balance would be needed to quantify retention.

The agronomic usefulness of mineralised nitrogen depends on synchrony with crop demand. Ammonium-rich digestate can provide a rapid nutrient response, yet it is also vulnerable to volatilisation, nitrification and leaching. Split application at 2, 4, 6, 8 and 10 weeks after planting was therefore an important feature of the field experiment. Repeated small doses likely maintained nutrient availability during canopy development and fruit filling while reducing the risk that a large initial application would exceed plant uptake. This strategy is particularly appropriate in Calabar, where intense rainfall can move nitrate below the effective rooting zone.

Phosphorus response was more complex because digestion can release phosphorus from organic compounds while also causing precipitation with calcium, magnesium or iron. The final bioslurry values therefore reflect both mineralisation and chemical partitioning. In the field, the four-way and watermelon + paw-paw treatments produced some of the highest available-phosphorus values, suggesting that organic ligands, pH adjustment and microbial processes increased the fraction extractable by plants. Organic acids and humic compounds can compete for phosphorus-sorption sites and complex aluminium and iron, which may reduce fixation in acid soils.

Exchangeable calcium, magnesium and potassium contributed to the broader fertility effect. These cations support cell-wall formation, chlorophyll function, enzyme activation, osmotic regulation and fruit quality. They also occupy exchange sites and increase base saturation. The bioslurry treatments supplied these elements while adding organic matter that increased retention capacity. This combination distinguishes organic amendments from a narrow nitrogen-only input. The four-way blend did not maximise every cation individually, but it produced a balanced chemical environment in which no major indicator was severely constrained.

Soil acidity, exchange processes and nutrient-use efficiency

The initial soil pH of 4.9 represents a major constraint to nutrient-use efficiency. At this reaction, exchangeable aluminium can inhibit root elongation, phosphorus can be strongly sorbed by iron and aluminium oxides, and the activity of many bacterial groups is reduced. Applying mineral fertilizer without correcting acidity may therefore produce a smaller response than the nutrient rate would suggest. The NPK treatment in the present study remained acidic and recorded lower organic carbon and effective exchange capacity than the leading bioslurries. Its performance demonstrates that nutrient addition and soil-condition improvement are related but distinct objectives.

Organic amendments increase pH through several mechanisms. Basic cations added with the material can replace hydrogen and aluminium on exchange sites. Organic anions generated during decomposition can consume protons, while functional groups in humified material can complex aluminium. Digestate may also contain bicarbonate and ammonium that contribute alkalinity. The relative importance of these processes differs among feedstocks. Cow-dung-rich treatments produced the largest pH increases, whereas fruit-dominated treatments generally moved the soil towards a moderately acidic or near-neutral range.

The most desirable pH response is not necessarily the highest. Cow dung alone increased soil pH to 8.2, which corrected acidity but may create micronutrient limitations if repeated over time. The four-way blend produced pH 6.8, a range suitable for pepper and favourable for the availability of many nutrients. This balanced response illustrates why treatment evaluation should consider target soil conditions rather than simply maximising an indicator. A formulation that raises pH excessively may require lower rates or blending with more acidic residues.

Increased organic carbon and effective cation-exchange capacity under the mixed bioslurries indicate greater nutrient-buffering potential. Weathered tropical soils often have variable-charge minerals whose exchange capacity increases with pH. Thus, the combination of added organic functional groups and higher soil pH can increase the number of negative exchange sites. More calcium, magnesium and potassium can then be retained against leaching. This mechanism provides a plausible explanation for the persistence of treatment effects through the season and for the improved crop response under high-rainfall conditions.

Base saturation integrates the proportion of effective exchange sites occupied by nutrient bases rather than acidic cations. The increase to more than 90% under several bioslurries indicates a root-zone environment dominated by calcium, magnesium, potassium and sodium rather than hydrogen and aluminium. Although sodium should not accumulate excessively, the observed values were modest relative to total exchange capacity. The lower base saturation of the control confirms continuing depletion, whereas the bioslurries replenished the exchange complex.

Microbial ecology and the meaning of viable counts

Culture-based bacterial and fungal counts are useful but incomplete indicators of soil biological quality. Only a fraction of soil organisms grow on standard laboratory media, and different media select for different physiological groups. The observed increases therefore show that the treatments supported a larger cultivable community, not that total microbial diversity was fully measured. Molecular sequencing, phospholipid fatty-acid analysis, microbial biomass carbon and enzyme assays would provide a more comprehensive view. Nevertheless, the consistent treatment differences remain valuable because all samples were assessed using the same procedures.

The decline in digester plate counts from day 1 to day 45 is compatible with ecological succession. Early in digestion, oxygen-tolerant and facultative organisms associated with fresh plant surfaces may be abundant. As oxygen is depleted and fermentation products accumulate, obligate anaerobes and syntrophic organisms become more important, many of which are not recovered by routine aerobic plating. By the end of the batch, depletion of readily available substrates can further reduce colony counts. The continued presence of millions of viable bacterial cells per gram indicates that the bioslurries remained biologically active.

After application, bioslurry microorganisms enter a complex soil community. Some may establish temporarily, while others may die and contribute nutrients to resident organisms. The amendment’s indirect effects may therefore be more important than permanent colonisation. Added carbon stimulates native decomposers, pH improvement expands suitable niches, and plant roots release exudates in response to improved growth. The observed field populations likely reflect the combined activity of introduced and indigenous communities rather than simple survival of digester isolates.

Bacterial and fungal responses differed among treatments because these groups exploit substrates differently. Labile compounds tend to favour fast-growing bacteria, while more complex plant polymers can support fungi. Cow-dung-based mixtures may introduce additional bacterial populations and nitrogen, whereas fruit residues provide pectin, cellulose and soluble sugars. The four-way treatment offered several carbon pools and a broad nutrient profile, explaining why it maintained high counts of both groups. A balanced bacterial-fungal response may support both rapid nutrient cycling and longer-term organic-matter transformation.

Microbial activity also interacts with plant health. Beneficial rhizobacteria can produce phytohormones, solubilise phosphorus, fix nitrogen or suppress pathogens through competition and antagonistic metabolites. Fungi contribute to decomposition and, where mycorrhizal propagules are present, may improve nutrient acquisition. The study did not directly identify functional genes or quantify disease suppression, so these mechanisms remain plausible rather than proven. Future work should connect community composition and enzyme activity with specific nutrient and plant-health outcomes.

Linking canopy development to fruit yield

The progression from early growth to fruit yield provides internal evidence that the treatment effects were biologically coherent. W+C+P+B produced a large canopy, high leaf-area index, strong shoot and root biomass and the greatest fruit mass. These variables represent connected stages of crop development. A larger root system improves resource acquisition; improved nutrient status supports leaf initiation and expansion; a larger canopy intercepts more radiation; and greater assimilate supply supports fruit growth. The agreement among variables strengthens the conclusion that the treatment effect was not an isolated statistical anomaly.

Plant height alone can be misleading because tall plants may be weak or sparsely foliated. In this study, the best treatments also increased leaf number and total leaf area. The four-way treatment produced exceptionally large leaf populations in both seasons. This canopy advantage likely increased photosynthetic capacity during fruit filling. The response of leaf-area index is especially informative because it relates leaf surface to ground area and therefore captures the capacity of the crop stand to intercept light. Values around 1.0–1.4 under leading treatments were substantially greater than those of the control.

Root biomass provided an additional explanation for seasonal consistency. During the dry season, plants depend more strongly on root exploration and irrigation management. The four-way treatment retained its advantage, suggesting that its effect was not restricted to high rainfall. Greater root mass may have improved access to water and nutrients and increased tolerance of short periods of water stress. Organic matter can also improve soil moisture retention and aggregation, although these physical properties were not fully reported after treatment and should be measured directly in future trials.

