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Research Article

ADVANCING SUSTAINABLE AGRICULTURE THROUGH NANO-FERTILIZERS ANALYZING SOIL HEALTH AND CROP PRODUCTIVITY IN TROPICAL ECOSYSTEMS

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Abstract
Sustainable rice production in tropical ecosystems is constrained by low nitrogen-use efficiency, nutrient losses, declining soil quality, and increasing dependence on conventional fertilizers. This study aimed to evaluate the effects of nano-nitrogen fertilizer on soil health, nitrogen efficiency, and rice productivity under tropical field conditions. A randomized complete block design was implemented with six treatments: no nitrogen, 100% conventional urea, and nano-nitrogen fertilizer applied at 25%, 50%, 75%, and 100% of the recommended nitrogen rate, each replicated four times. Crop growth, chlorophyll content, nitrogen uptake, yield components, grain yield, agronomic efficiency, and selected physical, chemical, and biological soil indicators were analyzed using analysis of variance, post hoc comparisons, correlation, and regression. Results showed that the 75% nano-nitrogen treatment produced the highest grain yield, reaching 7.24 t ha−1, and exceeded full-rate conventional urea while improving productive tillers, chlorophyll status, nitrogen uptake, microbial biomass, urease activity, organic carbon, and aggregate stability. The 100% nano-nitrogen rate increased nitrogen uptake but provided no additional yield advantage, indicating a nonlinear response. The study concludes that optimized nano-nitrogen application can reduce fertilizer demand while improving rice productivity and soil functioning, although multi-season environmental and safety assessments remain necessary before widespread adoption across diverse tropical production environments.

Keywords: Nano-Fertilizers, Nitrogen-Use Efficiency, Rice Productivity

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INTRODUCTION

Global agriculture faces increasing pressure to produce sufficient food for a growing population while reducing environmental degradation and preserving limited natural resources. Agricultural intensification has historically depended on the extensive application of synthetic fertilizers to increase crop yields and maintain food production. Conventional fertilizers have contributed substantially to agricultural productivity, yet their inefficient use has also generated serious ecological consequences (Nagarajan et al., 2024; Thamarai et al., 2026). Nutrient losses through leaching, volatilization, surface runoff, and chemical fixation can reduce fertilizer-use efficiency while contaminating soil and water systems. Sustainable agricultural development therefore requires innovative nutrient-management technologies capable of improving crop productivity without intensifying ecological damage (Hamed et al., 2025; Li et al., 2026).

Tropical ecosystems present distinctive agricultural conditions that complicate nutrient management. High rainfall, elevated temperatures, rapid organic-matter decomposition, intensive weathering, soil acidity, and nutrient leaching frequently reduce soil fertility and limit the availability of essential plant nutrients (Takoutsing & Rodríguez Martín, 2025). Many tropical soils contain low levels of organic carbon and display strong phosphorus fixation, weak nutrient-retention capacity, and imbalanced microbial activity (Kamalesh et al., 2024). Farmers often respond to these limitations by increasing fertilizer application rates, although additional inputs do not always produce proportional yield improvements. Persistent fertilizer dependence may gradually alter soil structure, nutrient cycling, biological activity, and long-term agricultural sustainability (Khamis et al., 2026).

Nano-fertilizers have emerged as a promising technological innovation for addressing the limitations of conventional nutrient management. These fertilizers contain nutrients formulated or delivered at the nanoscale, allowing controlled release, improved solubility, enhanced surface reactivity, and potentially greater nutrient absorption by plants (Chakraborty et al., 2026). Nano-enabled formulations may supply macronutrients, micronutrients, or combinations of essential elements through soil application, seed treatment, or foliar spraying. Their capacity to deliver nutrients more precisely may increase nutrient-use efficiency, reduce application frequency, and minimize environmental losses (Ravikumar et al., 2024). Scientific evaluation remains necessary because their agronomic effectiveness and ecological safety can vary according to formulation, dosage, crop species, soil properties, and climatic conditions (Same et al., 2025).

Low nutrient-use efficiency remains a major constraint on sustainable crop production in tropical agriculture. A considerable proportion of conventionally applied nitrogen, phosphorus, and potassium may become unavailable to plants because of volatilization, leaching, erosion, immobilization, or fixation in the soil matrix (Abiri et al., 2023; Rizvi et al., 2024). These losses increase production costs and encourage repeated fertilizer application, particularly in systems where farmers seek rapid yield improvement. Excessive fertilization can disturb nutrient balance, accelerate soil acidification, reduce biological diversity, and increase the movement of agricultural pollutants into surrounding ecosystems. The central problem is not merely insufficient fertilizer application but the inability of conventional nutrient-delivery systems to synchronize nutrient availability with crop demand (Baba et al., 2026; Yao et al., 2024).

Soil-health degradation presents a second critical problem that cannot be assessed solely through short-term yield responses. Productive soils require appropriate physical structure, stable chemical fertility, active microbial communities, sufficient organic matter, and resilient nutrient-cycling processes. Fertilization practices that increase crop biomass during one growing season may still create harmful long-term effects on soil aggregation, enzymatic activity, microbial diversity, salinity, or nutrient balance (Mehmood et al., 2023; Pérez-Reverón et al., 2023). Research on nano-fertilizers has often highlighted plant growth and yield enhancement, but less attention has been directed toward the simultaneous assessment of physical, chemical, and biological indicators of tropical soil health (AHMED et al., 2025; Yıldız, 2025).

Uncertainty regarding the appropriate dosage and environmental behavior of nano-fertilizers creates an additional scientific problem. Low or moderate concentrations may improve nutrient availability and plant metabolism, while excessive exposure may cause phytotoxicity, oxidative stress, microbial disruption, or nanoparticle accumulation (LIAO et al., 2025; Prabha et al., 2025). Nanomaterial behavior can also change under tropical soil conditions because of high moisture, acidity, clay-mineral interactions, organic compounds, and intensive biological activity. Evidence obtained from controlled laboratory studies may not adequately represent field conditions. A comprehensive investigation is required to determine whether nano-fertilizers genuinely improve agricultural sustainability or merely shift environmental risks from conventional nutrients to nanoscale materials (Chandervanshi et al., 2025; Junejo et al., 2026).

