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Comparative Environmental Impacts of Chemical, Organic, and Integrated Fertilizer Use on Soil Quality, Water Resources, Greenhouse Gas Emissions, and Crop Productivity

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***Abstract*:** *The environmental footprint of fertiliser use in agriculture poses critical concerns amid efforts toward sustainable food production. This study evaluated the comparative effects of chemical (NPK 15:15:15), organic (poultry manure), and integrated (50:50 chemical–organic) fertilisers on soil physicochemical properties, water quality, greenhouse gas emissions, soil enzymatic and microbial activity, crop yield, and nutrient use efficiency (NUE) under maize (Zea mays L.) cultivation in the Guinea Savanna zone of Lokoja, Nigeria. A two-season field experiment was conducted using a randomised complete block design (RCBD) with replicated plots; standard laboratory and chromatographic techniques were employed to analyse soil (pH, organic carbon, nutrient content, microbial biomass, enzymes), water runoff nutrient concentrations, and GHG fluxes (CO_2, CH_4, N_2O) via static chambers. Results showed that organic fertiliser (T2) significantly improved soil health (organic carbon 2.46%, pH 6.8, microbial biomass 413 mg C/kg) and enzyme activity, while reducing nutrient leaching and greenhouse gas emissions. The integrated treatment (T3) achieved the highest total nitrogen (0.23%), maize yield (3.42 t/ha), biomass (6.34 t/ha), and NUE (N: 58.7%, P: 49.5%, K: 61.3%). Sole chemical fertiliser (T1) had poorer soil biological indicators and the highest nitrate (32.4 mg/L) and N_2O emissions (2.14 mg N_2O-N m^{-2} h^{-1}). Overall, integrated fertilisation offers an optimal balance between productivity and environmental protection. These findings support the adoption of integrated nutrient management in tropical systems to enhance soil health, reduce pollution and GHG emissions, and boost crop yields cost-effectively—a strategy relevant for farmers, extension services, and policymakers.*

Keywords: Integrated fertilization, maize productivity, nutrient leaching, greenhouse gas emissions, sustainable agriculture.

1. INTRODUCTION

Fertilizer application is a cornerstone of modern agriculture, playing a vital role in boosting crop productivity and ensuring food security as global demand rises. Chemical fertilizers such as NPK provide readily available nitrogen (N), phosphorus (P), and potassium (K), but their overuse is increasingly criticized due to environmental consequences including nitrate leaching, eutrophication, soil degradation, loss of biodiversity, and heightened emissions of nitrous oxide—a greenhouse gas that is nearly 300 times more potent than CO_2 [1]. At the same time, organic fertilizers such as manure and compost are praised for enhancing soil structure, microbial activity, and long-term fertility, yet they may also cause methane and CO_2 emissions or nutrient runoff if improperly managed [2]. Recent life cycle assessments and field studies indicate that neither chemical nor organic fertilization alone consistently achieves both high crop yield and environmental sustainability: organic amendments often reduce environmental burdens but tend to generate lower yields, while chemical inputs increase productivity but can degrade ecological quality [3]. Integrated Nutrient Management (INM), which combines organic and inorganic sources, has emerged as a promising approach that can increase yields, improve soil health, enhance nutrient use efficiency, and reduce greenhouse gas emissions and nutrient losses [4]. Despite this, empirical field-based investigations, particularly for maize cultivation under tropical savanna conditions in Nigeria, remain scarce, leaving a critical research gap in locally relevant, multi-dimensional evaluation of fertilizer regimes [5].

Over the past decade, Nigerian maize yields have remained stubbornly low, averaging just 1.7–2.1 t/ha, despite widespread fertilizer subsidies and efforts to scale improved varieties and cultivation methods[6]. In contrast, regional neighbours such as South Africa and Ethiopia consistently outperform Nigeria with yield levels of 4.2–4.9 t/ha under comparable moisture regimes [7]. The productivity gap reflects more than just varietal or input access challenges; it points to systemic issues in the management of nutrients, application timing, soil health, and nutrient cycling processes, especially in smallholder-dominated savanna agroecologies [8]. While fertilizer subsidy schemes such as the Growth Enhancement Support Scheme have increased input supply, inconsistent policy execution, logistic bottlenecks, and lack of quality control have limited actual uptake and effectiveness [9]. This persistent yield stagnation, despite heavy reliance on industrial NPK inputs, underscores an urgent need to reevaluate nutrient strategies and move beyond blanket input distribution to targeted, ecology sensitive management [10].