The wet-season difference between fruit number and fruit mass under NPK is noteworthy. NPK produced slightly more fruits than W+C+P+B, but the fruits had much lower fresh and dry mass. This may indicate greater competition among fruits for assimilates, less sustained nutrient release during filling, or a smaller effective canopy. The mixed bioslurry supported both a high fruit number and much greater individual or aggregate fruit development. Market value often depends on fruit size and quality as well as number, so fresh and dry mass are critical indicators.

Dry fruit mass is particularly useful because it reduces the influence of temporary water content. The very high wet-season dry fruit mass under W+C+P+B indicates substantial accumulation of structural and storage compounds. This suggests that the treatment improved actual productivity rather than simply increasing fruit hydration. The result warrants further quality analysis, including vitamin C, capsaicin, mineral composition, colour, firmness and shelf life. A soil amendment that improves yield but reduces quality would require a different recommendation from one that improves both.

Seasonal performance and resilience

Treatment rankings were not identical in wet and dry seasons, which is expected because nutrient release, leaching, root-zone aeration and crop water relations change with weather. Wet conditions favour microbial decomposition but can increase nutrient losses and root disease, while dry conditions can limit nutrient diffusion unless irrigation is adequate. The consistent superiority of the four-way blend across both seasons therefore provides stronger evidence than a one-season advantage. It suggests that the formulation created a broad improvement in soil conditions rather than exploiting a narrow weather pattern.

The lower absolute fruit numbers and weights in the dry season reflect the different production environment, but relative treatment effects remained clear. The control performed poorly, whereas cow-dung-based mixtures and the four-way blend maintained greater biomass and fruit production. This resilience may be linked to improved soil organic matter, root development and nutrient retention. Repeated application over several seasons could strengthen these benefits, although long-term accumulation and residual effects must be measured rather than assumed.

High rainfall in Calabar creates a strong test of nutrient retention. Soluble mineral nutrients can be leached rapidly, especially on coarse-textured or low-CEC soils. Organic amendments release nutrients over time and can increase exchange capacity, potentially improving synchrony with crop demand. The wet-season performance of the mixed bioslurries is therefore consistent with improved nutrient buffering. Direct measurements of soil mineral nitrogen at intervals, leachate chemistry and nutrient-use efficiency would help confirm this mechanism.

Seasonal interpretation should also consider microbial dynamics. Soil moisture strongly affects oxygen diffusion and the relative activity of aerobic and anaerobic organisms. Very wet soil may reduce nitrification or promote denitrification, while dry soil can suppress microbial activity. Bioslurry may moderate some effects through organic matter and improved structure. Future experiments should monitor soil moisture, temperature and redox potential alongside microbial and nutrient measurements to explain seasonal treatment interactions more precisely.

Comparison with related Nigerian evidence

The present findings align with a growing body of Nigerian research showing that biological and organic inputs can improve soil properties and crop performance. Uko et al. (2020) reported improvement in chemical properties of an Ultisol following poultry manure and arbuscular mycorrhizal fungi application. The combined effect is conceptually similar to the present bioslurry response because organic matter supplies nutrients and modifies the soil environment while microorganisms extend or accelerate nutrient acquisition. Both studies indicate that biological processes are most effective when the soil resource base is also improved.

Akpan et al. (2018) showed that poultry manure and arbuscular mycorrhizal fungi affected microbial population dynamics and Amaranthus growth in crude-oil-affected soil. That study emphasised restoration under contamination, whereas the current work addresses nutrient-poor acid soil. Despite the different stressors, both demonstrate that organic amendments can stimulate microbial communities and support plant recovery. The consistency across crops and soil conditions strengthens the case for integrating organic matter with beneficial microbial processes.

Recent studies in Ibiae oil-palm plantation provide additional support for residue-based soil management. Peter et al. (2026a, 2026b) linked decomposed leaf litter with changes in soil physical, chemical and microbial properties, microbial biomass, enzyme activities and fertility indices. Those studies focused on surface litter decomposition within a perennial plantation, while the present study used anaerobically digested residues in an annual vegetable system. Together, they show that organic residues can be transformed through different pathways and still contribute to nutrient cycling and biological activity.

The soybean studies of Omeke et al. (2022a, 2022b) highlight the importance of biological nitrogen fixation, phosphorus supply and multivariate soil productivity indicators. Their work demonstrates that crop response is controlled by interacting soil properties rather than by a single nutrient. The present multi-criterion interpretation follows the same logic: the four-way bioslurry performed well because it improved several chemical and biological indicators simultaneously. Multivariate analysis of the current dataset could further identify which soil variables most strongly predict pepper yield.

Aberagi et al. (2025) and Nwanyieze et al. (2019) emphasised integrated nutrient management and the residual value of combined amendments. The present experiment compared bioslurries with NPK but did not test bioslurry-NPK combinations. This is an important next step. A reduced mineral-fertilizer rate combined with the four-way digestate may provide rapid early nutrition while maintaining soil carbon and pH. The optimum ratio should be determined experimentally because excess nutrient loading could increase losses and reduce economic efficiency.

Methodological strengths and sources of uncertainty

A major strength of the study is its connected design. The same feedstocks were tracked through chemical and microbial characterisation, digestion monitoring, bioslurry production, soil application and crop response. This allows plausible mechanisms to be examined rather than reporting yield without information on input quality. The use of both NPK and unfertilised controls also provides two relevant benchmarks: conventional nutrient supply and no-input soil productivity.

The randomized complete block design with three replications is appropriate for field variability, and the two-season evaluation improves external validity. Repeated growth measurements reveal the development of treatment effects through time. The range of soil indicators is another strength because it captures acidity, carbon, nutrient supply, exchange properties and biological response. The dataset is therefore richer than studies that measure only final yield.

The study also contains uncertainties that should be addressed before journal submission. Some units and table headings in the thesis are inconsistent, and a small number of leaf-area values appear unusually large. All values should be checked against laboratory sheets, field notebooks and statistical output. Gas-volume units should be explicitly stated and, where possible, converted to standard volume per kilogram of volatile solids. The composition of the biogas, especially methane percentage, should also be measured in future work.

The nutrient analyses would benefit from a complete mass balance. Concentration data alone cannot distinguish mineralisation from water loss, carbon loss and nutrient volatilisation. Recording initial and final dry mass, total Kjeldahl nitrogen, ammonium nitrogen, total and soluble phosphorus, potassium and volatile solids would permit calculation of nutrient recovery efficiency. Similarly, methane yield should be expressed relative to volatile solids added and destroyed.

Microbial analysis should be expanded beyond total plate counts. High-throughput sequencing could identify bacterial and fungal taxa enriched by each feedstock and after soil application. Quantitative PCR could track functional genes involved in nitrogen fixation, nitrification, denitrification, phosphorus cycling and methanogenesis. Enzyme assays for dehydrogenase, phosphatase, urease and beta-glucosidase would connect community change with nutrient-cycling function. These methods would clarify whether the observed population increases translate into greater ecosystem process rates.

Economic analysis is also necessary. The feedstocks may be free at source, but collection, sorting, transport, pulping, digester construction, labour, water, gas storage and slurry application have costs. Benefits include avoided waste-disposal cost, biogas value, reduced mineral-fertilizer purchase, higher pepper yield and potential long-term soil improvement. A partial budget and sensitivity analysis should compare single, binary and four-way formulations under realistic farm scales. The most productive treatment may not be the most profitable if feedstock logistics are difficult.

Research agenda for scalable circular biofertilizer systems

Future research should first validate the treatment across soil types and locations. Calabar soils are acidic and highly leached, so the liming and exchange effects of bioslurry are particularly valuable. Responses may differ on neutral, calcareous, saline or clay-rich soils. Multi-location trials should include representative coastal plain sands, basement-complex soils and inland Ultisols. Site-specific soil tests can then be used to develop application-rate recommendations.