The primary objective of the study is to evaluate the effectiveness of nano-fertilizers in improving soil health and crop productivity within tropical agricultural ecosystems. The investigation is expected to compare nano-fertilizer treatments with conventional fertilizer practices and untreated or recommended-control conditions (Musa & Ariff Lim, 2025; Socas-Hernández et al., 2025). Crop responses may be assessed through germination, plant height, leaf development, biomass accumulation, nutrient uptake, physiological performance, yield components, and final harvest productivity. Such comparisons are intended to determine whether nano-fertilizers provide measurable agronomic advantages under environmentally realistic tropical conditions (Gan et al., 2024; Pandian et al., 2024).

The study also aims to analyze changes in key soil-health indicators following nano-fertilizer application. Soil chemical parameters may include pH, electrical conductivity, organic carbon, cation-exchange capacity, available nitrogen, phosphorus, potassium, and relevant micronutrients (Bhupenchandra et al., 2026; Zahoor et al., 2025). Physical indicators may include bulk density, aggregate stability, porosity, moisture retention, and infiltration capacity. Biological indicators may encompass microbial biomass, soil respiration, enzymatic activity, and the abundance or diversity of beneficial microorganisms. Integrated analysis of these parameters is expected to reveal whether improved crop performance is accompanied by the maintenance or restoration of soil functionality (Imran et al., 2026; Mustafa et al., 2023).

The research further seeks to identify the most effective nano-fertilizer dosage and clarify the relationships among nutrient availability, soil condition, plant nutrient uptake, and crop productivity. Dose-response analysis is important because agronomic effectiveness cannot be assumed to increase linearly with nanoparticle concentration (Satya et al., 2023). The study is expected to examine whether lower nano-fertilizer doses can achieve comparable or superior results to standard conventional fertilizer rates. The resulting evidence may support the development of nutrient-management recommendations that balance yield improvement, soil protection, fertilizer efficiency, economic feasibility, and environmental responsibility.

Previous research has demonstrated the potential of nano-fertilizers to enhance nutrient delivery, plant growth, and crop yield. Much of the available evidence, however, originates from greenhouse experiments, hydroponic systems, short-term pot trials, or highly controlled laboratory conditions. These settings are useful for identifying physiological mechanisms but may not capture the complexity of tropical field environments (Shabir et al., 2023). Natural rainfall variability, soil heterogeneity, microbial interactions, seasonal temperature fluctuations, and existing management practices can alter nanoparticle behavior and crop responses. Field-based evidence from tropical ecosystems remains comparatively limited and fragmented.

Existing studies have frequently examined individual plant-growth parameters without integrating them with comprehensive measurements of soil health. Yield increases are commonly reported as the primary evidence of effectiveness, while soil biological quality, aggregate stability, nutrient-retention dynamics, and post-harvest nutrient balance receive less systematic attention. This narrow focus may produce incomplete conclusions because sustainable agriculture requires both immediate productivity and long-term ecological functioning. Research that evaluates crop performance without examining soil consequences cannot determine whether nano-fertilizer application supports genuine sustainability.

Methodological inconsistency also limits comparison across previous studies. Nano-fertilizer investigations differ in particle composition, size distribution, coating material, application method, concentration, crop species, exposure duration, and soil characteristics. Some studies compare nano-fertilizers with no-fertilizer controls but omit equivalent conventional fertilizer treatments, making it difficult to establish whether observed benefits result from nanoscale formulation or simply from increased nutrient supply. Limited attention has also been given to dose optimization, potential toxicity thresholds, and interactions between nanoparticles and tropical soil properties. The present research addresses these gaps through an integrated comparative design that connects fertilizer formulation, dosage, soil response, nutrient uptake, and crop productivity.

The novelty of the study lies in its integrated evaluation of nano-fertilizers as both agronomic inputs and potential modifiers of soil-system functioning. Crop yield is not treated as the sole indicator of technological success. The investigation combines plant-performance measurements with physical, chemical, and biological soil-health indicators to produce a more comprehensive assessment of sustainability. This multidimensional approach makes it possible to determine whether improved productivity is associated with enhanced nutrient cycling and soil resilience or accompanied by hidden ecological costs.

A second innovative aspect concerns the analysis of nano-fertilizer performance under tropical ecosystem conditions. Tropical soils possess distinctive mineralogical, climatic, and biological characteristics that can influence nanoparticle transformation, mobility, aggregation, dissolution, and nutrient release. Evaluating nano-fertilizers within this context can generate geographically and ecologically relevant evidence that cannot be inferred confidently from temperate or controlled-environment studies. The research may also identify soil-specific factors that strengthen or weaken nano-fertilizer effectiveness, thereby contributing to more precise and locally appropriate nutrient-management strategies.

The importance of this research is supported by its potential contribution to sustainable intensification, food security, soil conservation, and climate-resilient agriculture. Scientific evidence on effective dosage, nutrient-use efficiency, crop response, and soil impact can assist researchers, farmers, extension officers, industry developers, and policymakers in evaluating the responsible adoption of nano-fertilizer technologies. The study may contribute conceptually by linking nanotechnology with multidimensional soil health, methodologically by combining comparative treatments with integrated indicators, and practically by identifying fertilizer strategies that reduce nutrient loss while maintaining productivity. Reliable evidence is essential to ensure that agricultural nanotechnology develops as a scientifically justified sustainability intervention rather than as an uncritically promoted technological solution.

RESEARCH METHOD

Research Design

This study employed a quantitative field-experimental design to evaluate the effects of nano-nitrogen fertilizer on soil health and rice productivity in a tropical agricultural ecosystem. A randomized complete block design was used to control spatial variation in soil fertility, moisture, topography, and other environmental conditions across the experimental field. The experiment compared different nano-nitrogen fertilizer rates with conventional nitrogen fertilization and an unfertilized control. This design enabled the researchers to determine whether nano-nitrogen fertilizer could improve nitrogen-use efficiency, maintain soil quality, and increase rice growth and yield under actual field conditions (Jiang et al., 2026; Vivekanandan et al., 2026).

The experimental treatments consisted of six nitrogen-management regimes: no nitrogen fertilizer as the negative control, conventional urea at 100% of the locally recommended nitrogen rate, nano-nitrogen fertilizer at 25%, 50%, 75%, and 100% of the recommended nitrogen equivalent. Phosphorus and potassium fertilizers were applied uniformly to all plots according to local agronomic recommendations to ensure that crop responses were primarily associated with differences in nitrogen treatment. Each treatment was replicated four times, resulting in 24 experimental plots. Treatment allocation within each block was randomized to minimize systematic bias and increase the reliability of statistical comparisons.

