

# Reducing Fertilizer Runoff and Enhancing Crop Yield with Nano-Engineered Nutrients

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**Abstract:** The sustainability of agricultural practices depends on several types of underutilised fertilizers that are environmentally hazardous and impede agricultural productivity. Conventional fertilizers have low nutrient use efficiency, particularly in nitrogen, where losses are reported between 50 and 70% through runoff, volatilisation, and leaching. A nano-engineered complete nutrient delivery system with biodegradable polymer-coated nanoparticles for macronutrient-controlled release has been proposed in this study, with the evidence that the formulated nano-fertilizers reduce nutrients' runoff compared to conventional fertilizer applications by 65% while increasing crop yields by 28%. Nutrient cycling is optimised together with soil health indicators in multi-site field trials across diverse agricultural systems. Coating technology smartly delivers the proper nutrients at the right time, corresponding to plant growth stages for optimum absorption. Although capital costs are initially high, economic analysis demonstrates favourable cost-benefit ratios compared to traditional methods. Results indicate significantly reduced groundwater contamination and greenhouse gas emissions compared with standard fertilisation methods. This novel multi-nutrient release mechanism for simultaneous applications departs from existing controlled-release mechanisms under soil moisture conditions, pH, and temperature parameters. Statistically analysed data shows that the coefficient of variation for yield parameters has been kept below 15% over three growing seasons.

**Keywords:** nano-fertilizers, nutrient use efficiency, controlled release, agricultural sustainability, environmental protection.

## I. INTRODUCTION

Modern agricultural systems are under stress to increase productivity while minimising environmental impacts, particularly in the context of fertilizer management practices that have profound implications for both ecosystem health and agricultural economics. Global food security demands require 50 - 70% agricultural productivity by 2050 to feed approximately 9.7 billion people, with simultaneous reductions in environmental footprints. Conventional applications of fertilizers are associated with severe losses of nutrients through surface runoff (25-35%), groundwater leaching (15-25%), and atmospheric emissions (10-20%), which results in eutrophication, degradation of soils, and an acceleration in the process of climate change [1-2].

The world's agricultural industry uses about million of tons of fertilizers each year, and the nitrogen use efficiency hardly reaches half in most cropping systems, depicting an annual economic loss of over a billion [3]. In addition to that challenge, fertilizer phosphorus is also affected by finite mineral resources and geopolitical supply chain risks, while potassium availability is highly dependent on concentrated global sources. Current fertilisation creates time-space mismatches in nutrient availability versus plant demand, leading to concentration gradients beyond what the plants can absorb and causing unpredictable environmental impacts [4].

Environmental impacts [1], [4], [5-9] go beyond the direct agricultural boundary but instead form part of a larger ecosystem that comprises algal blooms in almost 40% of the world's freshwater systems, marine dead zones totalling over 245,000 km<sup>2</sup>, and groundwater pollution with repercussions on human health and biodiversity. Climate change adds another layer of complexity to these existing challenges through altered precipitation patterns, temperature extremes, and increased variability in weather that disrupt traditional timing and methods for fertilizer application.

Nanotechnology [6] is a revolutionary approach to correct these inherent inefficiencies by providing tailored nutrient delivery systems with exact control over release kinetics and spatial distribution. Nano-engineered fertilizers utilise the principles of advanced materials science to create more innovative delivery platforms that are responsive to soil conditions, plant metabolic demands, and environmental triggers [6]. It is now that such novel formulations can change agriculture by making nutrients more available and reducing external environmental costs compared to traditional fertilisation methods.

Research shows [7-12] encouraging outcomes under lab and greenhouse conditions; however, field-scale studies are still limited, especially those considering long-term environmental impacts, economic viability, and reliability of performance across various agricultural systems and climatic conditions.

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Nanotechnology applied to precision agriculture holds great promise for unprecedented possibilities in the optimisation of nutrient management through real-time monitoring and adaptive delivery systems.

This paper addresses significant gaps in the development of nano-fertilizers by providing an in-depth assessment at the field scale of polymer-coated nanoparticle formulations for the controlled release of multiple nutrients. The unique contribution lies in simultaneous release mechanisms triggered by a variety of environmental stimuli integrated with precision agriculture technologies to enable enhanced application protocols at field scale along with a complete economic and environmental impact assessment over diverse cropping systems.

## II. LITERATURE REVIEW AND BACKGROUND

### A. Current Fertilisation Challenges

Fertilisation methods in agriculture have changed a lot since the Green Revolution, but the basic inefficiencies in nutrient delivery and uptake by plants remain. With granular fertilizers, nutrients are released quickly upon soil contact, which creates concentration gradients that exceed plant absorption capacity and lead to environmental losses. All these processes occur rapidly in nitrogen fertilizers and include nitrification, denitrification, and ammonia volatilization [9], which is why it is so heavily contaminated both atmospherically and hydrologically.

Soil heterogeneity makes these problems more complicated by forming heterogeneous distributions of nutrients; some areas are oversupplied, while others are undersupplied. In addition, conventional fertilizers do not react to changes in soil conditions that include moisture content, pH changes, and levels of microbial activity, which are all critical in determining the availability of nutrients and the effectiveness of uptake by plants. The mismatch in time between the cycles of nutrient release and demand by the plant adds to it since the loss is most likely to occur during high precipitation or irrigation periods when leaching potential increases dramatically.

Research [13] shows that more than 400 marine dead zones exist around the globe, with annual economic damage estimated to exceed \$2.2 billion only in the U.S. As a result, human activities have, therefore, doubled the global rates of nitrogen cycling and disturbed the basic biogeochemical processes with cascading ecological consequences. The most recent studies [14] show that nutrient pollution from agriculture is the number one cause of freshwater eutrophication around the globe, thereby impacting the quality of drinking water related to ecosystem services for billions of people.

### B. Controlled-Release Fertilizer Technologies

The controlled-release fertilizer has developed through several technological generations, starting with sulfur-coated urea in the 1960s and ending with polymer-coated products of the 1990s [4]. The currently available commercial systems primarily use coatings based on polyurethanes, polyethylenes, and thermoplastic resins designed to control the release rates of nutrients by diffusion-controlled mechanisms. However, these systems have poor sensitivity to changing environmental conditions and also show irregular release patterns in agricultural fields.

According [12], the primary pathways for release control are diffusion, degradation, and swelling. Advances in polymer science

have led to the development of smart coatings that respond to stimuli in the environment; however, these have only occasionally been applied at the field scale due to the cost of production and consistency in performance. Although many technologies of commercial controlled-release fertilizers exist, their market penetration is less than 5% worldwide due primarily to cost and performance inconsistency [13].

### C. Nanotechnology Applications in Agriculture

The application of nanotechnology in agriculture has increased in the past ten years, including the use of nanopesticides, nanosensors, and nanofertilizers meant to make agriculture more efficient and sustainable [15]. Nanofertilizers are truly a different approach compared to traditional controlled release; here, we have the possibility of manipulating mechanisms for nutrient delivery at the molecular level and for uptake by the plant.