Long-term experiments are required to determine cumulative effects. Repeated digestate use may increase soil carbon, aggregate stability, infiltration and water-holding capacity, but it may also build phosphorus, potassium or salts. Annual nutrient budgets should quantify inputs, crop removal, leaching and residual pools. Monitoring should extend below the surface layer to determine whether nitrate or dissolved organic carbon moves into deeper horizons and groundwater.

Product safety should be assessed before commercialisation. Anaerobic digestion can reduce pathogens, but removal efficiency depends on temperature, retention time and organism. Tests should include faecal coliforms, Salmonella, helminth eggs and other relevant indicators. Fruit wastes may also contain pesticide residues, while manure can contain veterinary pharmaceuticals or antimicrobialresistance genes. Quality standards should define acceptable limits and specify whether post-digestion storage or sanitisation is required.

Process optimisation should compare different feedstock ratios rather than only equal-mass combinations. Response-surface or mixture-design experiments can identify the proportions that maximise methane yield, nitrogen retention and crop performance simultaneously. The optimum ratio may contain less cow dung than the present blend if buffering remains adequate, or more dung if a highly acidic fruit stream is used. Continuous or semi-continuous digesters should also be compared with batch systems to improve operational relevance.

Biogas and bioslurry should be evaluated as co-products within one system boundary. A formulation that maximises methane but produces a nutrient-poor slurry may be less valuable to a vegetable farm than one with moderate gas output and excellent fertilizer quality. Multi-criteria decision analysis can assign weights to energy, nutrient recovery, soil improvement, yield, cost and environmental risk. Different users may choose different weights: households may prioritise gas, while commercial growers may prioritise crop yield and soil health.

Finally, adoption research should examine farmer perceptions, labour requirements, gender roles, ownership models and willingness to pay. Technology succeeds when it fits local routines and provides visible benefits. Demonstration plots can show crop response, but users also need confidence in gas safety, odour control and product consistency. Cooperative ownership may spread capital costs, while service providers could collect waste and sell standardised bioslurry. Social and institutional design is therefore as important as biological performance.

Operational framework for farm-scale application

Feedstock collection, preparation and blending

A practical farm-scale programme should begin with predictable feedstock collection. Fruit vendors should separate watermelon, banana and paw-paw residues from plastics, paper, metals and spoiled packaged foods at the point of generation. Cow dung should be collected from a known source and protected from excessive soil contamination. Separate covered containers reduce odour, prevent rainwater dilution and make the material easier to weigh. A simple collection schedule linked to market activity can reduce storage time and maintain a more uniform feedstock quality.

Preparation should aim to increase surface area without adding unnecessary energy cost. Large peels can be chopped or pulped manually or with a low-power shredder. The material should be weighed before mixing so that the intended recipe is maintained. The equal-mass formulation used in the experiment offers a simple starting point, but operators should record the actual masses and water volume for every batch. These records allow poor-performing batches to be traced to a change in composition, dilution or retention time.

Water quality is also important. Water containing detergents, disinfectants, high salt concentrations or industrial contaminants can inhibit microorganisms and reduce digestate safety. Clean well water, rainwater or other uncontaminated sources are preferable. The slurry should be mixed thoroughly before loading to avoid floating layers and dead zones. Where fibrous banana peel is abundant, smaller particle size and effective mixing may improve hydrolysis and reduce scum formation.

Batch loading should leave sufficient headspace for gas accumulation and should not exceed the working volume of the digester. All joints, valves and tubing should be checked for leakage before operation. A water or soap-bubble test can identify escaping gas around fittings. The gas line should include a moisture trap where feasible, and the system should be kept away from naked flames. Operators should understand that methane is combustible and that enclosed spaces require adequate ventilation.

Routine monitoring and process control

Temperature and pH are the most useful low-cost monitoring variables. Temperature should be recorded at the same time of day because ambient conditions can create diurnal variation. In the Calabar climate, passive mesophilic digestion is feasible, but digesters exposed to direct sunlight may overheat while shaded units may remain cooler. A stable temperature is generally more important than achieving the highest possible value. Sudden changes can disturb microbial interactions and reduce gas production.

pH should be checked at regular intervals with a calibrated meter or reliable strips. A rapid decline below about pH 6 may indicate accumulation of volatile fatty acids and insufficient buffering. Corrective action should be gradual and based on the cause. Adding a buffered inoculum or adjusting the feedstock mix is preferable to indiscriminate addition of strong alkali, which can create local inhibition and unsafe digestate. Consistent records of pH and gas production help distinguish normal start-up behaviour from process failure.

Gas production should be interpreted as a trend rather than as a single reading. A rising cumulative curve indicates active conversion, while an early plateau may reflect substrate depletion or inhibition. Operators should check for leaks before concluding that microbial activity has failed. In a simple displacement system, the measuring liquid, tubing and valves must remain unobstructed. Standardising gas measurements to temperature, pressure and feedstock dry matter would improve comparability across batches and sites.

Retention time should be long enough to stabilise the slurry but not so long that digester capacity is used inefficiently. The 45-day period employed in the experiment produced substantial chemical transformation and a mature agronomic response. However, optimum retention time may change with temperature, particle size and loading rate. Pilot monitoring can determine when gas production has largely ceased and pH has stabilised. Digestate should then be removed in a way that prevents oxygen entry into the gas system and avoids uncontrolled discharge.

Bioslurry storage, handling and field delivery

Fresh digestate should be stored in a covered, leak-proof container. Covering reduces ammonia loss, prevents dilution by rainfall and limits mosquito breeding. Storage areas should be located away from wells, streams and flood-prone land. A secondary containment structure is advisable for larger systems. The slurry should be labelled by batch date and feedstock formulation because nutrient content can differ substantially among mixtures. Where laboratory analysis is available, the label should include pH, total nitrogen and key nutrient values.

Field application should be based on crop requirement and measured nutrient concentration. The experimental practice of adjusting volumes to nitrogen content is scientifically stronger than applying the same number of litres from every digester. Farmers may initially require extension support to convert laboratory concentrations into litres per plot or per plant. Simple calculators or printed rate charts can make this process practical. The rate should also consider residual soil fertility, expected yield and nutrients supplied by other organic or mineral inputs.

Split application is recommended for pepper because nutrient demand continues through vegetative growth, flowering and fruit development. Applying smaller amounts around the root zone at several growth stages can improve synchrony and reduce loss. The slurry should not be poured directly against the stem, and contact with edible fruits should be avoided. Light incorporation or application before irrigation can reduce ammonia volatilisation. Application immediately before intense rainfall should be avoided because runoff and leaching may remove nutrients and contaminate surface water.

Workers should use gloves and basic hygiene during handling, especially where the hygienic quality of the digestate has not been verified. Equipment used for slurry should not be used for drinking water or food. Hands and tools should be washed after application. Although anaerobic digestion can reduce pathogens, complete sanitation cannot be assumed in a low-temperature batch system. A short post-digestion storage period, pathogen testing or additional treatment may be required for commercial products or for crops eaten raw.

Farm economics and adoption pathways

The economic attractiveness of the technology depends on scale and the value assigned to each co-product. Costs include digester construction, feedstock collection, transport, chopping, water, labour, maintenance, gas appliances, slurry storage and field application. Benefits include biogas, reduced fertilizer purchase, higher crop yield, avoided waste-disposal cost and possible sale of surplus bioslurry. Long-term improvement in soil fertility may also reduce future input needs, although this benefit is difficult to value in a short experiment.

A partial-budget approach can compare the additional cost and additional return of each formulation. The four-way blend produced the highest yield response but requires access to all four feedstocks. A binary blend may be more profitable where transport distance is lower or one residue is available in large quantities. The correct economic comparison is therefore not simply yield per plot; it is net return per unit of land, labour and capital. Sensitivity analysis should test changes in pepper price, fertilizer price, labour cost and biogas value.

Adoption is likely to be easier when the system solves an existing waste problem. Market associations may be willing to provide fruit waste at low cost if collection reduces odour and disposal pressure. Abattoirs may benefit from cleaner manure management. Farmer cooperatives can share the capital cost of a digester and organise regular feedstock collection. In such arrangements, clear rules are needed for ownership, labour contribution, gas access, slurry allocation and maintenance responsibility.