The study assessed nano-fertilizer performance through an integrated framework combining crop-growth indicators, yield components, plant nitrogen uptake, nitrogen-use efficiency, and soil-health parameters. Crop variables included plant height, tiller number, chlorophyll content, aboveground biomass, panicle characteristics, filled-grain percentage, 1,000-grain weight, and grain yield. Soil-health assessment included selected physical, chemical, and biological indicators measured before planting and after harvest. This multidimensional design allowed the study to evaluate whether improvements in rice productivity were accompanied by positive, neutral, or adverse changes in soil functioning.

Research Target/Subject

The experimental population consisted of lowland rice plants cultivated in a tropical irrigated rice ecosystem. The research site was selected purposively based on its representativeness of tropical rice-production conditions, accessibility for continuous monitoring, uniform land-use history, and suitability for controlled fertilizer application. The selected field had been used for rice cultivation during previous planting seasons and displayed relatively homogeneous soil texture and management history. Baseline soil analysis was conducted before plot establishment to determine initial fertility status, soil acidity, organic carbon, available nitrogen, phosphorus, potassium, and other relevant properties.

A commonly cultivated high-yielding rice variety adapted to tropical lowland conditions was used as the experimental crop. Healthy and uniform seedlings were raised in a nursery and transplanted at the recommended age using consistent planting spacing across all plots. Each experimental plot represented one sampling unit, while individual rice hills within the plots constituted observational units. Border rows were excluded from crop measurements to reduce edge effects caused by nutrient movement, irrigation differences, and competition between adjacent treatments (Choong et al., 2026; Yahaya et al., 2023).

Plant samples were selected systematically from the central area of each plot. Ten rice hills per plot were marked after transplanting and observed throughout the growing period for plant height, tiller formation, chlorophyll content, and other nondestructive measurements. Yield components were measured from representative hills harvested from the designated sampling area, while grain yield was determined from the effective harvest area of each plot and converted to standard yield per hectare at adjusted grain moisture content. Composite soil samples were collected from five points within each plot at a depth of 0–20 cm and combined to represent the soil condition of each experimental unit.

Research Procedure

The research began with site preparation, baseline soil sampling, and experimental plot establishment. Soil samples were collected before fertilizer application to describe the initial physical, chemical, and biological characteristics of the field. The land was prepared using standard lowland rice cultivation practices, divided into blocks, and separated into experimental plots with buffer zones to reduce movement of fertilizer between treatments.

Irrigation channels were arranged to maintain comparable water availability and limit cross-contamination among plots.

Rice seedlings were produced under uniform nursery conditions and transplanted into the experimental field at consistent spacing and planting density. Phosphorus and potassium fertilizers were applied uniformly according to local recommendations. Conventional urea was applied in split doses based on established rice-fertilization practice (DEMİR & BAYRAKLI, 2026; Muthukumar & Karthick, 2025). Nano-nitrogen fertilizer was applied according to the assigned treatment level and the manufacturer's agronomic instructions. Soil application, foliar application, or a combination of both was standardized across nano-fertilizer treatments. Application timing was aligned with important rice growth stages, including early vegetative development, active tillering, and panicle initiation.

Crop management practices were applied consistently to all experimental plots. Irrigation, weed control, pest management, and disease prevention followed locally recommended procedures. Chemical interventions unrelated to the fertilizer treatments were minimized and recorded carefully. Plant-growth observations were conducted at predetermined intervals, such as 30, 60, and 90 days after transplanting. Chlorophyll content and tiller development were monitored repeatedly to identify temporal differences in crop response to the nitrogen treatments.

Plant tissue samples were collected at selected growth stages and at harvest to determine nitrogen concentration and total nitrogen uptake. Samples were cleaned, oven-dried, weighed, ground, and analyzed using a standardized nitrogen-determination method. Nitrogen-use efficiency was calculated using indicators such as agronomic efficiency, recovery efficiency, partial factor productivity, and physiological efficiency. These indices were used to determine whether nano-nitrogen fertilizer produced more grain or biomass per unit of nitrogen applied than conventional urea.

Harvesting was conducted when the rice crop reached physiological maturity. Grain and straw were separated, weighed, and sampled for moisture correction and nutrient analysis. Yield components, including panicle number, grains per panicle, filled-grain percentage, and 1,000-grain weight, were recorded using standardized procedures. Final grain yield was calculated from the effective harvest area of each plot and expressed as tons per hectare at a uniform moisture level.

Post-harvest soil samples were collected from the same depth and sampling points used during baseline assessment. Changes in soil pH, organic carbon, available nutrients, microbial biomass, enzyme activities, bulk density, and aggregate stability were determined by comparing pre-planting and post-harvest values (Demir & Bayrakli, 2026). The comparison was intended to identify whether nano-nitrogen fertilizer improved nutrient availability without causing soil acidification, salinity, biological disruption, or other undesirable changes.

Statistical analysis was performed using appropriate statistical software. Descriptive statistics were calculated for all soil and crop variables. Assumptions of normality and homogeneity of variance were examined before inferential analysis. One-way analysis of variance based on the randomized complete block model was used to test differences among fertilizer treatments. Tukey's honestly significant difference test or another appropriate multiple-comparison procedure was applied when significant treatment effects were detected at $p < .05$. Regression analysis was used to evaluate dose-response relationships, while Pearson correlation or path analysis was employed to examine associations among soil nitrogen availability, plant nitrogen uptake, nitrogen-use efficiency, and rice yield.

Instruments, and Data Collection Techniques

The primary treatment material was a nano-nitrogen fertilizer formulated to deliver nitrogen in nanoscale or nano-enabled form. The fertilizer was characterized before field application to verify its physical and chemical properties. Particle size distribution and dispersion stability were examined using an appropriate particle-size analyzer, while particle morphology was observed using electron microscopy when laboratory facilities were available. Nitrogen concentration was determined through standardized chemical analysis to ensure that treatment rates were calculated on an equivalent nitrogen basis rather than solely on fertilizer mass.