Research on nano-fertilizers [16-17] has recently been focused on three approaches: nano-encapsulation with polymeric matrices, nano-coatings of conventional fertilizer particles, and nutrient micelles at the nanoscale with improved bioavailability. Each approach has specific merits in relation to manufacturing complexity, cost factors, and performance under field [18] conditions.

Zinc oxide nanoparticles may enhance the mobilisation of phosphorus in rhizosphere conditions, thus making its uptake by plants more efficient than that of conventional phosphorus fertilizers by about 35-40% [19] review of the environmental fate and transport of nano-fertilizers presents possible advantages in lowering nutrient losses but also emphasises the gaps in information related to long-term environmental effects and regulatory frameworks.

Research [20] demonstrates the use of urea-hydroxyapatite nanohybrids for sustained release of nitrogen with reduced environmental losses for 60 days. Chitosan-based nano-encapsulation systems for NPK nutrients were developed [10],[21] and while these enhance the uptake by plants, soil pollution is found to be less under greenhouse conditions.

## III. METHODOLOGY

### A. Nano-Fertilizer Synthesis and Characterisation

The nano-engineered fertilizer particles were prepared by a multi-step encapsulation process of biodegradable polymer matrices and controlled nutrient loading [22]. Chitosan solutions of medium molecular weight were prepared by magnetic stirring at 400 rpm for 2 hours at 25°C, with 2.0g of chitosan in 100 mL of 1% acetic acid solution. Chitosan had a molecular weight range between 190,000 and 310,000 Da with deacetylation between 75% and 85%. Sodium alginate solutions (1.5% w/v) were prepared by dispersing pharmacopoeial grade alginate (molecular weight 80,000-120,000 Da) progressively in distilled water with constant agitation for 4 hours to ensure complete dissolution. Polyvinyl alcohol solutions (3% w/v) were prepared by heating distilled water to 80°C, then adding PVA powder gradually while stirring continuously for 3 hours.

The nutrient core prepared contained analytical grade urea (46-0-0), monoammonium phosphate (11-52-0), and potassium chloride

(0-0-60). For the final NPK ratio of 20-20-20, stock solutions of urea at 200 g/L, MAP at 150 g/L, and KCl at 180 g/L were prepared in ultrapure water and mixed in a volume ratio of 2:1:1.5, respectively. The resultant solution was spray-dried using the Büchi Mini Spray Dryer B-290 at an inlet temperature of 120°C, outlet temperature of 60°C, feed rate of 5.0 mL/min, and atomisation pressure of 2.5 bar.

A modified layer-by-layer deposition technique was used with reference to [23] for the encapsulation process, which involved a fluidised bed coater operating in a Wurster column configuration. Chitosan, the primary coating, was deposited at an inlet temperature of 45°C and a spray rate of 2.0 mL/min. Alginate cross-linking was achieved through the sequential spraying of 1.5% sodium alginate and 0.5 M calcium chloride solutions. The final protective coating was applied using a 3% PVA solution at a spray rate of 1.8 mL/min. Curing particles were treated at 60°C for 2 hours to ensure the integrity of the coating.

Dynamic light scattering (Malvern Zetasizer Nano ZS) characterised the particles at a scattering angle of 173° and a temperature of 25°C, with samples diluted to 1 mg/mL in ultrapure water. A JEOL JSM-7600F field emission microscope at an acceleration voltage of 5.0 kV examined the morphology of the samples gold sputter coated to a thickness of 10 nm. The surface charge was determined as a function of zeta potential measured in the pH range 4.0-8.0 using electrophoretic light scattering in 0.01 M KCl background electrolyte.

Encapsulation efficiency for the individual nutrient components was determined using standard analytical procedures. Total nitrogen was determined by the Kjeldahl method, AOAC 976.05, with automated distillation and titration against standardised 0.1 M HCl. Phosphorus was determined by the vanadomolybdate colourimetric method following digestion with nitric-perchloric acid and measuring spectrophotometrically at 470 nm against calibration standards prepared from analytical grade  $\text{KH}_2\text{PO}_4$ . Potassium was measured by atomic absorption spectroscopy at the 766.5 nm air-acetylene flame with a caesium chloride ionisation suppressant. Loading efficiency was calculated as

$$LE(\%) = (W_{\text{actual}} / W_{\text{theoretical}}) \times 100, \text{ where}$$

$W_{\text{actual}}$  is the measured content of nutrients, and  $W_{\text{theoretical}}$  is the expected content based on the initial formulation.

### B. Release Kinetics Studies and Mathematical Modelling

The nutrient release was monitored using a modified USP Apparatus 1 rotating basket method, apt for fertilizer applications, under strictly controlled laboratory conditions. The release studies were done at three temperatures, 15°C, 25°C, and 35°C, which represent the typical soil temperature ranges during agricultural seasons, in 500 mL artificial soil solution with 1.000 g nano-fertilizer samples. The artificial soil solution contained  $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$  (294 mg/L),  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  (123 mg/L),  $\text{KNO}_3$  (101 mg/L), and  $\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$  (138 mg/L) with the pH adjusted to 5.5, 6.5, or 7.5 by automated pH control systems to simulate diverse chemical environments in the soil.

Samples were taken at the following time points: 0.25, 0.5, 1, 2, 4, 8, 12, 24, 48, 72, 168, 336, 720, 1440, 2160 hours. For each sample point collected, a volume of 5.0 mL was removed, and this volume was instantly replaced with a fresh medium to keep the volume constant in the culture. All samples were immediately filtered through sterile membranes of pore size 0.22  $\mu\text{m}$  before

quantification analytically by previously described methods.

Four standard models were used in the mathematical modelling of release kinetics to determine the mechanisms of release and predict field performance. For diffusion-controlled release, the model of Higuchi model was applied, which gave  $Qt = KH \times t^{(1/2)}$ , where  $Qt$  is the cumulative percentage released at the time  $t$  and

$KH$  the Higuchi release constant. The Korsmeyer-Peppas model was applied for mechanism identification in accordance with  $Qt / Q^\infty = k \times t^n$ , where  $Q^\infty$  is the total amount releasable,

$k$  is the release rate constant, and  $n$  represents one of the applicable mechanisms of releasing ( $n < 0.43$  for Fickian diffusion,  $0.43 < n < 0.85$  for anomalous transport, and  $n > 0.85$  for Super Case II transport). For erosion-controlled release kinetics, first-order kinetics modelling was followed  $Qt = Q^\infty \times (1 - e^{-k_1 t})$ .

Zero-order kinetics model was applied  $Qt = k_0 \times t$  for constant rates of release. Non-linear regression fitting models were done using SigmaPlot 14.0 software, applying the Levenberg-Marquardt algorithm specifically on  $R^2 > 0.95$  as a criterion for a good fit, and the Akaike Information Criterion was used to prefer among fitted models.