Extension demonstrations should show the entire process rather than only the final crop response. Farmers need to see how feedstocks are selected, mixed and monitored and how application rates are calculated. Demonstration plots should compare the mixed bioslurry, a common local fertilizer practice and an untreated control. Visible differences in soil condition, plant growth and fruit yield can build confidence, while transparent discussion of labour and safety prevents unrealistic expectations.

Commercialisation requires consistent product quality. A producer who sells bioslurry should use a standard recipe, retention period and storage method and should periodically test nutrient composition. Product labels should avoid unsupported claims such as guaranteed disease control or universal yield increase. Instead, they should provide measurable information and clear application instructions. Trust in the market will depend on reproducibility, not merely on the use of the term biofertilizer.

Sustainability indicators for future evaluation

A complete sustainability assessment should combine agronomic, environmental, economic and social indicators. Agronomic indicators include nutrient concentration, soil pH, organic carbon, microbial activity, crop yield and product quality. Environmental indicators include waste diversion, methane capture, nutrient loss, water quality, greenhouse-gas emissions and soil-carbon change. Economic indicators include capital cost, operating cost, input savings, energy value, net return and payback period. Social indicators include labour demand, safety, participation, gender implications and user acceptance.

Waste-diversion performance should be measured as the mass of clean organic material processed per unit time. This allows communities to compare digestion with open dumping, composting or transport to a central facility. Nutrient-recovery efficiency should be calculated from the nutrient mass entering in feedstocks and leaving in bioslurry and harvested crop. Such accounting can reveal whether nitrogen is being lost as ammonia or whether phosphorus is accumulating in soil beyond crop demand.

Greenhouse-gas evaluation should include methane leakage from the digester and storage system, carbon dioxide from energy use and transport, nitrous oxide after field application and avoided emissions from uncontrolled decomposition and mineral-fertilizer manufacture. Soil-carbon sequestration should be measured over several years because a short-term increase in organic carbon may partly reflect undecomposed input. Life-cycle assessment can integrate these flows and identify the stages where design improvements have the greatest benefit.

Water-quality protection should be a core indicator in the humid tropics. High rainfall can transport nutrients from storage areas and fields into drains, streams and shallow groundwater. Monitoring nitrate, ammonium, phosphorus, biochemical oxygen demand and faecal indicators around demonstration sites would provide evidence of environmental safety. Buffer strips, covered storage and weather-based application scheduling can reduce risk. The aim of circular nutrient management is to close nutrient loops, not to transfer pollution from solid waste to water.

Social sustainability depends on who performs the work and who receives the benefits. Feedstock collection and slurry application can be labour intensive, and these tasks may fall disproportionately on women, youth or hired workers. Technology design should reduce unnecessary lifting and direct contact with waste. Training and decision-making should include all user groups. Where gas is used for cooking, reduced fuelwood demand and indoor smoke exposure may provide important household benefits that are not captured by crop yield alone.

Environmental and practical implications

The findings support a circular bioeconomy strategy in which biodegradable market and livestock wastes are collected, co-digested and returned to agricultural land as nutrient-rich bioslurry. This approach can reduce the amount of organic waste deposited in drains, open dumps and uncontrolled decomposition sites. It also captures a portion of the energy potential as biogas. The combined environmental value may exceed the fertilizer value alone, particularly where waste-management costs and cooking-energy needs are substantial.

Implementation should begin with source separation. Fruit wastes contaminated with plastics, metals or chemicals reduce digestate quality and increase handling costs. Collection agreements with fruit vendors, markets and abattoirs can provide predictable feedstock volumes. Small cooperatives, institutional farms and peri-urban producer groups may be suitable operators because they can aggregate residues and distribute both gas and bioslurry. Training is needed on digester loading, leak detection, pH monitoring, safe gas use and slurry storage.

Application rates should be nutrient based. The bioslurries differed considerably in nitrogen concentration and pH, so equal-volume application would create unequal nutrient loading. Farmers should use simple laboratory testing or validated formulation guidelines and avoid applying fresh slurry directly to seedlings at excessive rates. Storage should minimise nutrient loss and runoff, and application should be timed to crop demand. Split application, as used in this experiment, can improve synchrony and reduce leaching under high rainfall.

Soil testing remains essential. Strongly alkaline dung-rich bioslurries may be beneficial on very acid soils but could overcorrect pH or increase salt load with repeated use. Monitoring pH, electrical conductivity, organic carbon, nitrogen, phosphorus and exchangeable bases can prevent imbalance. Where digestate is used over several seasons, heavy metals, pathogens and emerging contaminants should also be evaluated, even when the feedstocks are predominantly plant residues and cattle manure.

The evidence has relevance for climate-smart agriculture, but a complete greenhouse-gas assessment was beyond the study. Capturing methane as biogas can reduce uncontrolled emissions from decomposing wastes, while replacing part of mineral fertilizer production may reduce embodied energy. However, methane leakage from digesters, nitrous-oxide emissions after slurry application and transport requirements can offset benefits. Future life-cycle assessment should therefore quantify the net climate effect rather than assuming that all digestion systems are automatically low carbon.

The approach also has educational and entrepreneurship value. Universities and agricultural colleges can operate demonstration digesters that integrate soil science, microbiology, crop production, engineering and environmental management. Students can learn how organic residues move through a production system and how process monitoring affects output quality. Local fabrication of digesters, feedstock logistics and bioslurry marketing may create rural and peri-urban enterprises, provided product quality is standardised and claims are supported by analysis.

Policy implications

State and local governments should recognise segregated organic residues as agricultural resources and support partnerships among markets, abattoirs, waste managers and producer groups. Pilot programmes can establish collection points for fruit peels and manure and provide matching support for small digesters.

Such programmes should include clear responsibilities for feedstock quality, plant operation, gas safety and digestate distribution.

Extension services should develop formulation-specific guidance rather than promoting “biofertilizer” as a single uniform input. Recommended materials should state feedstock composition, retention period, nutrient concentration, pH, application rate and suitable crops. The present results indicate that mixed feedstocks can outperform single wastes, but the best formulation may differ with available residues and soil type. Locally validated decision charts would improve adoption and reduce misuse.

Quality standards are needed for commercial bioslurry. Minimum labelling requirements should include total nitrogen, available phosphorus, potassium, organic carbon, pH, electrical conductivity, moisture content and hygienic status. Where microbial claims are made, the organisms, viable concentration and shelf-life conditions should be specified. Standards would protect farmers from poorly stabilised or nutrient-deficient products and create confidence in a developing biofertilizer market.

Research funding should support multi-location and long-term trials. A single-season yield increase does not establish sustained soil improvement. Repeated application may build organic carbon and microbial function, but it may also accumulate phosphorus or salts. Long-term experiments should measure nutrient budgets, crop rotations, residual effects, soil enzymes, microbial diversity, greenhouse gases and economic returns. The National Research Fund and agricultural innovation programmes can support this interdisciplinary work.

Urban planning and waste policy should include decentralised biological treatment in areas where organic residues are concentrated. The proximity of markets, abattoirs and peri-urban farms creates an opportunity for short nutrient loops. Spatial planning can identify suitable digester sites that minimise transport distance while protecting water bodies and residential areas. Environmental permitting should address odour, effluent containment, gas storage and emergency procedures without imposing barriers that make small, well-managed systems impossible.

Implications for soil-health assessment and extension practice

Soil-health assessment should move beyond routine measurement of pH, nitrogen and phosphorus. The present study shows that amendment effects are better understood when chemical indicators are interpreted together with organic carbon, exchange properties, microbial populations and crop response. A treatment may supply nutrients but fail to improve acidity or carbon status, while another may improve soil reaction without producing the strongest yield. Extension recommendations should therefore use a small dashboard of indicators rather than a single laboratory value. For acid tropical soils, the most informative minimum set would include pH, organic carbon, total nitrogen, available phosphorus, exchangeable calcium and magnesium, effective cation-exchange capacity and base saturation.