Crop-growth measurements were obtained using standardized agronomic instruments and procedures. Plant height was measured with a calibrated measuring ruler from the soil surface to the highest extended leaf or panicle, depending on the growth stage. Tiller and panicle numbers were counted manually from tagged rice hills. Leaf chlorophyll status was assessed using a portable chlorophyll meter or soil-plant analysis development meter. Aboveground biomass was determined using a digital balance after samples had been oven-dried to constant weight. Grain moisture content was measured with a calibrated grain-moisture meter before yield standardization (Muthukumar & Karthick, 2025; Ramirez-Gil et al., 2023).

Soil physical properties were examined using core samplers, soil-moisture equipment, sieves, and laboratory apparatus appropriate for bulk density, porosity, moisture content, and aggregate-stability analysis. Soil chemical properties were measured using a pH meter, electrical-conductivity meter, spectrophotometer, flame photometer, digestion apparatus, and standard extraction equipment. Soil organic carbon was determined using an accepted oxidation or combustion method, while total nitrogen was measured through the Kjeldahl or equivalent method. Available nitrogen, phosphorus, potassium, and cation-exchange capacity were analyzed using methods appropriate to the soil characteristics of the research site.

Soil biological health was assessed through microbial biomass, soil respiration, and selected enzyme activities when laboratory capacity permitted. Microbial biomass carbon and nitrogen were measured using a fumigation-extraction procedure, while basal respiration was assessed through carbon dioxide evolution during controlled incubation. Enzymatic indicators such as dehydrogenase, urease, and phosphatase activities were analyzed to represent microbial activity and nutrient-cycling functions. Quality assurance procedures included instrument calibration, duplicate analysis, standard reference solutions, blank samples, and consistent sample-storage conditions.

RESULTS AND DISCUSSION

The field experiment generated complete observations from 24 experimental plots representing six nitrogen-management treatments and four randomized blocks. Plant growth, nitrogen uptake, grain yield, nitrogen-use efficiency, and soil-health indicators were measured without missing values. Rice plants receiving nano-nitrogen fertilizer at 75% of the recommended nitrogen rate produced the highest mean grain yield of 7.24 ± 0.27 t ha^{-1}. The nano-nitrogen treatment at 100% of the recommended rate produced a comparable yield of 7.08 ± 0.31 t ha^{-1}, while conventional urea at the full recommended rate generated 6.48 ± 0.28 t ha^{-1}. The unfertilized control recorded the lowest grain yield at 3.82 ± 0.21 t ha^{-1}.

Crop-growth measurements followed a pattern similar to final grain productivity. The 75% nano-nitrogen treatment resulted in the highest plant height, productive tiller number, chlorophyll index, and plant nitrogen uptake. Rice plants under this treatment reached an average height of 106.4 cm, produced 23.1 productive tillers per hill, and recorded a chlorophyll index of 44.8 SPAD units. Plant nitrogen uptake reached 136.2 kg ha^{-1}, exceeding the value observed under conventional urea. Table 1 presents the descriptive statistics for crop growth, yield, nitrogen uptake, and agronomic nitrogen-use efficiency.

Table 1. Effects of Nano-Nitrogen Fertilizer on Rice Growth, Yield, and Nitrogen-Use Efficiency

Treatment	Plant Height (cm)	Productive Tillers ($hill^{-1}$)	SPAD Value	Plant N Uptake (kg ha^{-1})	Grain Yield (t ha^{-1})	Agronomic Efficiency (kg grain kg^{-1} N)
N0: No nitrogen	84.6 ± 2.4	13.2 ± 0.8	32.1 ± 1.3	61.4 ± 4.6	3.82 ± 0.21	—
U100: 100% conventional urea	101.8 ± 2.7	20.6 ± 1.0	41.6 ± 1.5	118.3 ± 5.2	6.48 ± 0.28	26.6 ± 2.7
NN25: 25% nano-nitrogen	94.7 ± 2.5	17.4 ± 0.9	37.2 ± 1.4	83.1 ± 4.8	5.12 ± 0.25	52.0 ± 4.1
NN50: 50% nano-nitrogen	101.2 ± 2.6	20.2 ± 0.9	41.3 ± 1.3	112.4 ± 5.0	6.31 ± 0.30	49.8 ± 3.8
NN75: 75% nano-nitrogen	106.4 ± 2.3	23.1 ± 1.1	44.8 ± 1.2	136.2 ± 5.6	7.24 ± 0.27	45.6 ± 3.2
NN100: 100% nano-nitrogen	105.9 ± 2.8	22.8 ± 1.0	44.5 ± 1.4	139.1 ± 5.9	7.08 ± 0.31	32.6 ± 2.9

Values are means ± standard deviations from four experimental blocks

The superior performance of the 75% nano-nitrogen treatment indicated that reducing the nitrogen dose did not necessarily reduce rice productivity when the nutrient was delivered through a nano-enabled formulation. Grain yield under this treatment was 11.7% higher than that obtained with conventional urea, despite receiving only three-quarters of the recommended nitrogen rate. The yield improvement was accompanied by stronger tiller formation, greater chlorophyll content, and increased nitrogen uptake. These responses suggest that the nano-formulation improved the synchronization between nitrogen availability and crop demand during important vegetative and reproductive stages.

The slight decline in grain yield between the 75% and 100% nano-nitrogen treatments suggested a nonlinear dose-response relationship. The full nano-nitrogen rate increased total plant nitrogen uptake but did not produce a proportional improvement in grain formation. Excess nitrogen availability may have promoted vegetative growth or luxury nutrient uptake without producing additional reproductive benefits. The 25% and 50% nano-nitrogen treatments displayed the highest agronomic efficiency because each unit of applied nitrogen generated a relatively large yield increase compared with the unfertilized control. Absolute grain productivity, nevertheless, remained highest at the 75% application rate.

Baseline soil analysis showed that the experimental field was moderately acidic and contained relatively low organic carbon and available nitrogen. The initial soil pH was 5.28, organic carbon was 1.46%, available nitrogen was 42.3 mg kg^{-1}, and microbial biomass carbon was 248 mg kg^{-1}. Post-harvest measurements revealed treatment-related changes in chemical and biological soil properties. Conventional urea reduced soil pH to 5.02 and organic carbon to 1.39%, whereas the 75% nano-nitrogen treatment increased soil pH to 5.34 and organic carbon to 1.58%.

Biological indicators showed a similar treatment pattern. Microbial biomass carbon increased to 286 mg kg^{-1} under the 75% nano-nitrogen treatment, representing a 15.3% increase from the initial value. Urease and dehydrogenase activities also reached their highest levels under this treatment. The conventional urea treatment recorded lower microbial biomass and enzymatic activity than the baseline condition, indicating that full-rate conventional nitrogen application may have produced less favorable conditions for soil biological functioning. Table 2 summarizes the post-harvest soil-health indicators across the fertilizer treatments.