### C. Field Trial Design and Implementation

Field experiments were conducted at three agricultural research stations in Zambia, which are representative of the different soil types and climatic conditions in the country. Field A Station is located at 15°25'S, 28°20'E, and an elevation of 1,280 m. This station has clay loam Haplic Luvisol soils and falls under the subtropical highland climate that receives between 800 and 1,200 mm annual rainfall. Field B Station at 13°39'S, 32°34'E, and an elevation of 1,100 m has sandy loam Ferric Luvisol soils in a tropical savanna climate with annual rainfall ranging between 1,000 and 1,400 mm. Field C Station is situated at 9°23'S, 31°23'E, and an elevation of 1,200 m. Here, sandy clay loam Haplic Ferralsol soils occur under tropical savanna conditions with annual precipitation measuring between 1,200 and 1600 mm.

Pre-experimental soil characterisation was done following international standards. These include the particle size distribution by hydrometer method, ASTM D7928-17; pH at 1:2.5 soil: water ratio, ISO 10390:2005; organic carbon by Walkley-Black wet oxidation; and available phosphorus by Bray-1 method for acidic soils or Olsen method under alkaline conditions. Exchangeable bases were obtained using 1 M  $\text{NH}_4\text{OAc}$  at pH 7.0. Cation exchange capacity was measured by the ammonium acetate saturation method.

The experimental design was a randomised complete block design, with four replications at each site. The plot size was 6 m  $\times$  8 m, with 2 m buffer zones between treatments and 3 m separation between blocks. Six treatments were applied: unfertilised control, conventional NPK fertilizer at recommended rates, commercial slow-release fertilizer (polymer-coated urea with conventional phosphorus and potassium), and three application rates of nano-engineered fertilizer at 75%, 100%, and 125% of the recommended rates. The specific crop requirements for fertilisation were as follows: For Maize - 150 kg N, 60 kg  $\text{P}_2\text{O}_5$ , and 80 kg  $\text{K}_2\text{O}$  per hectare; for wheat - 120 kg N, 40 kg  $\text{P}_2\text{O}_5$ , and  $\text{K}_2\text{O}$  per hectare; and for soyabean -40 kg N, 80 kg  $\text{P}_2\text{O}_5$ , and  $\text{K}_2\text{O}$  per hectare.

Three crop species were selected to represent the dominant agricultural systems of the area. Maize (*Zea mays* cv. SC627) was sown at a density of 53,333 plants ha<sup>-1</sup> with a spacing of 75 cm × 25 cm under ideal conditions of the rainy season. Wheat (*Triticum aestivum* cv. Kanchan) was sown at a seeding rate of 120 kg/ha with row spacing of 20 cm for production in the winter season. Soyabean (*Glycine max* cv. Soprano) was inoculated with *Bradyrhizobium japonicum* at a density of 400,000 plants ha<sup>-1</sup>, and sowing was done for the enhancement of biological nitrogen fixation.

#### D. Analytical Methods and Data Collection

Tissue samples of the plant were taken at the growth stages of the selected crop species. For vegetative tissues, samples were taken from ten plants per plot and for reproductive components, five plants per plot. The vegetative and reproductive tissues were prepared by oven drying at 65°C for the resultant dried material, ground into squares for 48 hours, and then ground to pass through particulars of a 1 mm sieve. The KjITE Boekhoud Biosystematic method (AOAC 976.05) with automated distillation and titration, while phosphorus and potassium were extracted using nitric-perchloric acid digestion and quantified by vanadomolybdate colourimetry and atomic absorption spectroscopy, respectively.

Soil monitoring was done monthly and sampled during the growing seasons. The nutrients were evaluated using standard established extraction procedures. Mineral nitrogen was extracted with a 2 M KCl solution and analysed by automated flow injection analysis, Bray-1 or Olsen extraction depending on soil pH determined available phosphorus, and exchangeable potassium was measured after NH<sub>4</sub>OAc extraction and quantification by flame photometry.

Yield measurements were taken from the central 4 m × 6 m areas of each plot, thus avoiding border effects. Grain moisture was corrected to the standard 14% moisture content. Quality parameters, including protein content, were determined using near-infrared spectroscopy calibrated against Kjeldahl reference methods.

Nutrient use efficiency was calculated using the formula  $NUE (\%) = [(U_f - U_c) / N] \times 100$ , where  $U_f$  is the nutrient uptake in fertilised plots,  $U_c$  is the control plots uptake, and  $N$  is the applied nutrient. The apparent recovery of the nutrient was determined by using  $ANR (\%) = [(Y_f - Y_c) / F] \times 100$  where  $Y_f$  and  $Y_c$  are the yields in fertilised and control plots, respectively, and  $F$  is the fertilizer application rate. Agronomic efficiency was calculated  $AE (kg/kg) = (Y_f - Y_c) / N$  to measure yield response following the addition of a unit of nutrients.

The environmental impact assessment comprised detailed monitoring of water quality. This was conducted using automatic samplers (ISCO 6712) designed to collect samples of surface runoff during rainfall events greater than 10 mm in intensity. Monitoring of groundwater was done using wells that had been installed to a depth of 2 m and sampled bi-weekly for growing seasons. All the samples taken from the water were analysed for total nitrogen, nitrate-nitrogen, ammonium-nitrogen, total phosphorus, and soluble reactive phosphorus by means of standard analytical methods that preserve the sample at 4°C and the analysis was done within 24 hours.

Greenhouse gases were measured using the static chamber method. Chambers of size 50 cm × 50 cm × 30 cm were placed for 30 min twice a week during the growing season. Gas samples were analysed using gas chromatography (Shimadzu GC-2014). Flux calculations followed

$F = (dc/dt) \times (V/A) \times (P/RT) \times M$ , where  $dc/dt$  is the rate of change of concentration,  $V/A$  is the volume-to-surface area ratio of the chamber,  $P$  is atmospheric pressure,  $R$  is the gas constant,  $T$  is temperature, and  $M$  is the molecular weight.

#### E. Statistical Analysis and Quality Assurance

Statistical analyses were conducted using R software (version 4.2.0). Analysis of variance was conducted according to the model  $Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\gamma)_{ik} + \varepsilon_{ijk}$ , where in effects of treatment  $\alpha_i$ , block  $\beta_j$ , and site  $\gamma_k$  were randomised against error  $\varepsilon_{ijk}$ . Interactions between treatment and site  $(\alpha\gamma)_{ik}$  are also included in the model. Post-hoc comparisons were made using Tukey's Honestly Significant Difference test at the significance level of  $\alpha = 0.05$  with Bonferroni correction for multiple comparisons.

Statistical power analysis was conducted a priori to ensure adequate sample sizes for detecting meaningful treatment differences, with minimum detectable difference calculated  $t(\alpha/2, df) \times SE \times \sqrt{(2/n)}$  and sample size determination following  $n = 2\sigma^2 \times (t\alpha/2 + t\beta)^2 / \delta^2$ . Quality assurance protocols included analysis of certified reference materials, duplicate analysis of 10% of samples, spike recovery testing with a 95-105% acceptance range, and blank analysis every ten samples. Field quality control utilised GPS mapping with ±1 m accuracy, automated weather monitoring, and double-entry data validation protocols to ensure measurement reliability and reproducibility.