Biological indicators should also be incorporated where facilities permit. Total plate counts are relatively inexpensive and can provide an initial indication of microbial response, but microbial biomass carbon, respiration and enzyme activities may be more closely related to nutrient cycling. Soil-health laboratories could develop standard packages that combine chemical and biological measurements for organic-amendment trials. Such packages would help distinguish a product that simply adds soluble nutrients from one that improves the functioning and resilience of the soil system.

Extension messages should explain that organic amendments are not automatically safe, mature or effective. Feedstock quality, digestion conditions and application rate determine performance. Raw fruit wastes applied directly to soil can immobilise nitrogen, attract pests or create local acidity, whereas properly digested material is more stabilised and nutrient available. Farmers should therefore be trained to recognise signs of incomplete digestion, including persistent foul odour, unstable pH, vigorous residual gas release and undecomposed feedstock. Simple maturity checks can reduce crop damage and improve confidence in the technology.

Local recommendations should be expressed in practical units. Farmers need to know the litres of bioslurry per plant, per planting bed or per hectare, the amount of dilution required and the timing of each application. These values should be linked to measured nitrogen concentration and expected crop demand. Demonstrations should show how to calibrate a bucket or watering can so that the target rate is delivered consistently. Without such translation, laboratory evidence may not become reliable farm practice.

The response of pepper also suggests that extension advice should include crop-management conditions that allow the amendment to perform. High-quality seedlings, appropriate spacing, weed control, irrigation during dry periods and timely harvesting remain necessary. Biofertilizer cannot compensate for severe water stress, poor plant population or uncontrolled pests. Integrated crop management is therefore the correct framework: the amendment improves the soil-plant environment, while other agronomic practices protect the crop's ability to use those resources.

Farmer field schools could compare formulations using participatory scoring. Farmers may evaluate plant vigour, leaf colour, fruit size, harvest frequency, labour requirement, odour and ease of application alongside measured yield. Their observations can identify practical advantages or constraints that formal experiments overlook. For example, a thicker slurry may have high nutrient concentration but be difficult to transport and apply. Participatory evaluation can therefore improve both technology design and adoption.

The university has an important role in supporting evidence-based scaling. A demonstration and testing centre could receive local feedstocks, prepare standard formulations, analyse bioslurry quality and provide training to farmers, students and entrepreneurs. The centre could maintain a database linking feedstock composition with gas output, nutrient recovery, soil response and crop performance. Over time, this would create locally relevant decision-support tools and reduce dependence on recommendations developed for different climates and waste streams.

Partnership with environmental-health agencies would strengthen safety. Organic-waste recovery should be designed to reduce public-health risks at markets and abattoirs, not merely to obtain fertilizer. Collection containers, transport vehicles and processing areas should be cleaned regularly, and runoff should be contained. Operators should have access to protective equipment and clear procedures for spills, gas leaks and equipment failure. Safety standards are especially important if the technology is promoted among schools, youth groups or community cooperatives.

For policymakers, the most useful evidence from this study is not that one recipe will be universally optimal, but that locally available wastes can be engineered into higher-value products through purposeful blending and process control. This shifts policy from indiscriminate waste disposal towards resource recovery. Incentives should reward measurable outcomes such as tonnes of organic waste diverted, methane safely utilised, nutrient recovery, reduced fertilizer expenditure and improved soil carbon. Outcome-based programmes are more likely to encourage quality than subsidies based only on the number of digesters installed.

Ultimately, soil restoration is a cumulative process. The strong one-cycle response of W+C+P+B is encouraging, but sustainable management requires repeated measurement and adaptive application. Farmers should test soil periodically, reduce rates when nutrient levels become high and combine bioslurry with crop rotation, residue retention and erosion control. Used in this way, anaerobic biofertilizer becomes one component of a broader soil-health strategy rather than a stand-alone input. The long-term objective is productive soil that retains nutrients, supports diverse biological activity and remains resilient under variable rainfall and rising input costs.

Data reporting and publication readiness

Before formal journal submission, the dataset should be subjected to a final audit that reconciles every table with the laboratory sheets, field notebooks and statistical output. Treatment codes should be standardised throughout, especially where the order of letters differs between C+W and W+C or B+P and P+B. Units should be stated once in each table heading and used consistently. Values with unusually large magnitudes, particularly selected wet-season leaf-area observations, should be verified and corrected only where the primary record supports a change. Transparent data checking strengthens the manuscript without altering valid experimental findings.

The article would also benefit from a compact supplementary dataset containing the treatment structure, replicate-level observations, analysis-of-variance output and mean-separation results. Sharing these materials would allow readers to reproduce the major comparisons and apply alternative analyses. A data dictionary should define every variable, season, sampling time, unit and treatment code. Where raw microbial counts were transformed before analysis, the transformed values should be retained. Reproducible reporting is especially valuable for complex experiments in which multiple soil, microbial and crop indicators are measured repeatedly.

Future publication should clearly distinguish measured findings from proposed mechanisms. The increases in soil pH, organic carbon, microbial counts, biomass and fruit mass are direct observations. Explanations involving aluminium complexation, improved nutrient retention, phytohormone production or microbial functional diversity are scientifically plausible and supported by related literature, but they were not all measured directly. Maintaining this distinction prevents overstatement and identifies the most useful variables for follow-up experiments.

Finally, author information, correspondence details, ethical or institutional approvals where applicable, data ownership and acknowledgement of technical support should be confirmed before submission. The current manuscript is structured as a full research article and retains the JESBER visual pattern, but journal-specific requirements for word count, citation style, table number, data availability and declarations should be checked at the point of submission. These final steps will ensure that the scientific contribution is presented with the same care applied to the experimental work.

The manuscript also creates a foundation for comparative work across vegetable crops. Pepper has a relatively long reproductive phase and high nutrient demand, but leafy vegetables, tomato, okra and maize may respond differently to the same bioslurries. Short-duration crops may benefit more from immediately mineralised nutrients, whereas longer-duration crops may exploit gradual release and residual effects. A coordinated series of trials using a common soil-health protocol would clarify whether the four-way blend is broadly effective or specifically suited to pepper under the tested conditions.

Another priority is to examine product consistency across batches and seasons of feedstock supply. Fruit composition varies with maturity and moisture, and cow-dung chemistry changes with animal diet. Replicate digesters prepared at different times should be compared for gas production, nutrient concentration, pH, microbial quality and field performance. Establishing acceptable ranges rather than one fixed value will make recommendations more realistic and will support development of quality-control limits for commercial production.

These additional evaluations would convert a successful experimental formulation into a dependable production technology. Scientific scaling requires evidence that the process can be repeated, that the product remains safe and agronomically effective, and that farmers can operate it at a reasonable cost. The present results provide a strong biological basis for that progression and identify the measurements needed at each stage.

Conclusion

The study demonstrates that banana, paw-paw and watermelon peels and cow dung can be transformed through anaerobic digestion into useful biofertilizers for acid-soil restoration and hot pepper production. Feedstock combination strongly influenced process behaviour and agronomic value. The four-substrate blend produced the highest cumulative gas output, the greatest final nitrogen concentration, high residual microbial populations and the most balanced improvement in soil chemical properties.

In the field, W+C+P+B increased soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable bases, effective cation-exchange capacity and base saturation. These improvements were accompanied by larger microbial populations, greater canopy development, higher shoot and root biomass and the highest fresh and dry fruit masses across wet and dry seasons. Its performance indicates that complementary feedstocks can create a bioslurry whose value is greater than that of its individual components.