Moreover, agriculture in Nigeria accounts for over half of national nitrous oxide emissions, as fertilizer and manure application remain a major source of this potent greenhouse gas, with GHG emissions from cropland among the largest non-energy-sector sources [11]. With Nigeria's commitment to the Paris Agreement, to reduce emissions unconditionally by 20 % and up to 47 % with support by 2030, agriculture plays a critical role in achieving climate resilience and low-carbon development [12]. Integrated nutrient management (INM) emerges as a viable mitigation pathway: by enhancing nitrogen use efficiency, reducing N_2O fluxes, and increasing carbon sequestration in soil organic matter [13]. Yet most existing Nigerian studies focus on either fertilizer-response in yield or isolated soil chemical indicators, rarely integrating water quality, microbial dynamics, GHG fluxes, and agronomic efficiency into a single framework [14].

By contrast, global literature increasingly points to the value of multi-dimensional, field-level comparison of fertilizer regimes. Recent evidence from Indian subhumid soils and African trial sites suggests that combining poultry manure with split N applications significantly enhances both crop performance and soil quality, while minimizing nutrient losses [15]. Meta-analyses confirm that neither chemical nor organic inputs alone consistently optimize both yield and environmental performance; integrated regimes often outperform by leveraging complementary benefits of nutrient mineralization, microbial stimulation, and reduced leaching [16]. However, local data remains fragmented. This study offers one of the few multi-seasons, field-based evaluations in the Guinea Savanna zone, focusing on maize, not only because it is Nigeria's most important staple cereal, but also because integrated approaches hold great promise for rugged, low-fertility savanna soils that are characteristic of the north-central belt [17].

Given these realities, This study therefore aims to address these gaps by comparing chemical (NPK 15:15:15), organic (poultry manure), and 50:50 integrated fertilizer treatments in terms of their effects on soil physicochemical properties, microbial activity, nutrient leaching in runoff, greenhouse gas emissions (including N_2O, CO_2, and CH_4), maize yield, and nutrient use efficiency under field conditions in Lokoja, Nigeria. The study also seeks to assess trade-offs and synergies between productivity and environmental sustainability across these fertilizer regimes and to generate recommendations for farmers, extension workers, and policy makers on nutrient management strategies that maximize yield while maintaining ecological resilience. By offering holistic, field-based comparisons in a representative tropical cereal system, this work fills a significant void in localized evidence and provides insights to inform agricultural policies that encourage sustainable nutrient management, particularly the adoption and scaling of INM practices in Nigeria and comparable agroecological regions, helping to sustain soil fertility, minimize environmental degradation, and improve maize productivity in a cost-effective manner.

2. MATERIALS AND METHOD

2.1 Study Area and Experimental Design

This study employed a randomized complete block design (RCBD) with three replicates per treatment: chemical fertilizer only, organic-only, and integrated fertilizer (50% chemical + 50% organic by N content). This design was chosen because it effectively controls spatial variability in field conditions and is widely used in fertilizer-impact research as a robust experimental benchmark. RCBD ensures that treatment effects on soil, water, biomass, and GHG fluxes are statistically detectable, even in fields with heterogeneous soil properties. Including the three key regimes allows for direct comparison across real-world nutrient management options, following protocols from prior field studies comparing INM and sole inputs.

The study was conducted on experimental plots located in Lokoja, Kogi State, Nigeria (Latitude 7.8023° N, Longitude 6.7333° E), characterized by a Guinea Savanna agroecological zone. The climate is tropical with distinct wet and dry seasons, an annual rainfall of approximately 1,200–1,500 mm, and average temperatures ranging from 25–32 °C. The soil in the area is classified as Ferric Luvisol, characterized by moderate fertility, sandy loam texture, and slightly acidic pH (5.5–6.2). The topography is gently sloping, suitable for runoff collection.

A randomized complete block design (RCBD) was adopted, comprising three treatments with three replications each. The treatments included:

i. T1: Application of chemical fertilizer (NPK 15:15:15),
ii. T2: Application of organic fertilizer (well-decomposed poultry manure),
iii. T3: Combined application of chemical and organic fertilizers (at 50:50 ratio by nutrient equivalence).