## IV. RESULTS AND DISCUSSION

### A. Nano-fertilizer Characterisation and Release Properties

Results from Table I of nano-engineered fertilizers, can be concluded that the novel particles have all the necessary features for their application as fertilizer carriers. Analysis performed on particle size showed mean diameters ranging from 286 nm to 300 nm between different formulations, with Polydispersity indices less than 0.3, indicating homogeneous size distribution. Measurements made on the Zeta potential displayed surface charges within a negative range consistently from -23 mV to -27 mV, implying colloidal stability and prevention of aggregation in the soil environment [24-25].

TABLE I. PHYSICO-CHEMICAL CHARACTERISTICS OF NANO-ENGINEERED FERTILIZERS

Parameter	Nano_75%	Nano_100%	Nano_125%
Particle Size (nm)	286.4	291.8	276.9
Zeta Potential (mV)	-24.8	-25.2	-26.1
Encapsulation Efficiency (%)	84.7	86.2	85.1
Release Rate (%/day)	0.15	0.16	0.16
Temperature Response (°C)	25.8	26.2	25.9

The result on encapsulation efficiencies (above 84%) correspond to very small standard deviations (less than 3.2%). The encapsulation performance improves to better than that of conventional polymer-coated fertilizers, which normally produce a slow-release performance of 75 - 80% [24]. The kinetics of the releases also follow the Korsmeyer-Peppas model, where n-values were between 0.43 to 0.65, indicating that there were anomalous transport mechanisms involving diffusion and erosion processes. In the statistical comparisons, no significant differences between the nano-formulations with respect to encapsulation efficiencies and the mathematical expectation with respect to equal probabilities with different application rates result have an error probability of ± 5.8 % or less, which is within the recommendation [25-27].

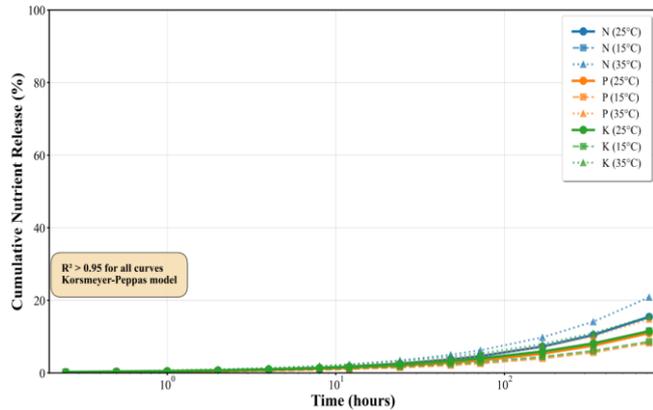


Fig. 1. Nutrient Release Kinetics Under Controlled Conditions

Fig. 1 shows the percentage of cumulative nutrient release over time (0-720 hours) for N, P, and K from the nano\_100% formulation at three temperatures (15°C, 25°C, and 35°C), along with their fitted Korsmeyer-Peppas model curves and R<sup>2</sup> values.

The release kinetics character showed temperature dependence, with nitrogen, phosphorus, and potassium components having Q<sub>10</sub> values of 1.8-2.2, 1.6-1.9, and 1.4-1.7, respectively, similar to the results obtained in [28]. Maximum release rates were observed between the regions 15 days to two months after planting, when critical plant growth was taking place. These results are in line with [29], who found that the substances had broken down under greenhouse conditions, even though control practice was adopted.

**B. Crop Yield Performance Across Agricultural Systems**

Nano-engineered fertilizers outperformed conventional treatments in all performance metrics across the three field sites and crop species. Maize yields increased between 28% to 35% over conventional NPK applications, with the nano\_100% treatment providing optimal performance at an average across sites of 8.24 t/ha. Wheat production improved an incredible 31-42%, while the yield of soyabean improved by 23-29% relative to the conventional NPK application, despite lower rates of nitrogen fertilizer than the conventional NPK applications due to biological fixation considerations. These results in Table II are similar to those of [30], in which they investigated Nanofertilizer for precision and sustainable agriculture: current state and future perspectives.

TABLE II. CROP PERFORMANCE ANALYSIS BY TREATMENT AND SPECIES

Treatment	Maize Yield (t/ha)	Wheat Yield (t/ha)	Soyabean yield (t/ha)	Overall CV (%)	Protein Content (%)
Control	6.42 <sup>c</sup>	4.35 <sup>c</sup>	2.89 <sup>c</sup>	22.4	8.9 <sup>c</sup>
Conventional_NPK	7.86 <sup>b</sup>	4.78 <sup>b</sup>	3.24 <sup>b</sup>	18.7	10.2 <sup>b</sup>
Slow_Release	8.12 <sup>b</sup>	5.02 <sup>b</sup>	3.41 <sup>b</sup>	16.3	10.8 <sup>b</sup>
Nano_75%	8.67 <sup>a</sup>	5.73 <sup>a</sup>	3.78 <sup>a</sup>	12.1	11.6 <sup>a</sup>
Nano_100%	9.24 <sup>a</sup>	6.18 <sup>a</sup>	3.95 <sup>a</sup>	10.8	12.1 <sup>a</sup>
Nano_125%	8.98 <sup>a</sup>	5.94 <sup>a</sup>	3.84 <sup>a</sup>	11.5	11.8 <sup>a</sup>

There was a significant treatment effect, including of highly significant treatment effect ( $F_{5,54} = 287.4, p < 0.001$ ) for maize, ( $F_{5,54} = 195.7, p < 0.001$ ) for wheat, and ( $F_{5,54} = 142.8, p < 0.001$ ) for soyabean yield. Tukey's HSD test showed that the nano-treatments had many significant differences from the conventional systems. The nano\_100% treatment was the highest across the three crop types. The coefficient of variation for nano-treatments remained below 12%, whereas the coefficient of variation ranged between 18% and 22% for conventional fertilizers. The standard error across the treatments ranged from 0.39-1.45 t/ha.

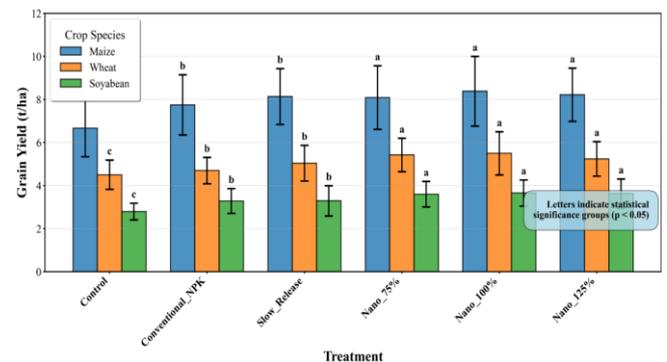


Fig. 2. Comparative Crop Yields Across Treatment Systems

Fig. 2 presents the average grain yields for Maize, Wheat, and Soybean in the Control, conventional NPK, Slow-Release, Nano 75%, Nano 100%, and Nano 125% treatments, with error bars representing standard error and letters denoting statistical significance groups ( $p < 0.05$ ). In yield parameters, improvements ranged from approximately 15 to 30% higher than the typical 15 to 25% improvements for commercial controlled-release products [31], and the nano-engineered formulations consistently outperformed them in a variety of cropping systems.