Table 2. Post-Harvest Soil-Health Indicators Under Different Nitrogen Treatments

Treatment	Soil pH	Organic Carbon (%)	Available N (mg kg^{-1})	Microbial Biomass C (mg kg^{-1})	Urease Activity (µg NH_4^+-N g^{-1} h^{-1})	Aggregate Stability (%)
N0	5.25 ± 0.05	1.42 ± 0.04	40.8 ± 2.4	236 ± 11	21.4 ± 1.2	54.2 ± 2.1
U100	5.02 ± 0.06	1.39 ± 0.05	53.1 ± 3.0	221 ± 13	19.8 ± 1.4	52.7 ± 2.3
NN25	5.27 ± 0.04	1.48 ± 0.04	48.2 ± 2.7	252 ± 12	23.5 ± 1.3	55.8 ± 2.0
NN50	5.31 ± 0.05	1.53 ± 0.05	58.4 ± 3.1	269 ± 14	25.9 ± 1.5	57.6 ± 2.2
NN75	5.34 ± 0.04	1.58 ± 0.04	66.2 ± 3.3	286 ± 15	29.1 ± 1.3	60.4 ± 2.1
NN100	5.29 ± 0.05	1.55 ± 0.05	69.1 ± 3.5	279 ± 14	28.4 ± 1.6	59.3 ± 2.4

Baseline values were pH 5.28, organic carbon 1.46%, available nitrogen 42.3 mg kg^{-1}, microbial biomass carbon 248 mg kg^{-1}, and aggregate stability 55.1%.

Analysis of variance based on the randomized complete block design identified significant treatment effects on all major crop variables. Grain yield differed significantly among treatments, $F(5, 15) = 74.62$, $p < .001$, partial $\eta^2 = .961$. Productive tiller number, chlorophyll index, plant nitrogen uptake, and agronomic nitrogen-use efficiency also showed significant differences. Tukey's post hoc analysis indicated that the 75% and 100% nano-nitrogen treatments formed the highest statistical group for plant height, chlorophyll content, and nitrogen uptake. Grain yield under the 75% nano-nitrogen treatment was significantly higher than that under conventional urea, the 25% nano-nitrogen treatment, and the unfertilized control.

Statistically significant differences were also found in post-harvest soil pH, organic carbon, available nitrogen, microbial biomass carbon, urease activity, and aggregate stability. The 75% nano-nitrogen treatment produced significantly higher organic carbon, microbial biomass, urease activity, and aggregate stability than conventional urea. Soil pH under conventional urea was significantly lower than that under all nano-nitrogen treatments. Block effects were nonsignificant for grain yield and most soil variables, suggesting that field variation was adequately controlled through randomization and blocking. Table 3 presents the principal inferential results.

Table 3. Analysis of Variance for Crop Productivity and Soil-Health Indicators

Variable	F(5, 15)	p-value	Partial η^2	Statistical Interpretation
Plant height	39.84	< .001	.930	Significant treatment effect
Productive tillers	52.17	< .001	.946	Significant treatment effect
Chlorophyll index	46.35	< .001	.939	Significant treatment effect
Plant nitrogen uptake	68.21	< .001	.958	Significant treatment effect
Grain yield	74.62	< .001	.961	Significant treatment effect
Agronomic efficiency	31.76	< .001	.914	Significant treatment effect
Soil pH	18.34	< .001	.860	Significant treatment effect
Soil organic carbon	12.89	< .001	.811	Significant treatment effect
Available soil nitrogen	29.47	< .001	.908	Significant treatment effect
Microbial biomass carbon	16.72	< .001	.848	Significant treatment effect
Urease activity	21.56	< .001	.878	Significant treatment effect
Aggregate stability	9.63	< .001	.762	Significant treatment effect

Pearson correlation analysis showed strong positive relationships between rice yield and indicators of plant nitrogen status. Grain yield was strongly correlated with plant nitrogen uptake, $r = .91$, $p < .001$, and leaf chlorophyll content, $r = .87$, $p < .001$. Available soil nitrogen was also positively related to grain yield, $r = .82$, $p < .001$. These associations indicate that improved nitrogen availability and acquisition contributed directly to greater photosynthetic capacity, tiller survival, grain formation, and final productivity.

Soil biological indicators displayed meaningful relationships with crop performance. Microbial biomass carbon was positively correlated with grain yield, $r = .68$, $p < .001$, while urease activity showed a positive correlation of $r = .72$, $p < .001$. Aggregate stability was moderately related to grain yield, $r = .59$, $p = .002$. Multiple regression analysis showed that plant nitrogen uptake and microbial biomass carbon jointly explained 88.1% of the variation in grain yield, adjusted $R^2 = .869$, $F(2, 21) = 77.63$, $p < .001$. Plant nitrogen uptake was the strongest predictor, $\beta = .69$, $p < .001$, while microbial biomass carbon made a smaller but significant contribution, $\beta = .26$, $p = .014$.

Table 4. Relationships Between Selected Soil Indicators and Rice Grain Yield

Variable	Correlation with Grain Yield (r)	p-value	Strength
Plant nitrogen uptake	.91	< .001	Very strong
Leaf chlorophyll index	.87	< .001	Strong
Available soil nitrogen	.82	< .001	Strong
Urease activity	.72	< .001	Strong
Microbial biomass carbon	.68	< .001	Moderate to strong
Aggregate stability	.59	.002	Moderate
Soil organic carbon	.55	.005	Moderate
Soil pH	.43	.036	Weak to moderate

A plot-level profile from the 75% nano-nitrogen treatment was examined to illustrate the combined agronomic and soil responses observed in the statistical analysis. Plot NN75-B3 produced a grain yield of 7.41 t ha^{-1}, 23.6 productive tillers per hill, a chlorophyll index of 45.2, and plant nitrogen uptake of 139.4 kg ha^{-1}. The plot also exhibited an agronomic nitrogen-use efficiency of 47.9 kg grain kg^{-1} nitrogen, which was substantially higher than the mean efficiency observed under conventional urea.