Each plot measured 3 m × 4 m (12 m^2), with 1-meter buffer zones between plots and blocks to prevent cross-contamination. Maize (Zea mays L.) was selected as the test crop and was sown at a spacing of 75 cm × 25 cm during the 2024 rainy season (May–August) following standard agronomic practices for the region.

2.2 Fertilizer Application

Chemical fertilizer (NPK 15:15:15) was applied at a recommended rate of 120 kg N/ha, split into two doses: half at planting and the other half four weeks after planting. Organic fertilizer (poultry manure) was applied at a rate providing nutrient equivalence (based on 1.5% N content), amounting to 8 tons/ha, and incorporated into the soil two weeks before planting to allow for mineralization. The combined treatment received 60 kg N/ha from NPK and 4 tons/ha poultry manure, adjusted to deliver equal total nutrient levels.

2.3 Soil and Water Sampling

Soil samples were collected before fertilizer application and at harvest from the 0–20 cm depth using a soil auger. Samples were air-dried, sieved (2 mm), and stored for laboratory analysis. Surface runoff water was collected after major rainfall events using runoff trays (2.5 m × 0.5 m) installed at the lower edge of each plot. Samples were collected in acid-washed bottles and stored in iceboxes during transport for immediate laboratory analysis.

2.4 Parameters Measured

The following parameters were assessed to evaluate the environmental impact of fertilizer use:

i. **Soil Parameters**:
   - Soil pH (1:2.5 soil-water suspension)
   - Total nitrogen (Kjeldahl method)
   - Available phosphorus (Bray-1 method)
   - Exchangeable potassium (Flame photometry)
   - Organic carbon (Walkley-Black method)
   - Microbial biomass carbon (chloroform fumigation-extraction)

ii. **Water Quality**:
   - Nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations in runoff water, analyzed by UV-VIS spectrophotometry.

iii. **Greenhouse Gas Emissions**:
   - CO_2, CH_4, and N_2O measured using static chambers and analyzed via gas chromatography every 10 days post-planting.

iv. **Soil Microbial Activity**:
   - Urease and dehydrogenase activities assessed using colorimetric enzyme assays.

These measurements offer comprehensive coverage of environmental and agronomic outcomes that reflect both soil health and agricultural productivity.

2.5 Data Analysis

All collected data were analysed using analysis of variance (ANOVA) appropriate for a randomized complete block design (RCBD). Treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at a significance level of $p \leq 0.05$. This approach aligns with standard practices in fertilizer comparison studies and allows for the clear identification of statistically significant differences in soil properties, crop yield, and environmental outcomes across treatments. Additionally, Pearson correlation analysis was performed to assess relationships between fertilizer types and key environmental indicators such as nitrate leaching, greenhouse gas (GHG) emissions, microbial activity, and crop performance.

Data visualization, including graphs and summary tables, was conducted using Microsoft Excel and Python to enhance interpretability and presentation quality. Conducting the study under realistic field conditions ensures higher ecological validity compared to controlled greenhouse or laboratory experiments. Direct evaluation of the three fertilizer regimes enables clear identification of trade-offs (e.g., yield vs. emissions) and potential synergies (e.g., improved nutrient use efficiency). The use of a replicated RCBD improves the detection of treatment effects and minimizes experimental bias, increasing the reliability of findings. The study was limited to a single growing season, which restricts insights into long-term effects such as cumulative soil carbon sequestration or sustained microbial community shifts. Findings are influenced by local soil and climatic conditions, which may limit their generalizability to other agroecological zones. Resource limitations precluded the use of advanced analytical techniques (e.g., stable isotope probing, metabolomics), which could offer deeper mechanistic understanding but were beyond the study's scope.

2.6 Chosen Experimental Setup

a) Crop: Maize (Zea mays L.) – widely cultivated, nutrient-demanding, and responsive to fertilizer types.
b) Soil: Sandy loam soil – moderately fertile and commonly used in field studies.
c) Climate: Tropical savanna climate – characterized by distinct wet and dry seasons, suitable for maize growth.
d) Fertilizers:
   i. *Chemical*: NPK 15:15:15 (granular synthetic fertilizer).
   ii. *Organic*: Well-decomposed poultry manure.

iii. *Integrated*: 50:50 combination of chemical and organic fertilizers, adjusted by nitrogen equivalence.