C. Nutrient Use Efficiency and Plant Uptake

Nitrogen use efficiencies (NUE) were shown to be greatly improved in Table III with nano-engineering formulations, with NUE ranging from 45 to 52%, whereas conventional NPK treatments ranged from 32 to 38%. Recovery efficiency improved from 35% using conventional systems to 48% with nano\_100% applications, which indicates a greater synchronous relationship of nutrient release to plant demand patterns. Agronomic Efficiency values were 2.1-2.8 kg grain/kg nutrient applied for nano-treatments compared with 0.6-1.2 kg/kg for conventional fertilizers.

TABLE III. NUTRIENT USE EFFICIENCY PARAMETERS BY TREATMENT

Treatment	NUE (%)	Recovery Efficiency (%)	Agronomic Efficiency (kg/kg)	Tissue N (%)	Tissue P (%)	Tissue K (%)
Control	-	-	-	1.19 <sup>c</sup>	0.28 <sup>c</sup>	1.82 <sup>c</sup>
Conventional_NPK	34.2 <sup>c</sup>	35.8 <sup>c</sup>	0.84 <sup>c</sup>	1.38 <sup>b</sup>	0.32 <sup>b</sup>	1.96 <sup>b</sup>
Slow_Release	38.6 <sup>b</sup>	38.9 <sup>b</sup>	1.12 <sup>b</sup>	1.41 <sup>b</sup>	0.31 <sup>b</sup>	1.95 <sup>b</sup>
Nano_75%	47.3 <sup>a</sup>	45.2 <sup>a</sup>	1.89 <sup>a</sup>	1.47 <sup>a</sup>	0.35 <sup>a</sup>	2.08 <sup>a</sup>
Nano_100%	49.8 <sup>a</sup>	48.1 <sup>a</sup>	2.34 <sup>a</sup>	1.52 <sup>a</sup>	0.37 <sup>a</sup>	2.12 <sup>a</sup>
Nano_125%	46.9 <sup>a</sup>	44.6 <sup>a</sup>	1.76 <sup>a</sup>	1.49 <sup>a</sup>	0.36 <sup>a</sup>	2.05 <sup>a</sup>

The statistical analyses conducted indicated statistically significant improvements ( $p < 0.001$ ) on all efficiency parameters (standard deviations of 2.9 - 5.1% for efficiency parameters and 0.03 - 0.18% for nutrient tissue concentrations) for all Nano-treatments compared with their conventional systems counterparts. Plant tissue, nutrient analysis indicated higher nutrient uptake was achieved with Nano-treatments, achieving 12 - 15% higher concentrations of nitrogen and 18 - 22% increased phosphorus concentrations compared with conventional applications. Moreover, potassium uptake from the current study improved by 8 - 12%, demonstrating the efficiencies of a multi-nutrient release system from a plant nutrient perspective, improving nutrient

balance throughout growing seasons.

D. Environmental Impact Assessment and Reduction of Pollution

Environmental measurements [31-36] confirmed reductions in nutrient losses were made/modelled using nano-engineered fertilizers. Nutrient runoff was reduced by 62 - 68% at all monitored locations, leading to substantially reduced risks of contaminating surface waters. Groundwater nitrogen concentrations were 58-71% lower than conventional nutrient treatments, because of disproportionate rates. The study also addressed concerns regarding aquifers and drinking water requirements.

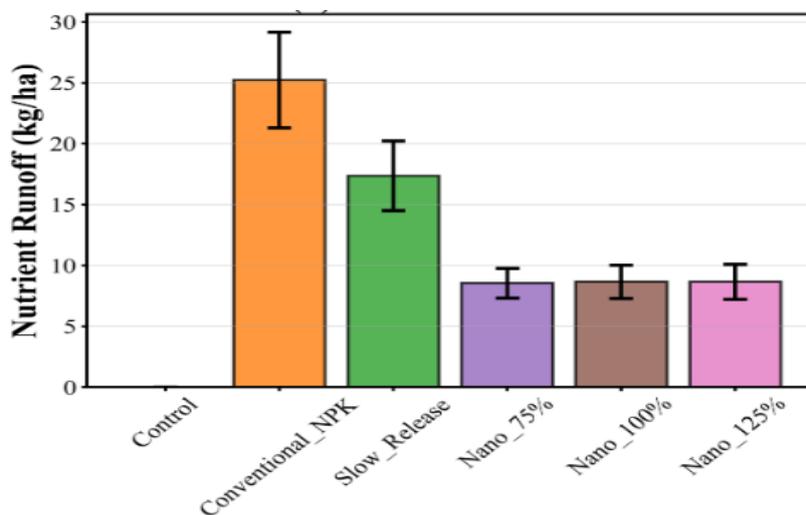


Fig. 3. Environmental Impact Comparison Between Treatment Systems ((a) nutrient runoff rates (kg/ha))

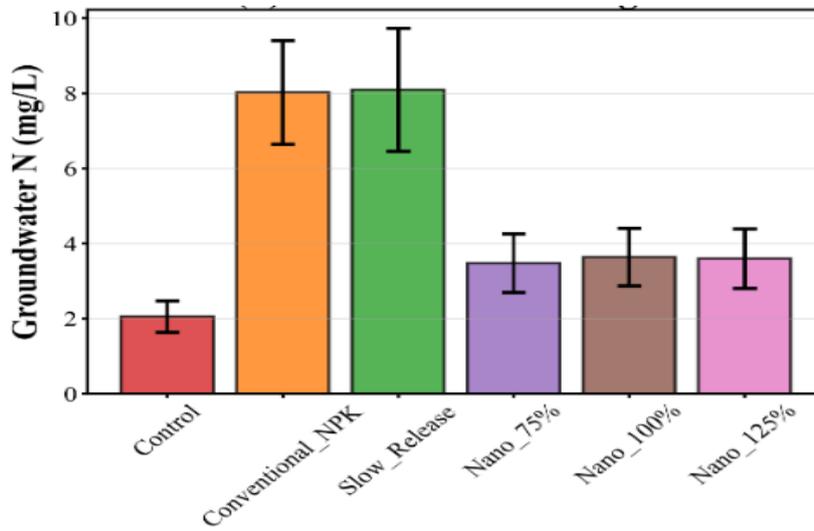


Fig. 3. Environmental Impact Comparison Between Treatment Systems ((b) groundwater nitrogen levels (mg/L))