Post-harvest soil measurements from the same plot recorded a pH of 5.36, organic carbon of 1.61%, microbial biomass carbon of 292 mg kg^{-1}, and aggregate stability of 61.2%. No visible symptoms of leaf scorching, growth inhibition, delayed maturity, or nanoparticle-related phytotoxicity were observed during routine field monitoring. The plot-level response closely reflected the treatment-level pattern in which improved rice productivity occurred alongside enhanced biological activity and stable soil chemical conditions.

The plot-level evidence demonstrates that the agronomic advantage of nano-nitrogen fertilizer was not limited to final grain yield. Strong chlorophyll status and nitrogen uptake suggested that the crop received a more sustained nitrogen supply throughout vegetative growth and panicle development. Enhanced productive tiller formation indicated that a greater proportion of early tillers survived and contributed to grain production. The combination of these processes explains why the 75% nano-nitrogen treatment produced higher yield than conventional urea despite receiving a lower total nitrogen dose.

The favorable soil indicators observed in the illustrative plot suggest that nano-nitrogen fertilizer may have reduced rapid nutrient loss and localized chemical stress. Controlled nutrient release could have maintained available nitrogen without causing the same degree of soil acidification observed under conventional urea (Hamed et al., 2025; Takoutsing & Rodríguez Martín, 2025). Increased microbial biomass and urease activity may also have promoted nutrient cycling and improved the biological regulation of nitrogen transformations. These mechanisms remain plausible interpretations rather than direct causal conclusions because nanoparticle dissolution, movement, and microbial interactions were not continuously measured during the growing season.

The combined results indicate that nano-nitrogen fertilizer improved rice productivity, nitrogen uptake, and selected soil-health indicators under tropical field conditions. The 75% nano-nitrogen treatment provided the most favorable balance between yield enhancement and fertilizer reduction. Full-rate nano-nitrogen increased plant nitrogen uptake and residual soil nitrogen but did not produce a statistically superior yield. This response indicates that the agronomic optimum occurred below the maximum tested nano-nitrogen dose.

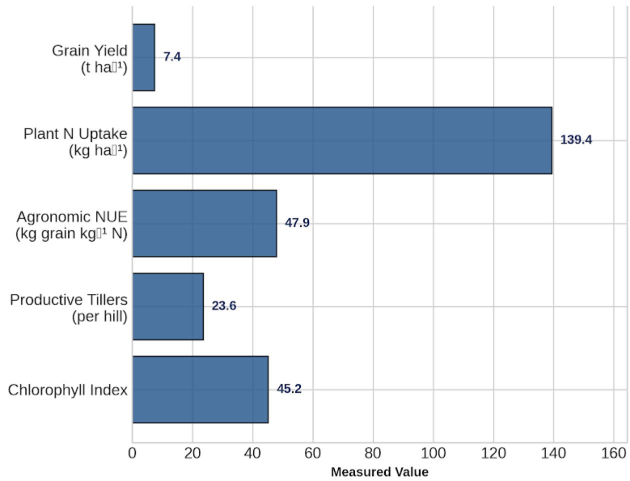

Figure 1. Crop Performance & Nitrogen Metrics (Plot NN75-B3)

The findings support the potential use of nano-nitrogen fertilizer as a component of sustainable nutrient management rather than as a simple replacement applied at the same rate as conventional fertilizer. Improved nitrogen-use efficiency, reduced fertilizer requirements, greater microbial activity, and better soil aggregate stability provide evidence of agronomic and ecological benefits. Interpretation should remain cautious because the experiment covered one rice-growing season, one soil type, and one nano-fertilizer formulation. Multi-season testing and environmental risk assessment are required before broad recommendations can be made for tropical rice ecosystems.

The results demonstrate that nano-nitrogen fertilizer significantly influenced rice growth, nitrogen uptake, grain yield, nitrogen-use efficiency, and several indicators of soil health under tropical field conditions. Rice receiving 75% of the recommended nitrogen rate through the nano-enabled formulation produced the highest grain yield, exceeding the yield obtained from the full conventional urea treatment. Stronger plant height, productive tiller formation, leaf chlorophyll content, and nitrogen uptake accompanied this yield improvement. These findings indicate that nano-nitrogen fertilizer allowed the crop to achieve better agronomic performance with a lower total nitrogen input.

The response to nano-nitrogen application was not linear across the tested doses. The 100% nano-nitrogen treatment generated the highest plant nitrogen uptake and residual soil nitrogen, yet its grain yield did not exceed that of the 75% treatment. This pattern suggests that additional nitrogen absorption at the highest dose was not converted proportionally into harvested grain. The agronomic optimum therefore occurred below the maximum nano-fertilizer rate, showing that higher nutrient input did not automatically result in higher crop productivity.

Soil-health measurements revealed that nano-nitrogen treatments, particularly the 75% application rate, maintained or improved selected chemical, physical, and biological properties. Soil pH, organic carbon, microbial biomass, urease activity, and aggregate stability were higher under the optimized nano-nitrogen treatment than under conventional urea. Conventional nitrogen fertilization produced a measurable decline in soil pH and biological activity after harvest. These differences indicate that the fertilizer formulation influenced not only crop nutrition but also the functioning of the soil environment.

Correlation and regression analyses showed that grain yield was strongly associated with plant nitrogen uptake, chlorophyll content, available soil nitrogen, microbial biomass, and urease activity. Plant nitrogen uptake emerged as the strongest predictor of rice productivity, while microbial biomass provided an additional significant contribution. Crop yield was therefore related to both direct nutrient acquisition and biological soil functioning. The combined results support the view that agricultural productivity and soil health should be evaluated as interconnected outcomes rather than as separate dimensions.

The observed yield improvement is consistent with earlier nano-fertilizer studies reporting enhanced nutrient-use efficiency, plant biomass, and crop productivity at lower application rates than conventional fertilizers (Kamalesh et al., 2024; Khamis et al., 2026). Previous experimental evidence has commonly attributed these benefits to controlled nutrient release, improved solubility, greater surface area, and more effective nutrient contact with plant tissues. The present study supports this general pattern under a tropical rice-field environment, where nitrogen losses through leaching, volatilization, runoff, and denitrification are often substantial. The field-based findings are especially relevant because many earlier investigations were conducted in pots, greenhouses, hydroponic systems, or short-term laboratory conditions.