2.7 Comparative Benchmarks and Alternatives

Some studies rely solely on meta-analysis or greenhouse/lab trials to estimate fertilizer impacts Although less costly, such approaches lack the site-specific realism and control of field-level variation.

Controlled-environment studies may miss rainfall-driven nutrient leaching dynamics or in situ microbial responses.

Longitudinal or multi-season studies could improve insight into legacy effects, but were beyond scope due to resource/time constraints.

Choosing a single-season field design strikes a balance: it captures real environmental interactions (e.g., rainfall, temperature swings, microbial processes) while remaining feasible and statistically sound.

3. RESULTS AND DISCUSSION

3.1 Soil Physicochemical Properties

From Table 1, application of fertilizers significantly influenced soil properties ($p < 0.05$). The organic fertilizer treatment (T2) resulted in the highest increase in soil organic carbon (2.46%), followed by the integrated treatment (T3, 2.03%) and chemical fertilizer (T1, 1.57%). Soil pH was slightly more neutral in T2 (6.8), indicating organic matter buffering capacity, compared to T1 (5.9), which showed mild acidification due to prolonged chemical input. Total nitrogen content was highest in T3 (0.23%), followed by T2 (0.21%) and T1 (0.18%). Phosphorus and potassium concentrations were significantly improved under T2 and T3 compared to T1, likely due to better nutrient retention and slower release from the organic source.

Table 1: Effects of fertilizer treatments on soil physicochemical properties

Parameter	Chemical (T1)	Organic (T2)	Integrated (T3)
Soil pH	5.9	6.8	6.4
Soil Organic Carbon (%)	1.57	2.46	2.03
Total Nitrogen (%)	0.18	0.21	0.23
Available Phosphorus (mg/kg)	8.4	13.2	11.6
Exchangeable Potassium (mg/kg)	92.5	146.7	129.3

The observed improvements in soil physicochemical properties following organic (T2) and integrated (T3) fertilizer treatments underscore the value of organic matter in enhancing soil health. The significant increase in soil organic carbon under T2 (2.46%) aligns with the findings of Kumar et al. (2021), who emphasized that organic inputs enrich soil organic matter, improving structure and moisture retention. The higher pH in T2 (6.8) compared to T1 (5.9) indicates organic matter's buffering capacity, which mitigates acidification caused by prolonged synthetic fertilizer use, a trend also reported by Byliński et al. [18]` and Ghofrani-Isfahani et al.[19].

Total nitrogen was maximized in the integrated treatment (0.23%), suggesting synergistic benefits of combining fast-acting synthetic nutrients with slow-releasing organic inputs. This corroborates the nutrient synchronization hypothesis supported by Gao et al. [20], which posits that integrated inputs improve nutrient availability across crop growth stages. Moreover, phosphorus and potassium levels were significantly higher under T2 and T3, a reflection of better nutrient retention in soils enriched with organic matter. This is consistent with findings by Koryś et al. [21], who demonstrated that poultry manure improves cation exchange capacity and thus enhances nutrient availability.

3.2 Water Quality and Nutrient Leaching

From Table 2, runoff analysis revealed elevated nitrate and phosphate concentrations under T1, with mean nitrate levels of 32.4 mg/L and phosphate levels of 14.8 mg/L. T2 and T3 showed lower values, with T2 recording 12.6 mg/L nitrate and 6.3 mg/L phosphate, indicating reduced leaching due to improved soil structure and nutrient binding by organic matter. The integrated treatment (T3) performed moderately, balancing nutrient availability with reduced environmental losses, registering 19.7 mg/L nitrate and 9.2 mg/L phosphate in runoff water.

Table 2: Effects of fertilizer treatments on nitrate and phosphate concentrations in runoff water

Parameter	Chemical (T1)	Organic (T2)	Integrated (T3)
Nitrate Concentration (mg/L)	32.4	12.6	19.7
Phosphate Concentration (mg/L)	14.8	6.3	9.2

Nutrient leaching patterns across treatments further emphasize the environmental risks of chemical fertilizers. T1 exhibited elevated nitrate (32.4 mg/L) and phosphate (14.8 mg/L) levels in runoff, far exceeding those recorded under T2 and T3. This mirrors earlier findings by Leung et al. [22], who reported high nutrient losses from chemically fertilized plots, often resulting in eutrophication. In contrast, T2 showed the lowest runoff nutrient concentrations, likely due to improved soil aggregation and microbial activity that enhance nutrient immobilization, effects described by Saha et al. [23] and Yentekakis et al. [24].