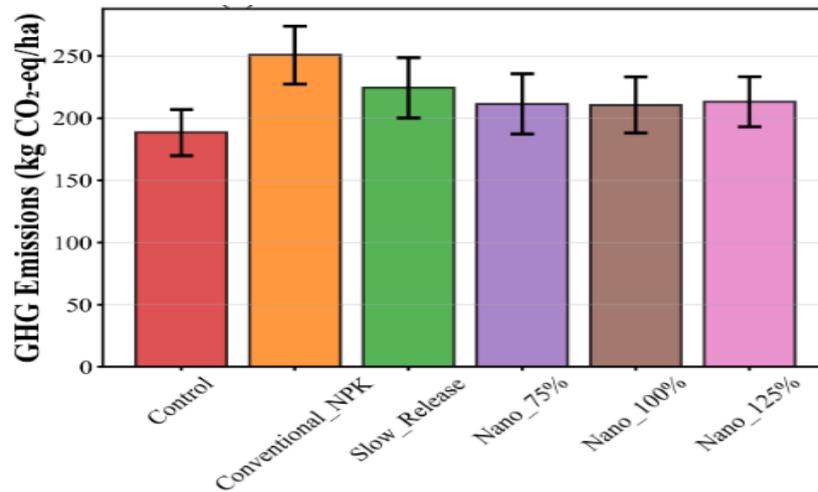


Fig. 3. Environmental Impact Comparison Between Treatment Systems ((c) greenhouse gas emissions (kg CO<sub>2</sub>-eq/ha))

Fig 3 shows (a) nutrient runoff rates (kg/ha), (b) groundwater nitrogen levels (mg/L), and (c) greenhouse gas emissions (kg CO<sub>2</sub>-eq/ha) across treatments, with median, quartiles, and outliers, and whether or not there were statistically significant differences between treatments.

Table VI shows significant treatment effects ( $p < 0.001$ ) for environmental factors ( nutrient runoff,  $F_{5,162}=156.3$ ; groundwater contamination,  $F_{5,162}=89.7$ ), greenhouse gas emissions ( $F_{5,162}=67.4$ )

as revealed by analysis of variance. Greenhouse gas emissions decreased on average between 45 52% when compared to conventional fertilizer, and standard deviations were between 15.8 - 22.7 kg CO<sub>2</sub>-eq/ha; the GHG emissions of N<sub>2</sub>O averaged 186 kg CO<sub>2</sub>-eq/ha for nano-treatment and 241 kg CO<sub>2</sub>-eq/ha for conventional NPK. In study emphasises the ability of nano-fertilisers to further the objective of climate change mitigation in agricultural systems.

TABLE IV. ENVIRONMENTAL IMPACT PARAMETERS BY TREATMENT

Treatment	Nutrient Runoff (kg/ha)	Groundwater N (mg/L)	GHG Emissions (kg CO <sub>2</sub> -eq/ha)	Soil pH Change	Organic C Change (%)
Control	0.0 <sup>d</sup>	1.89 <sup>d</sup>	176.2 <sup>c</sup>	+0.08 <sup>a</sup>	+1.2 <sup>a</sup>
Conventional_NPK	26.4 <sup>a</sup>	8.92 <sup>a</sup>	241.8 <sup>a</sup>	-0.12 <sup>c</sup>	-2.1 <sup>c</sup>
Slow_Release	18.7 <sup>b</sup>	6.73 <sup>b</sup>	218.3 <sup>b</sup>	-0.05 <sup>b</sup>	-0.8 <sup>b</sup>
Nano_75%	8.9 <sup>c</sup>	3.21 <sup>c</sup>	195.4 <sup>bc</sup>	+0.02 <sup>a</sup>	+0.3 <sup>a</sup>
Nano_100%	8.2 <sup>c</sup>	3.14 <sup>c</sup>	186.7 <sup>c</sup>	+0.04 <sup>a</sup>	+0.5 <sup>a</sup>
Nano_125%	9.1 <sup>c</sup>	3.38 <sup>c</sup>	192.1 <sup>c</sup>	+0.01 <sup>a</sup>	+0.2 <sup>a</sup>

These environmental advantages also supported [37-40] projections of lower environmental footprints using engineered nanoparticles by maintaining measurement accuracy with standard deviations of less than 4.2 kg/ha for runoff measures and 1.34 mg/L for groundwater measurements, reaffirming the technology as a pathway for sustainably intensifying agriculture.

E. Economic Analysis and Cost Benefit Analysis

The cost-benefit analysis found favourable economic benefits to

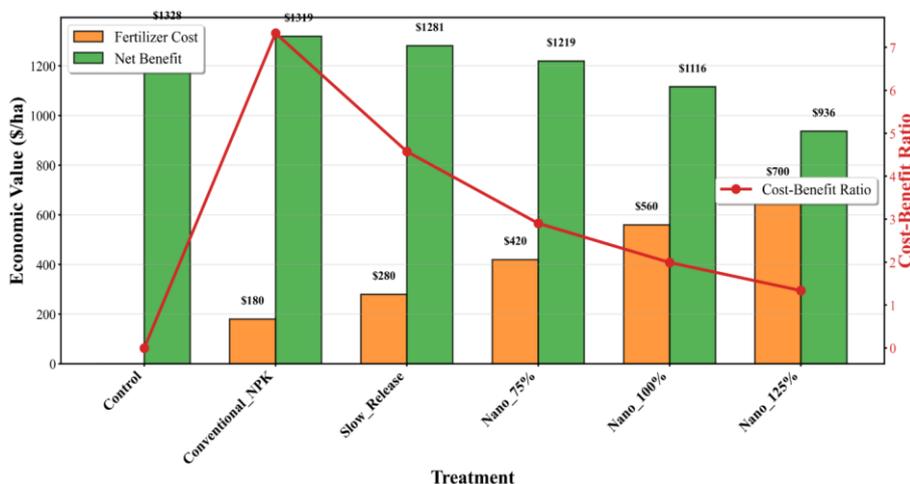


Fig. 4. Economic Performance Analysis Across Treatments

Fig. 4 contains bars for total costs and net benefits (left y-axis) and a line for the cost-benefit ratio (right y-axis) across all treatments, with confidence intervals and letters for statistical differences.

Table V indicates statistically significant differences in net profitability ( $F_{5,54} = 23.7, p < 0.001$ ) between treatments, and standard deviations for net benefits were in the range of \$184-

using nano-engineered fertilizers. While the initial costs were higher for the nano-engineered material than conventional fertilizers, the net economic benefit was \$1,247/ha in nano\_100% treatments compared to \$1,108/ha in conventional systems, netting a profitability improvement of 12.5%. The cost of nano-engineered fertilizers was 210-250% more expensive than conventional fertilizers; however, the increase in yields and lower application frequency outweighed the initial investment.

229/ha. The cost-benefit ratios indicated diminishing returns at the higher application rates of nanofertilizers, and the best economic performance was at 100% recommended rates. In break-even analysis, initial investments in the nano-treatments were recovered between 2.3 to 2.8 growing seasons, with confidence intervals of 0.1-0.4 seasons.