The principal contribution of the article is the integration of waste conversion, digestion dynamics, bioslurry microbiology, soil restoration and crop response within one analytical pathway. The evidence supports co-digestion as a practical circular-agriculture strategy for humid tropical environments, but recommendations should remain nutrient based and quality controlled. Multi-location validation, long-term soil monitoring, pathogen and contaminant assessment, molecular microbial analysis, economic evaluation and life-cycle greenhouse-gas accounting are required to support large-scale adoption. The study recommended that:

1. The four-substrate formulation should be prioritised for further field validation because it gave the most consistent combined performance in the digester, soil and crop.
2. Farmers and cooperatives should apply bioslurry according to measured nutrient concentration rather than equal volume, with split application timed to crop demand.
3. Fruit markets and abattoirs should establish source-separated collection systems to supply clean feedstocks for decentralised anaerobic digestion.
4. Extension agencies should provide practical training on feedstock ratios, digester pH, gas safety, slurry maturation, storage and field application.
5. Long-term trials should evaluate residual fertility, nutrient accumulation, soil enzymes, microbial community composition, pepper quality and profitability.
6. Commercial products should be subject to minimum nutrient, pH, electrical-conductivity and hygienic-quality standards before sale.

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Author contribution

The author did the entire study

References

Abbassi, M. K., Sharif, S., Kazmi, M., Sultan, T., & Aslam, M. (2011). Isolation of plant growth-promoting rhizobacteria from wheat rhizosphere and their effect on improving growth, yield and nutrient uptake of plants. Plant Biosystems, 145, 159–168.

Abdul, B. R. (2009). Use of biofertilizers in crop production. Soil and Environment, 28, 1–10.

Aberagi, F. V., Akpan, J. F., Otie, V. O., Olim, D. M., Achia, H. L., Ikor, M. S., et al. (2025). Impact of organic and inorganic amendments on soil chemical properties and soybean crop performance in Nsukka, southeastern Nigeria. Faculty of Agriculture International Conference Book of Proceedings, 89–98.

Agbor, C. N., Etim, O. E., Arikpo, E. B., Apeh, C. A., Orji, E. I., Ugbaka, M. A., Odey, F. I., Atemgweye, G. I., Effiom, A., & Eneyo, V. B. (2026). Socio-economic impacts of conservation policies on women's livelihoods in forest-dependent communities around Cross River National Park, Nigeria. African Journal of Hospitality, Tourism and Leisure, 15(2), 306–315. https://doi.org/10.46222/ajhtl.19770720.740

Ahemad, M., & Kibret, M. (2014). Mechanisms and applications of plant growth-promoting rhizobacteria: Current perspective. Journal of King Saud University – Science, 26, 1–20.

Akpan, J. F., Aberagi, F. V., Achia, H. L., Umunnakwe, O. C., & Effiom, D. O. (n.d.). Effects of NPK and biofertilizer on some soil properties, growth and yield of fluted pumpkin (Telfairia occidentalis) in Calabar, Cross River State, Nigeria.

Akpan, J. F., Afangide, A., & Peter, P. G. (2026). Influence of mycorrhiza inoculation methods and rhizobial inoculants on the growth and yield of soybean (Glycine max Merr. L.) in Calabar, Nigeria. Global Journal of Agricultural Sciences, 25, 19–25.

Akpan, J. F., Dijeh, A. E., Peter, P. G., & Elemi, E. D. (2026). Evaluation of microbial characteristics of soil influenced by decomposed leaf litter in Ibiae oil palm plantation, Cross River State, Nigeria. Journal of Environmental Sciences and Built Environment Research, 1(1), 51–65.

Akpan, J. F., Ijah, C. J., Isong, I. A., Umunnakwe, O. C., & Aberagi, F. V. (2023). Distribution of soil organic carbon and important soil nutrient ratios along toposequence in humid tropics of Nigeria. Agro-Science, 22(4), 51–63.

Akpan, J. F., Isong, I. A., & Solomon, M. G. (2019). Comparative studies of microbial properties in wetland and coastal plain soils of Calabar agro-ecological zone. Proceedings of the 43rd Annual Conference of the Soil Science Society of Nigeria, 372–382.

Akpan, J. F., Njoku, N. R., & Ochim, E. (2020). Assessment of pH and microbial properties of limestone and basement complex soils derived from Akamkpa Local Government Area, Cross River State. Proceedings of the 44th Conference of the Soil Science Society of Nigeria, 388–395.

Akpan, J. F., Udo, I. A., Afu, S. M., Isong, I. A., & Solomon, M. G. (2020). Influence of biofertilizer on soil properties, growth and yield of hot pepper (Capsicum frutescens) in Calabar, Cross River State, Nigeria. Research article.

Akpan, J. F., Udo, I. A., Etukudo, N. E., & Solomon, M. G. (2013). The effects of arbuscular mycorrhizal fungi on the growth of tomatoes. Proceedings of the 37th Annual Conference of the Soil Science Society of Nigeria, 19–24.

Akpan, J. F., Udo, I. A., Ibrahim, A., Iren, O. B., & Ijah, C. J. (2018). Effects of poultry manure amendment and arbuscular mycorrhizal fungi inoculation on microbial population dynamics and growth of Amaranthus cruentus in crude-oil-affected soil. Nigerian Journal of Soil Science, 28(1), 308–315.

Asikong, B. E. (2013). Design and performance evaluation of a locally fabricated anaerobic digester. Unpublished research report, University of Calabar.

Atieno, M., Herrmann, L., Nguyen, H. T., Phan, H. T., Nguyen, N. K., Srean, P., et al. (2012). Assessment of biofertilizer use for sustainable agriculture. Journal of Environmental Management, 95, S214–S220.

Berova, M., & Karanatsidis, G. (2009). Physiological response and yield of pepper plants to organic fertilization. Journal of Central European Agriculture, 9(4), 715–722.

Berova, M., Karanatsidis, G., Sapundzhieva, K., & Nikolova, V. (2010). Effect of organic fertilization on growth and yield of pepper plants. Folia Horticulturae, 22, 3–7.

Bhattacharya, P., & Kumar, R. (2000). Liquid biofertilizer: Current knowledge and future prospect. Fertilizer News, 45, 29–31.

Bokhtiar, S. M., & Sakurai, K. (2005). Effects of organic manure and chemical fertilizer on soil fertility and productivity of plant and ratoon crops of sugarcane. Archives of Agronomy and Soil Science, 51, 325–334.

Boraste, A., Vamsi, K. K., Jhadav, A., Khairnar, Y., Gupta, N., Trivedi, S., et al. (2009). Biofertilizers: A novel tool for agriculture. International Journal of Microbiology Research, 1(2), 23–31.

Chen, J. H. (2006). The combined use of chemical and organic fertilizers and/or biofertilizer for crop growth and soil fertility. International Workshop on Sustained Management of the Soil-Rhizosphere System, Bangkok, Thailand.

Cioabla, A. E., Ionel, I., Dumitrel, G. A., & Popescu, F. (2012). Comparative study on factors affecting anaerobic digestion of agricultural vegetal residues. Biotechnology for Biofuels, 5, 39.

Clark, P. J., & Evans, F. C. (1954). Distance to nearest neighbor as a measure of spatial relationships in populations. Ecology, 35(4), 445–453. https://doi.org/10.2307/1931034

Debska, B., Dlugosz, J., & Piotrowska-Dlugosz, A. (2016). The impact of a biofertilizer on soil organic matter status and carbon sequestration: Results from a field-scale study. Journal of Soils and Sediments, 16, 2335–2344.

El-Ghany, B. F. A., Arafa, R. A. M., El-Rahmany, T. A., & El-Shazly, M. M. (2010). Effect of some soil microorganisms on soil properties and wheat production under north Sinai conditions. Journal of Applied Sciences Research, 6, 124–132.

Eneyo, V. B. (2025a). Environment: An introduction to environmental science. IDbeyond Printing Press.

Eneyo, V. B. (2025b). Essentials of tourism for beginners. University of Calabar Press.