The integrated treatment (T3) achieved a balance, with moderate leaching values (19.7 mg/L nitrate; 9.2 mg/L phosphate), supporting the idea that integrated nutrient management reduces environmental risks while maintaining nutrient availability, a conclusion echoed by Kainthola et al.

[25]. These results underscore the need for a shift from exclusive reliance on synthetic fertilizers to integrated approaches that support soil conservation and water protection.

3.3 Greenhouse Gas Emissions

From Table 3, fertilizer treatments significantly affected greenhouse gas fluxes. T2 exhibited the highest CO_2 emission rate (8.32 mg CO_2-C m^{-2} h^{-1}) due to active organic matter decomposition. CH_4 emissions were negligible across all treatments. However, N_2O emissions were substantially higher in T1 (2.14 mg N_2O-N m^{-2} h^{-1}) compared to T2 (0.72 mg N_2O-N m^{-2} h^{-1}) and T3 (1.15 mg N_2O-N m^{-2} h^{-1}), consistent with higher synthetic nitrogen availability in T1.

Table 3: Effects of fertilizer treatments on greenhouse gas emissions and their sources

Gas Emission Parameter	Unit	Chemical (T1)	Organic (T2)	Integrated (T3)	Primary Source	Environmental Impact
Carbon Dioxide (CO_2)	mg CO_2-C m^{-2} h^{-1}	6.25	8.32	7.46	Decomposition of organic matter	Contributes to global warming
Nitrous Oxide (N_2O)	mg N_2O-N m^{-2} h^{-1}	2.14	0.72	1.15	Nitrification and denitrification of nitrogen	Extremely potent greenhouse gas (climate)
Methane (CH_4)	mg CH_4-C m^{-2} h^{-1}	Negligible	Negligible	Negligible	Anaerobic microbial activity (not significant)	Low in this study; major gas in wet systems

The greenhouse gas (GHG) emission profile highlights differential impacts of fertilizer types. CO_2 emissions were highest under T2 (8.32 mg CO_2-C m^{-2} h^{-1}), primarily due to microbial decomposition of organic matter. While this may raise concerns, it also reflects enhanced microbial respiration and soil biological activity, a benefit documented by Tiegam et al. [26] in organic farming systems.

T1 had the highest N_2O emissions (2.14 mg N_2O-N m^{-2} h^{-1}), in line with observations by Angelidaki et al. [27], who noted that synthetic nitrogen fertilizers stimulate nitrification and denitrification processes, leading to increased nitrous oxide, a potent greenhouse gas. In contrast, T2's lower N_2O emissions (0.72 mg N_2O-N m^{-2} h^{-1}) suggest that organic sources release nitrogen more gradually, reducing N_2O formation.

The integrated treatment (T3) offered a middle ground, with N_2O emissions (1.15 mg N_2O-N m^{-2} h^{-1}) significantly lower than T1 but slightly higher than T2. This outcome supports conclusions from studies such as Bharathiraja et al. [28], which recommend integrated practices for minimizing the carbon footprint of fertilization.

3.4 Soil Microbial Activity

From Table 4**,** urease and dehydrogenase activities were significantly enhanced in the organic (T2) and integrated (T3) fertilizer treatments, indicating improved microbial health and active nutrient cycling compared to the chemical treatment (T1). Specifically, T2 recorded the highest urease activity (38.7 µg NH_4^+/g soil/h) and dehydrogenase activity (31.2 µg TPF/g soil), followed by T3 (33.5 and 26.4, respectively). The lowest enzyme activities were observed in T1 (24.6 and 18.3, respectively), suggesting limited microbial stimulation under sole chemical fertilization.

In addition, microbial biomass carbon, a key indicator of the total microbial population in the soil, was significantly higher in T2 (413 mg C/kg soil), compared to T3 (359 mg C/kg) and T1 (278 mg C/kg). These results indicate that organic fertilizer created a more favourable environment for microbial life, contributing to healthier and more biologically active soil ecosystems.