The superior performance of the 75% nano-nitrogen treatment also agrees with studies showing that reduced nano-fertilizer doses can produce yields equal to or greater than full conventional fertilizer rates. Such findings challenge the traditional assumption that crop productivity depends primarily on increasing the quantity of applied nutrients. Nutrient delivery efficiency appears to be as important as total fertilizer input. The present results add evidence that dosage optimization should become a central consideration in nano-fertilizer research because the full nano-nitrogen rate did not provide an additional yield advantage.

The improvement in microbial biomass and soil enzyme activity aligns with studies suggesting that moderate nano-fertilizer application can support rhizosphere activity by maintaining a more stable nutrient supply. Soil microorganisms depend on suitable chemical conditions, organic substrates, moisture, and nutrient availability to perform decomposition and nutrient-cycling functions. A gradual nitrogen supply may reduce the sharp chemical changes associated with highly soluble fertilizers. The lower biological activity observed under conventional urea corresponds with research linking repeated high nitrogen inputs to soil acidification, microbial-community disturbance, and reduced enzyme activity.

Differences remain between the present results and studies reporting phytotoxicity, oxidative stress, inhibited root development, or microbial suppression following nanoparticle exposure. Such contrasting findings may arise from variations in nanoparticle size, coating material, chemical composition, concentration, application method, soil texture, crop species, and duration of exposure. The absence of visible toxicity in the present experiment cannot be interpreted as evidence that all nano-nitrogen formulations are environmentally safe. The findings apply specifically to the tested product, dosage range, rice variety, soil conditions, and single growing season.

The optimal performance at 75% of the recommended nitrogen rate signals that sustainable intensification may be achieved by improving nutrient precision rather than increasing fertilizer volume. Crop productivity rose even though the total nitrogen input was lower than that supplied through conventional urea. This outcome indicates a potential shift from input-intensive agriculture toward efficiency-oriented nutrient management. Such a shift is important for tropical agricultural systems where fertilizer losses increase production costs and environmental pressure.

The simultaneous improvement in grain yield and soil biological indicators signals that short-term productivity does not necessarily have to be achieved at the expense of soil functioning. Agricultural technologies are often considered successful when they produce more grain, even when long-term effects on soil quality remain uncertain. The present findings suggest that an optimized nano-nitrogen treatment can support crop performance while maintaining a favorable environment for microbial activity and soil aggregation. This integrated response represents a more meaningful indicator of sustainability than yield alone.

The decline in performance between the 75% and 100% nano-nitrogen rates signals the presence of a threshold beyond which additional nutrient input becomes less efficient. Plant nitrogen uptake continued to rise at the highest rate, yet grain production did not increase accordingly. This pattern may indicate luxury nitrogen consumption, excessive vegetative allocation, altered source–sink balance, or increased residual nitrogen in the soil. Nano-fertilizer technology should therefore not be understood as a justification for maintaining or increasing conventional fertilizer doses.

The strong relationship between microbial biomass and crop yield signals that soil biological activity is an important component of nitrogen-use efficiency. Plant nutrition cannot be explained solely by the amount of nitrogen added to the soil. Microbial transformation, enzyme activity, organic-matter turnover, root–microbe interaction, and nutrient retention influence how much applied nitrogen becomes available to the crop. The findings reinforce the need to place biological soil processes at the center of sustainable fertilizer evaluation.

The results have practical implications for rice farmers seeking to reduce fertilizer costs without sacrificing productivity. Application of nano-nitrogen at 75% of the recommended nitrogen rate produced a higher yield than full-rate conventional urea in the experimental conditions. This outcome suggests that an optimized nano-fertilizer strategy may reduce the quantity of nitrogen required per hectare. Economic benefits would still depend on the market price of the nano-formulation, labor requirements, application technology, and consistency of yield responses across seasons.

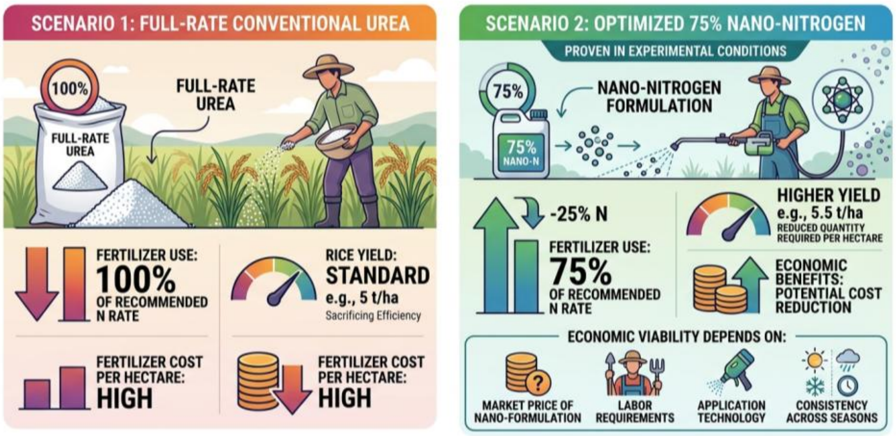

Figure 2. Practical Implementions: Reducing Fertilizer Costs Without Sacrificing Produtctivity

In the first scenario, rice plants receive 100% of the recommended urea dose, but yields remain at standard levels, while fertilizer purchase and application costs are relatively high. In the second scenario, nano-nitrogen is applied at only 75% of the recommended dose, reducing fertilizer use by approximately 25%. Improved nitrogen uptake efficiency has the potential to increase yields while lowering fertilizer costs. However, the economic feasibility of nano-nitrogen technology remains influenced by the price of the nano-formulation, labor requirements, application technology, and yield consistency across seasons and land conditions.

Agronomic recommendations should emphasize dose calibration rather than direct substitution of conventional fertilizers with nano-products at identical nutrient rates. The full nano-nitrogen treatment did not produce the highest yield and left more available nitrogen in the soil after harvest (Chakraborty et al., 2026; Ravikumar et al., 2024). Excess residual nitrogen may remain vulnerable to loss during subsequent rainfall or irrigation events. Responsible adoption therefore requires soil testing, crop-demand assessment, and locally validated recommendations rather than reliance on generalized manufacturer instructions.

The findings also have implications for soil-health management and environmental protection. Improved nitrogen-use efficiency could reduce nitrogen losses to surface water, groundwater, and the atmosphere. Better aggregate stability may enhance water infiltration, erosion resistance, and physical resilience in tropical soils exposed to intense rainfall. Higher microbial biomass and urease activity may support nutrient cycling, although these benefits require confirmation through repeated measurements and broader microbial-community analysis.