Eneyo, V. B. (2025c). Tourism for beginners II. University of Calabar Press.

Eneyo, V. B. (2026a). Tourism support services, environmental management and sustainable destination development in Uyo, Nigeria: Spatial and socio-economic evidence. Journal of Environmental Sciences and Built Environment Research, 1(1), 227–240. https://doi.org/10.83374/jesber.vol1no1.23

Eneyo, V. B. (2026b). Where the city eats: Spatial clustering, distance-decay and patronage rhythms of eateries in Calabar, Nigeria. Journal of Environmental Sciences and Built Environment Research, 1(1), 1–13.

Eneyo, V. B., & Archibong, A. A. (2024). Examining socio-economic implications of tourism development in Nigeria. World Tourism Journal, 2(2), 61–82.

Eneyo, V. B., & Ekpenyong, E. J. (2018). Spatial distribution of petrol filling stations in Calabar South Local Government Area, Cross River State. Multi-Disciplinary Journal of Research and Development Perspectives, 7(1), 66–83.

Eneyo, V. B., Atemgweye, G. I., Imanyi, V. U., & Essien, D. A. (2023). Tourism as a catalyst for entrepreneurial development: Insights from Cross River State, Nigeria. World Tourism Journal, 1, 1–19.

Eneyo, V. B., Onnoghen, U. N., Apeh, C. A., Ajom, S. K.-O., Ugbaka, M. A., Odey, F. I., Odinka, G. E., Effiom, A. F., Atemgweye, G. I., Anake, C. B., & Imanyi, V. U. (2026). Conservation constraints and aquatic livelihood transitions among riverine women in the Cross River Basin, Nigeria. Egyptian Journal of Aquatic Biology and Fisheries, 30(3), 3845–3869. https://doi.org/10.21608/ejabf.2026.486766.7906

Eneyo, V. B., Talib, J., Attah, F. M., & Offiong, E. E. (2022). Iran’s nuclear policy: Nature, ambition, and strategy. Journal of Liberty and International Affairs, 8(2), 202–222. https://doi.org/10.47305/JLIA2282202e

Enwezor, W. O., Udo, E. J., Usoroh, N. J., Ayotade, K. A., Adepetu, J. A., Chude, V. O., & Udegbe, C. I. (1989). Fertilizer use and management practices for crops in Nigeria. Federal Ministry of Agriculture, Water Resources and Rural Development, Lagos.

Eyo, E. E., Eneyo, V. B., Apeh, C. A., Ekpo, E. E., Ajom, S. K.-O., Ugbaka, M. A., Odinka, G. E., Effiom, A., Imanyi, V. U., & Ajake, A. O. (2026). Strengthening hotel safety protocols through routine inspections: Evidence of regional compliance disparities in Cross River State, Nigeria. African Journal of Hospitality, Tourism and Leisure, 15(2), 419–427. https://doi.org/10.46222/ajhtl.19770720.750

Fawzy, Z. F., El-Bassiony, A. M., Li, Y., Ouyang, Z., & Ghoname, A. A. (2012). Effect of mineral, organic and bio-N fertilizers on growth, yield and fruit quality of sweet pepper. Journal of Applied Sciences Research, 8, 3921–3933.

Giller, K. E., & Wilson, K. J. (1991). Nitrogen fixation in tropical cropping systems. CAB International.

Gomez, K. A., & Gomez, A. A. (1984). Statistical procedures for agricultural research (2nd ed.). John Wiley & Sons.

Grubben, G. J. H., & Denton, O. A. (2004). Plant resources of tropical Africa 2: Vegetables. PROTA Foundation/Backhuys Publishers.

Harrison, M. J. (2005). Signaling in the arbuscular mycorrhizal symbiosis. Annual Review of Microbiology, 59, 19–42.

Hazarika, B. N., & Ansari, S. (2007). Biofertilizers in fruit crops: A review. Agricultural Reviews, 28(1), 69–74.

Igelle, E. I., Abua, M. A., Agbor, C. N., Esuabana, S. B., Akpanika, E. N., Arikpo, E. B., Onnoghen, U. N., Akintoye, O. A., Eneyo, M. B., & Eneyo, V. B. (2023). Relative influence of XCO_2 on climate variables and rice yield in Ohafia, Abia State, Nigeria. Environment and Ecology Research, 11(4), 586–603. https://doi.org/10.13189/eer.2023.110407

Inah, E. O., Eneyo, V. B., Odey, S. A., Ushie, M. A., Udonwa, R. E., Esuabana, S. B., Ekpo, E. E., Akintoye, O. A., & Ajake, A. O. (2022). Anthropogenic impacts on water quality of Kedong Stream in Idomi, Yakurr, Nigeria. Environment and Ecology Research, 10(6), 738–748. https://doi.org/10.13189/eer.2022.100609

International Institute of Tropical Agriculture. (1979). Selected methods for soil and plant analysis. Manual Series No. 1. IITA.

Kalemelawa, F., Nishihara, E., Endo, T., Ahmad, Z., Yeasmin, R., Tenywa, M. M., & Yamamoto, S. (2012). An evaluation of aerobic and anaerobic composting of banana peels treated with different inoculums for soil nutrient replenishment. Bioresource Technology, 126, 375–382.

Klasson, K. T., & Nghiem, N. P. (2003). Energy production from zoo animal wastes. Oak Ridge National Laboratory.

Li, M., Fang, L., Huang, X., & Goh, C. (2015). A spatial-temporal analysis of hotels in urban tourism destination. International Journal of Hospitality Management, 45, 34–43. https://doi.org/10.1016/j.ijhm.2014.11.005

Lim, S., & Mutu, S. U. (2015). Utilization of agro-waste to produce biofertilizer. International Journal of Energy and Environmental Engineering, 16(1), 31–35.

Manyi-Loh, C. E., Mamphweli, S. N., Meyer, E. L., Okoh, A. I., Makaka, G., & Simon, M. (2013). Microbial anaerobic digestion as an approach to decontamination of animal wastes, pollution control and renewable energy generation. International Journal of Environmental Research and Public Health, 10, 4390–4417.

Mohammadi, K., & Sohrabi, Y. (2012). Bacterial biofertilizers for sustainable crop production: A review. ARPN Journal of Agricultural and Biological Science, 7(5), 307–316.

Nahed, M. M., El-Sayed, E., El-Badawy, H. M., & Tolba, H. I. (2015). Response of sweet pepper plants to some organic and biofertilizers and their effect on fruit yield and quality. Middle East Journal of Agriculture Research, 4(3), 435–445.

Nasir, A., Khan, F. H., Riaz, M., & Khan, M. A. (2014). Comparative effect of biogas slurry and farmyard manure as fertilizer on maize. Pakistan Journal of Agricultural Sciences, 49(4), 527–531.

Nelson, D. W., & Sommers, L. E. (1982). Total carbon, organic carbon and organic matter. In A. L. Page et al. (Eds.), Methods of soil analysis, Part 2 (2nd ed.). ASA and SSSA.

Nwanyieze, R. N., Akpan, J. F., & Ogbonna, M. C. (2019). Residual effect of integrated nutrient management as a tool to combat soil degradation in continuously cropped Ultisol. Proceedings of the Crop Science Society of Nigeria, 6, 39–44.

Ogbaji, D. I., Unimtiang, U. S., Onnoghen, U. N., & Ogar, T. O. (2025). Communal feud and social vices among youths in Cross River State, Nigeria. International Journal of Economics, Environmental Development and Society, 6(2), 190–208.

Omeke, J. O., Uzoma, K. C., & Akpan, J. F. (2022a). Biological nitrogen fixation and biomass production under soybean genotypes and phosphorus fertilizer application in the Northern Guinea Savanna agro-ecology of Nigeria. Nigerian Journal of Soil Science, 32(2), 62–69.

Omeke, J. O., Uzoma, K. C., & Akpan, J. F. (2022b). Multivariate analysis of soil productivity indicators in the Northern Guinea Savanna agro-ecology of Nigeria. Ukrainian Journal of Ecology, 12(11), 12–22.