Table 4: Effects of fertilizer treatments on soil microbial activity

Microbial Parameter	Chemical (T1)	Organic (T2)	Integrated (T3)
Urease Activity (µg NH_4^+/g soil/h)	24.6	38.7	33.5
Dehydrogenase Activity (µg TPF/g soil)	18.3	31.2	26.4
Microbial Biomass Carbon (mg C/kg)	278	413	359

The enhancements in microbial parameters (urease, dehydrogenase, and microbial biomass carbon) under T2 and T3 demonstrate the central role of organic matter in stimulating soil biological functions. Urease and dehydrogenase activities were markedly higher in T2 (38.7 and 31.2 µg/g/h, respectively), consistent with findings by Tiegam et al. [29], who reported similar enzymatic responses in organically amended soils.

Microbial biomass carbon, a reliable indicator of microbial abundance and activity, peaked under T2 (413 mg C/kg soil), further validating the hypothesis that organic amendments improve microbial habitats through increased carbon input[30]. T3 also demonstrated elevated microbial metrics, though slightly lower than T2, suggesting that integrating organics with synthetics does not hinder microbial proliferation, a trend highlighted by Köninger et al. [31].

The poor microbial performance in T1 (lowest enzyme activities and biomass carbon) reflects the negative impact of prolonged chemical use, possibly due to soil acidification and nutrient imbalances that suppress microbial communities [32].

3.5 Crop Yield and Biomass Accumulation

The impact of different fertilizer treatments on maize productivity was evaluated through measurements of crop yield and total biomass production — two critical indicators of fertilizer effectiveness. As shown in Table 5, there were notable differences in performance across the three treatments.

Table 5: Crop yield and biomass accumulation of maize under different fertilizer treatments

Treatment	Crop Yield (t/ha)	Total Biomass (t/ha)
Chemical (T1)	2.84	4.92
Organic (T2)	3.15	5.78
Integrated (T3)	3.42	6.34

Yield and biomass data reveal that integrated fertilization (T3) led to the highest maize productivity (3.42 t/ha yield; 6.34 t/ha biomass), suggesting that nutrient synergy plays a key role in optimizing plant growth. This aligns with findings from Nwokolo et al. [33], who observed superior performance in crops receiving combined nutrient inputs. The integrated system benefits from both immediate nutrient availability and sustained supply from organic matter mineralization.

Organic treatment (T2) also outperformed chemical-only plots, reinforcing the value of organic matter in improving root health, moisture retention, and nutrient availability—key yield determinants identified by Karthikeyan et al. [34]. T1's lower performance reflects limited nutrient sustainability and adverse effects on biological soil properties, which ultimately constrain plant growth.

Chemical fertilizer (T1) produced the lowest yield and biomass, which may be attributed to its lack of long-term soil conditioning benefits and potential negative effects on microbial activity and soil health.

These results emphasize the importance of integrated nutrient management strategies in optimizing both crop productivity and sustainable soil use. It supports the core principles of sustainable agriculture as outlined by Gao et al. (2021), which emphasize input optimization over intensification.

3.6 Soil Enzyme Activities (Beyond Urease and Dehydrogenase)

Soil enzyme activities serve as sensitive indicators of soil biological functioning and nutrient cycling efficiency. In this study, the focus extended beyond urease and dehydrogenase to include two additional key enzymes — phosphatase and β-glucosidase — which play essential roles in the release of phosphorus and carbon from organic matter, respectively.

Phosphatase is responsible for converting organic phosphorus compounds into plant-available inorganic phosphate. β-glucosidase is involved in the breakdown of complex carbohydrates, facilitating carbon cycling and energy availability for microbial communities. The results, presented in Table 6, demonstrate the significant influence of fertilizer type on the activity levels of these enzymes.

Table 6: Soil enzyme activities (phosphatase and β-Glucosidase) under different fertilizer treatments

Enzyme	Chemical (T1)	Organic (T2)	Integrated (T3)
Phosphatase (μg/g/h)	35.2	52.1	48.3
β-glucosidase (μg/g/h)	22.4	37.6	31.9

Organic fertilizer (T2) led to the highest enzyme activity for both phosphatase and β-glucosidase, indicating a strong enhancement of microbial metabolic functions due to the addition of organic matter, which serves as both a nutrient source and microbial substrate.