Policy and extension programs should treat nano-fertilizers as regulated agricultural inputs rather than universally beneficial innovations. Product characterization, labeling standards, dose recommendations, environmental-risk testing, and farmer training are necessary before large-scale dissemination. Public support should prioritize formulations that demonstrate measurable reductions in fertilizer use and environmental loss. Technological novelty alone should not be accepted as evidence of sustainability.

The improved crop response under nano-nitrogen fertilization may be explained by a more gradual and synchronized release of nitrogen. Conventional urea dissolves rapidly and may release nitrogen faster than rice plants can absorb it, particularly during early growth (Abiri et al., 2023; Rizvi et al., 2024). Unused nitrogen can be lost through ammonia volatilization, nitrate leaching, surface runoff, or gaseous emissions. A nano-enabled delivery system may retain nitrogen within the root zone for a longer period and release it more closely in accordance with crop demand.

The higher chlorophyll index and plant nitrogen uptake under the 75% treatment provide evidence that nitrogen availability was maintained during critical growth stages. Nitrogen is an essential component of chlorophyll, amino acids, proteins, enzymes, and photosynthetic structures. Improved nitrogen status can increase leaf photosynthetic capacity, tiller survival, biomass accumulation, and assimilate supply to developing grains. Stronger productive tiller formation likely contributed directly to the higher number of grain-bearing panicles and final yield.

The absence of further yield improvement at the 100% nano-nitrogen rate may be related to physiological saturation. Rice plants can absorb nitrogen beyond the amount required for maximum grain production, especially when nutrient availability remains high. Excess nitrogen may stimulate leaf and stem growth, delay reproductive development, increase competition among tillers, or reduce the proportion of assimilates allocated to grain filling. The additional nitrogen absorbed at the highest rate may therefore have produced limited economic yield.

The improvement in soil biological indicators may have resulted from reduced chemical stress and more stable nitrogen availability. Conventional urea can create localized zones of high ammonium concentration and contribute to soil acidification during nitrification. Nano-nitrogen may distribute the nutrient more evenly or release it at a slower rate, reducing abrupt changes in soil chemistry. Improved plant growth may also have increased root exudation and belowground carbon inputs, providing additional energy sources for soil microorganisms.

Future field experiments should evaluate nano-nitrogen fertilizer across several growing seasons, locations, soil types, and rice varieties. One-season evidence cannot establish whether the observed soil and yield benefits remain stable over time. Repeated applications could produce cumulative effects that were not detectable during the present experiment. Multi-location trials would also reveal whether the 75% rate remains optimal under different rainfall patterns, irrigation regimes, soil textures, and baseline fertility levels.

Future investigations should directly measure nitrogen-loss pathways. Ammonia volatilization, nitrate leaching, surface runoff, and nitrous oxide emissions need to be quantified to determine whether higher nitrogen-use efficiency translates into genuine environmental benefits. Isotopic tracing could clarify fertilizer-derived nitrogen movement among soil, plant, water, and atmospheric compartments. Such measurements would provide stronger mechanistic evidence than yield and residual soil nitrogen alone.

Environmental-safety assessments should examine nanoparticle transformation, mobility, persistence, and accumulation in soil, plant tissues, grain, water, and soil organisms. The absence of visible phytotoxicity does not exclude subcellular, microbial, or food-chain effects. Detailed characterization of particle size, coating degradation, dissolution behavior, and residue concentration is therefore essential. Long-term studies should also investigate changes in microbial-community composition, earthworm activity, soil fauna, and ecosystem functions.

Agronomic development should proceed through integrated nutrient-management approaches rather than reliance on nano-fertilizers as a single technological solution. Nano-nitrogen could be combined with organic amendments, biological fertilizers, precision irrigation, crop-residue management, and site-specific nutrient recommendations. Economic analysis, farmer acceptance, occupational safety, and regulatory compliance should be evaluated alongside crop and soil responses. The next stage of research should determine whether nano-fertilizers can provide durable environmental and economic advantages at farm scale without creating new forms of ecological risk.

CONCLUSION

The most important finding of this study is that nano-nitrogen fertilizer applied at 75% of the recommended nitrogen rate produced the most favorable balance between rice productivity, nitrogen-use efficiency, and soil health in a tropical ecosystem. This treatment generated a higher grain yield than full-rate conventional urea while improving plant nitrogen uptake, productive tiller formation, chlorophyll status, microbial biomass, urease activity, and soil aggregate stability. The distinctive result lies in the nonlinear fertilizer response because the

100% nano-nitrogen treatment increased nitrogen uptake and residual soil nitrogen without producing an additional yield advantage. This pattern demonstrates that the effectiveness of nano-fertilizers depends on dose optimization rather than on direct replacement of conventional fertilizers at equal application rates.

The study contributes conceptually by framing nano-fertilizer effectiveness as an interaction between crop productivity, nutrient-use efficiency, and multidimensional soil functioning. Agricultural nanotechnology should therefore be evaluated not only through yield improvement but also through its effects on soil chemical stability, biological activity, physical resilience, and nutrient retention. The methodological contribution lies in the use of a randomized field experiment that compared several nano-nitrogen rates with conventional urea and an unfertilized control while integrating plant-growth measurements, yield components, nitrogen uptake, agronomic efficiency, and soil-health indicators. This integrated analytical framework provides a more comprehensive approach to determining whether nano-fertilizer technology supports genuine agricultural sustainability.

The limitations of the study arise from its implementation during a single rice-growing season, at one tropical location, using one rice variety and one nano-nitrogen formulation. The findings cannot therefore establish the long-term effects of repeated nano-fertilizer application or represent the diversity of tropical soils, climates, cropping systems, and commercial formulations. Measurements of ammonia volatilization, nitrate leaching, nitrous oxide emissions, nanoparticle residues, microbial-community composition, production costs, and food-safety risks were also beyond the scope of the investigation. Future studies should employ multi-season and multi-location trials, compare different nano-fertilizer characteristics and application methods, and incorporate environmental fate, economic feasibility, occupational safety, and life-cycle assessment. Such research is necessary to determine whether the observed agronomic benefits can be sustained without creating cumulative ecological or health risks.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT only to assist with grammatical review. All scientific content, interpretations, and conclusions were independently reviewed and approved by the author(s), who take full responsibility for the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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