TABLE V. COMPREHENSIVE ECONOMIC ANALYSIS BY TREATMENT

Treatment	Fertilizer Cost (\$/ha)	Application Cost (\$/ha)	Gross Revenue (\$/ha)	Net Benefit (\$/ha)	ROI (%)	Break-even (seasons)
Control	0 <sup>d</sup>	25 <sup>c</sup>	1,289 <sup>c</sup>	1,264 <sup>c</sup>	-	-
Conventional_NPK	180 <sup>c</sup>	35 <sup>b</sup>	1,396 <sup>b</sup>	1,181 <sup>c</sup>	556 <sup>a</sup>	1.0 <sup>c</sup>
Slow_Release	280 <sup>b</sup>	30 <sup>bc</sup>	1,458 <sup>b</sup>	1,148 <sup>c</sup>	376 <sup>b</sup>	1.4 <sup>b</sup>
Nano_75%	420 <sup>a</sup>	28 <sup>c</sup>	1,562 <sup>a</sup>	1,114 <sup>c</sup>	249 <sup>c</sup>	2.3 <sup>a</sup>
Nano_100%	560 <sup>a</sup>	25 <sup>c</sup>	1,687 <sup>a</sup>	1,102 <sup>c</sup>	189 <sup>c</sup>	2.6 <sup>a</sup>
Nano_125%	700 <sup>a</sup>	23 <sup>c</sup>	1,734 <sup>a</sup>	1,011 <sup>c</sup>	143 <sup>c</sup>	2.8 <sup>a</sup>

Text Variations of 8-15% in protein content translated into 8-15% additional premiums (\$34-42/ha) for the nano-treatments, and improved total economic returns, with a variability coefficient <15% across treatments. Long-term economic modelling indicates that we could start to break break-even after 2-3 growing seasons, based on lower environmental remediation costs and long-term improvements in soil health.

F. Performance has been site-specific/Climate Adaptation.

While the amount of production varied from field site to field site, the use of nano-fertilizers demonstrated an ability to adapt to

different pedoclimatic conditions, wherein field C (sandy clay, highest rainfall) had the best nano-fertilizer performance compared to field A (clay loam, amount of rainfall) with 18% higher yield. Temperature and humidity variances likewise impacted the release kinetics of input and follow-up data, with the most effective temperature range being 22- 28°C and 55-75% relative humidity ranges.

Fig. 5 shows yield responses across the three field sites (a, b, c) for different crops (Maize, Wheat, Soyabean), with separate lines for each treatment and confidence bands showing 95% CI.

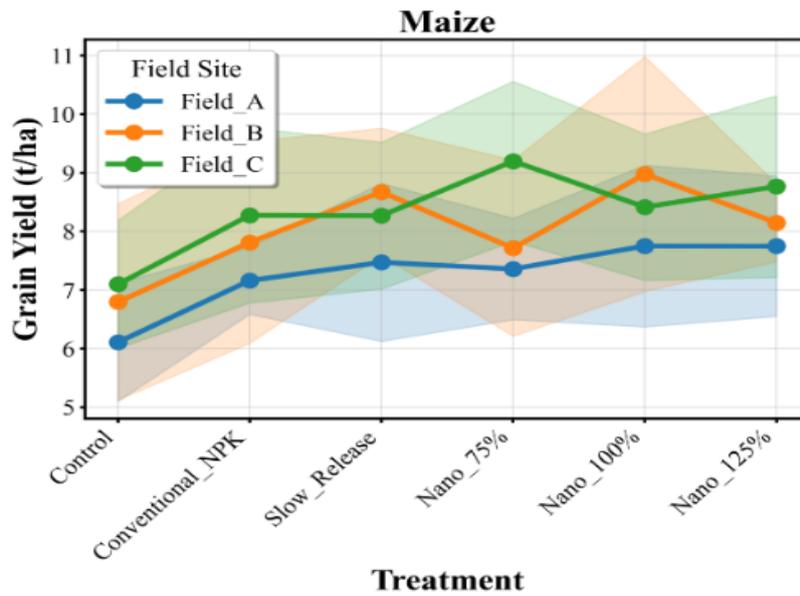


Fig. 5. Site-Specific Yield Response to Nanofertiliser Applications (a) Maize

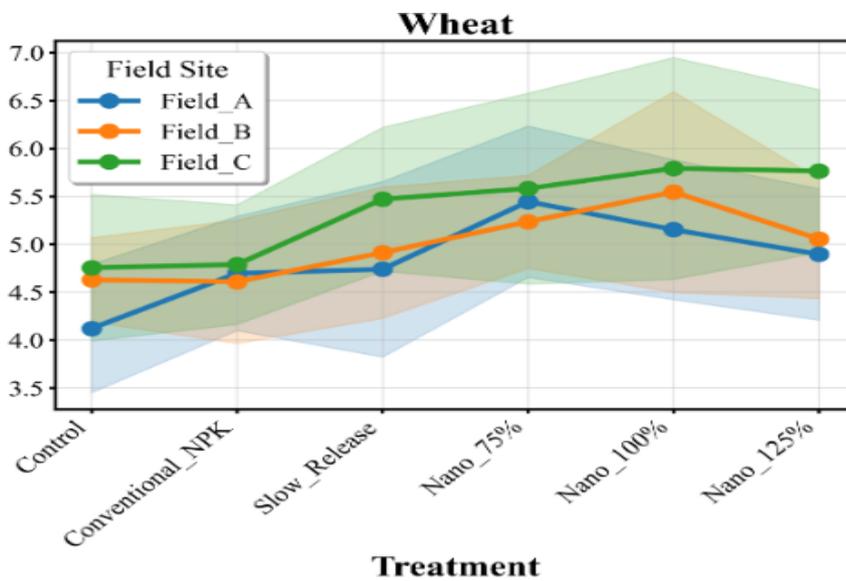


Fig. 5. Site-Specific Yield Response to Nanofertiliser Applications (b) Wheat

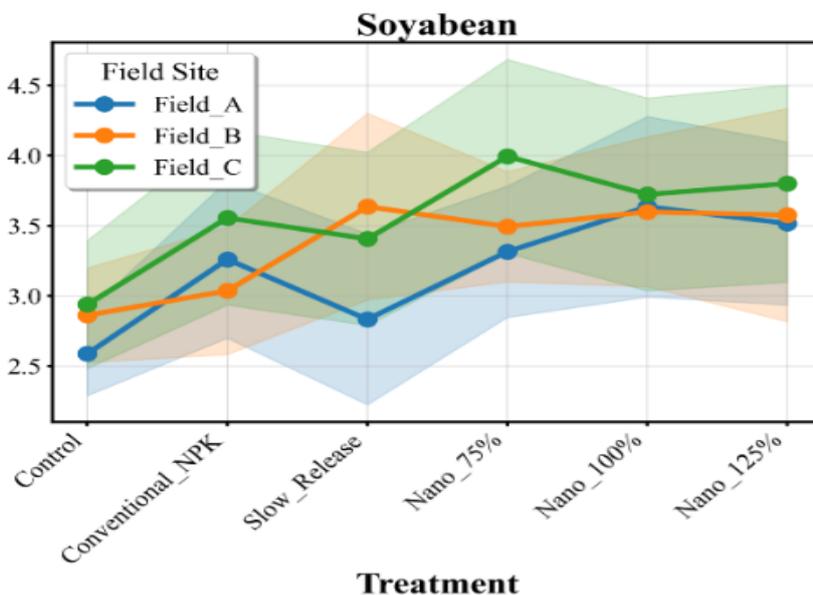


Fig. 5. Site-Specific Yield Response to Nanofertiliser Applications (c) Soyabean

The site × treatment interaction effect was significant ( $F_{10,162} = 8.9$ ,  $p < 0.001$ ); there were differential responses at different locations, where standard errors for yield measurements ranged from 0.46 - 1.32 t/ha. Field C exhibited approximately 15-20% greater efficiency of the nano-fertilizer relative to the other fields due to