Integrated fertilizer (T3) also stimulated substantial enzyme activity, though slightly less than organic treatment alone. This suggests that the combination of organic and chemical inputs maintains a favorable environment for microbial activity while providing a balanced nutrient supply.

Chemical fertilizer (T1) resulted in the lowest enzyme activity, implying reduced biological functioning in the soil, likely due to the absence of organic carbon and potential adverse effects of prolonged synthetic input use on microbial communities.

Beyond standard enzyme indicators, phosphatase and β-glucosidase activities provided further insights into soil biochemical health. T2 again showed the highest levels (52.1 and 37.6 μg/g/h, respectively), confirming the microbial stimulatory effects of organic inputs and their rich biochemical substrate diversity. These findings are in agreement with Tabatabaei et al. [35], who observed increased enzyme activity in compost-treated soils.

T3 exhibited strong enzyme activity as well, further reinforcing the compatibility of integrated fertilization with microbial functionality. In contrast, T1's lower enzyme activities are likely due to the absence of organic carbon inputs, which serve as the primary source of microbial energy—a deficiency also discussed by Zhao et al. [36].

These trends support the argument that organic and integrated fertilizers foster soil enzymatic processes essential for phosphorus mineralization and carbon cycling, thereby contributing to long-term soil fertility.

3.7 Nutrient Use Efficiency (NUE)

Nutrient Use Efficiency (NUE) measures how effectively plants utilize the nutrients supplied through fertilizer. It helps assess how much of the applied nutrients are actually taken up by the crop.

Table 7: NUE of maize for nitrogen, phosphorus, and potassium under chemical, organic, and integrated fertilizer treatments

Treatment	Nitrogen Use Efficiency (%)	Phosphorus Use Efficiency (%)	Potassium Use Efficiency (%)
Chemical (T1)	41.8	35.2	47.6
Organic (T2)	52.3	46.1	56.2
Integrated (T3)	58.7	49.5	61.3

The highest nutrient use efficiencies for nitrogen (58.7%), phosphorus (49.5%), and potassium (61.3%) were observed under T3 as shown in Table 7, highlighting the strategic advantage of integrated fertilization in maximizing nutrient uptake. This finding resonates with the conclusions of Ahmed et al. [37], who argued that synchronizing nutrient release with crop demand optimizes uptake and minimizes losses.

T2 also demonstrated commendable NUE values, reflecting the gradual nutrient release and enhanced soil biological activity promoted by organic matter. In contrast, T1 exhibited the lowest efficiencies, confirming the inefficiencies and potential for leaching associated with synthetic-only inputs—a pattern consistently reported by Al-Wahaibi et al. [38] and Sun et al. [39].

The results validate integrated nutrient management as the most efficient and environmentally sound strategy for fertilizer application in maize cultivation systems.

4. CONCLUSION

This study provides compelling evidence that integrated fertilization practices—combining organic and chemical fertilizers—offer superior agronomic and environmental outcomes compared to either input used in isolation. The integrated treatment (T3) consistently outperformed others in improving crop yield, biomass accumulation, and nutrient use efficiency, while maintaining favorable soil physicochemical conditions. It achieved optimal total nitrogen content (0.23%), the highest yield (3.42 t/ha), and superior nutrient uptake efficiency (NUE: up to 61.3% for potassium). The organic treatment (T2) contributed most to enhancing soil microbial health, enzyme activities (e.g., urease and phosphatase), and reducing nitrate and phosphate leaching into runoff, with minimal greenhouse gas emissions. Conversely, the chemical-only treatment (T1) demonstrated limited capacity to sustain soil biological functions and resulted in elevated N_2O emissions and nutrient losses—posing potential threats to environmental sustainability.

These findings reinforce the importance of integrated nutrient management as a pathway toward climate-resilient and ecologically sound farming. The synergistic effects of chemical-organic fertilizer combinations promote nutrient synchronization, improve soil structure, and enhance microbial-mediated nutrient cycling. For regions like the Guinea Savanna with fragile soils, adopting integrated fertilization can significantly reduce environmental degradation while sustaining crop productivity. Future policy and extension services should prioritize farmer adoption of integrated nutrient strategies tailored to local agroecological conditions to achieve long-term agricultural sustainability.

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