Onnoghen, U. N. (2026a). Reproductive agency, women’s community mobilisation and environmental health education in localising Sustainable Development Goals 3, 5 and 6: Evidence from Calabar Education Zone, Nigeria. Journal of Environmental Sciences and Built Environment Research, 1(1), 66–77. https://doi.org/10.83374/jesber.vol1no1.11

Onnoghen, U. N. (2026b). Women’s environmental leadership and community advocacy for localising Sustainable Development Goals 3, 5 and 6 in Ikom Education Zone, Cross River State, Nigeria. Journal of Environmental Sciences and Built Environment Research, 1(1), 14–25. https://doi.org/10.83374/jesber.vol1no1.7

Onnoghen, U. N., Adeniyi, T. F., Omeokachie, A. I., Olisah, N. C., & Anabaraonye, B. (2024). Mitigating the negative effects of flooding on sustainable economic growth in Nigeria. Environmental Pollution and Health, 2(1), 1–6. https://doi.org/10.61148/EPH/008

Onnoghen, U. N., Anabaraonye, B., & Enwereuzo, D. C. (2024). The role of non-governmental organizations in enhancing climate resilience in Nigeria. International Journal of Climate Change and Environmental Sustainability, 1.

Onnoghen, U. N., Anabaraonye, B., Owoh, I. M., Aganyi, O. A., & Odoh, C. C. (2025). Climate-resilient strategies for enhancing eye health care for sustainable development in Nigeria. Academic Research Journal of Science and Technology, 1(10), 125–135.

Onnoghen, U. N., Inyang, I. O., Agbor, C. N., Ajom, S. K., Apeh, C. A., Osaji, N. N., Onuoha, E., Iwuanyanwu, I. O., & Eneyo, V. B. (2025). Balancing livelihoods and conservation in protected areas: Insights from forest-adjacent communities. African Journal of Hospitality, Tourism and Leisure, 14(2), 481–490. https://doi.org/10.46222/ajhtl.19770720.625

Onnoghen, U. N., Kujoh, J. U., Unachukwu, S. S., Orji, E. I., & Anabaraonye, B. (2025). Enhancing eco-tourism through eco-volunteerism in Nigeria. Eco-Tourism and Sustainable Development, 1(2). https://doi.org/10.63385/etsd.v1i2.231

Onnoghen, U. N., Nwobu, E. A., Odoh, C. C., & Anabaraonye, B. (2024). Enhancing climate resilience through ecumenism for sustainable development in Nigeria. Annals of Reviews and Research, 12(1), Article 555830. https://doi.org/10.19080/ARR.2024.12.555830

Onnoghen, U. N., Olisah, N. C., Ewa, B. O., Nwobu, E. A., & Anabaraonye, B. (2024). Youth engagement in eco-poetry for enhancing climate change education in Nigeria. Journal of Current Trends in Agriculture, Environment and Sustainability, 5(4), 1–5.

Onnoghen, U. N., Onwuzurike, U., & Anabaraonye, B. (2025). Tree planting: A veritable strategy for climate adaptation and disaster risk reduction in Nigeria. Modern Concepts & Developments in Agronomy, 15(1), 1464–1467. https://doi.org/10.31031/MCDA.2025.15.000855

Onnoghen, U. N., Sylvanus, U. U., Abeng, T. I., Onnoghen, O. R., Anthony, E. A., & Bassey, S. O. (2023). Religious tourism and the economic development of Calabar Municipal, Cross River State, Nigeria. Journal of Institute of Africa Higher Education Research and Innovation, 1(1). https://doi.org/10.59479/jiaheri.v1i001.23

Onnoghen, U. N., Unachukwu, S. S., Orji, E. I., Ewa, B. O., & Anabaraonye, B. (2024). The role of libraries in promoting climate literacy in Nigeria. Recent Archives of Journalism and Mass Communication, 1(2), 1–5. https://doi.org/10.19080/RAJMC.2024.01.555559

Onnoghen, U. N., Unimtiang, U. S., Nwagbara, M. O., Onnoghen, R. U., Amadi, J. O., & Chinwemeri, B. C. (2024). Firewood extraction and forest resources degradation in Yakurr Local Government Area of Cross River State. Journal of Environmental and Tourism Education, 7(1), 69–78.

Onnoghen, U. N., Unimtiang, U. S., Onnoghen, R. U., Amadi, J. O., & Chinwemeri, B. C. (2024). WhatsApp usage and academic achievement of environmental education students in the post-COVID-19 era in Cross River State, Nigeria. Journal of Environmental and Tourism Education, 7(1), 119–132.

Onnoghen, U.N., Inyang, I.O., Agbor, C.N., Ajom, S. K., Apeh, C.A., Osaji, N.N., Onuoha, E., Iwuanyanwu, I.O. & Eneyo, V.B. (2025). Balancing Livelihoods and Conservation in Protected Areas: Insights from Forest-Adjacent Communities. African Journal of Hospitality, Tourism and Leisure, 14(2):481-490.

Peter, P. G., Akpan, J. F., Akpan, J. L., & Dijeh, A. E. (2026a). Impact of decomposed leaves on soil physical, chemical and microbial properties in Ibiae oil palm (Elaeis guineensis) plantation, Cross River State, Nigeria. Global Journal of Agricultural Sciences, 25(1), 85–92.

Peter, P. G., Akpan, J. F., Akpan, J. L., & Dijeh, A. E. (2026b). Toposequence-depth dynamics of soil microbial biomass, enzyme activities and fertility indices under decomposed oil palm leaf litter in Ibiae Plantation, Nigeria. Journal of Environmental Sciences and Built Environment Research, 1(1), 214–226.

Rodríguez-Rangel, M. C., Sánchez-Rivero, M., & Ramajo-Hernández, J. (2020). Spatial intensity in tourism accommodation: Modelling the case of Extremadura. ISPRS International Journal of Geo-Information, 9(8), 473. https://doi.org/10.3390/ijgi9080473

Saha, S., Mina, B. L., Gopinath, K. A., Kundu, S., & Gupta, H. S. (2010). Organic amendments affect biochemical properties of a subtemperate soil of the Indian Himalayas. Nutrient Cycling in Agroecosystems, 80, 233–242.

Singh, J. S., Pandey, V. C., & Singh, D. P. (2011). Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. Agriculture, Ecosystems & Environment, 140, 339–353.

Uko, A. E., Effa, E. B., Isong, I. A., & Akpan, J. F. (2020). Improvement of chemical properties of Ultisol affected by arbuscular mycorrhizal fungi inoculation and poultry manure application. Asian Journal of Plant Sciences, 19(3), 279–286.

Unimtiang, U. S., Onnoghen, U. N., Efut, E. N., & Ogar, T. O. (2025). Environmental education strategies and wildlife resources conservation in Calabar Education Zone, Cross River State, Nigeria. International Journal of Institutional Leadership, Policy and Management, 7(2), 191–201.

Unimtiang, U. S., Onnoghen, U. N., Ogbaji, D. I., & Ogar, T. O. (2025). The prediction of education inequality on social vices among youths in the post-COVID-19 era in Cross River State, Nigeria. International Journal of Scientific Research in Education, 18(2), 177–188.

Vessey, J. K. (2003). Plant growth-promoting rhizobacteria as biofertilizers. Plant and Soil, 255, 571–586.

Wemedo, S. A., Etukudoh, N., & Akpan, J. F. (2015). Determination of rhizosphere effects on soil chemical and bacterial properties in an Ultisol of Southern Nigeria. International Journal of Environmental Science and Technology, 5(1), 1494–1505.

Youssef, M. M. A., & Eissa, M. F. M. (2014). Biofertilizers and their role in management of plant-parasitic nematodes: A review. E3 Journal of Biotechnology and Pharmaceutical Research, 5, 1–6.