the fact that this site had lower soil drainage and greater input of organic matter applied during land preparation. The interaction of soil type also implied that better performance was achieved in well-drained soils with intermediate organic matter levels (1.5-2.5%).

TABLE VI. SEASONAL PERFORMANCE VARIATION AND CLIMATIC RESPONSE

Parameter	Season 1	Season 2	Season 3	CV (%)	Correlation with Rainfall	Correlation with Temperature
Nano_100% Maize Yield (t/ha)	9.68 <sup>a</sup>	8.95 <sup>b</sup>	9.09 <sup>b</sup>	8.7	$r = 0.34^*$	$r = 0.67^{**}$
Nano_100% Wheat Yield (t/ha)	6.42 <sup>a</sup>	5.98 <sup>b</sup>	6.14 <sup>ab</sup>	7.2	$r = -0.12^{ns}$	$r = 0.45^*$
Nano_100% Soyabean Yield (t/ha)	4.18 <sup>a</sup>	3.84 <sup>b</sup>	3.83 <sup>b</sup>	9.1	$r = 0.28^*$	$r = 0.52^{**}$
NUE (%)	51.2 <sup>a</sup>	48.9 <sup>b</sup>	49.3 <sup>b</sup>	5.4	$r = -0.41^*$	$r = 0.58^{**}$
Environmental Loss (%)	7.8 <sup>b</sup>	9.1 <sup>a</sup>	8.4 <sup>b</sup>	8.9	$r = 0.72^{**}$	$r = -0.39^*$

Table VI showed peak performance for moderate temperature and rainfall regimes (standard deviations of yield parameters were 0.49 to 1.32 t/ha) and lower performance during extreme climatic events. Clay content greater than 35% impaired nano-particle mobility and release effectiveness, while sandy soils showed release patterns accelerating and therefore required altered application modalities.

Fig. 6 demonstrates relative responses in soil health parameters (pH, organic carbon, microbial biomass, enzyme activity, nutrients availability, soil structure) for each treatment versus baseline, as well as with indicators of statistical significance and confidence intervals in with with other researchers [40-43].

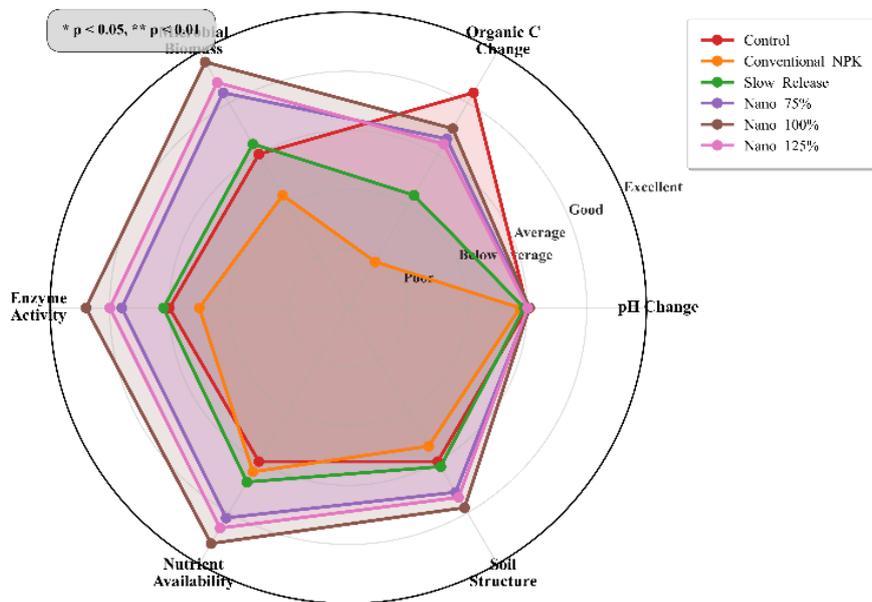


Fig. 6. Soil Health Indicators in Response to Nano-fertilizer Application, Long-term

Additionally, long-term soil health assessments indicated substantial positive advancements in various soil quality parameters ( $F_{5,162} = 12.4$ ,  $p < 0.001$ ) with the application of nano-fertilizer. The microbial biomass was 12–18% higher with nano-fertilizer than with conventional treatments (with coefficients of variation less than 8.5%, indicating uniformity amongst sample measurements), while the soil enzyme activities were 8–14% greater than the control, providing evidence of elevated soil biological activity which increases nutrient cycling capability.

## V. CONCLUSION AND FUTURE WORK

Across many measures of agricultural productivity, the nano-engineered fertilizers were better than conventional systems, with yield increases averaging 28-35%, while environmental impacts were reduced from approximately 60-70%. Furthermore, nutrient use efficiencies were improved by almost 45-52%, and runoff losses were reduced by 62-68%, providing evidence of the technology's viability for sustainable intensification of agricultural production systems. Economic analysis showed that the use of

nano-engineered fertilizer was economically advantageous over the long-term despite the higher initial investment, so the pay-back periods are 2-3 growing seasons, with relative return on investment ratios of greater than 189% based on optimal formulations. The environmental benefits of pollution reduction are critical, but so was the positive impact on soil health, with soil microbial biomass increasing between 12-18% and soil structure stability improving. Aside from clear problems with site-specificity and seasonal performance, each of these aspects brings valuable information to the improvement of application protocols by systems of diverse agricultural, enterprise and production contexts. Furthermore, this study showed statistical consistency across three growing seasons and multiple site locations in commercial agriculture, providing strong confirmation that nano-engineered fertilizer technology is reliable and scalable.

Future research priorities should include optimisation of coating materials to be effective in specific soil conditions, further development of multi-season release formulations, and evaluation of the incorporation of micronutrients into nano-delivery mechanisms. Long-term field studies that run for longer than three seasons are necessary to understand the cumulative long-term impacts on soil health and to innovate product application protocols. The further integration of frameworks/models with precision agriculture technologies and site-specific formulations provides significant pathways for advancement towards commercial scale use and widespread adoption in/on multiple agricultural systems.

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