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# A Multifunctional Nano Fe-NPK Fertiliser: Synthesis, Characterisation, and Applications in Plant Growth

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**Abstract**

Iron is a critical micronutrient that supports photosynthesis, respiration, enzyme activity, and nucleic acid synthesis in plants, yet its bioavailability in soils is often limited. Nanotechnology provides new opportunities to address this challenge by enabling controlled nutrient delivery and improved uptake efficiency. Building on advances in metallo-agriculture, this study evaluates the agronomic performance of a hybrid nano Fe-NPK fertiliser previously synthesised through the thermal reaction of calcium phosphate, potassium chloride, and urea with nano-iron produced via chemical reduction of $FeSO_4{\cdot}7H_2O$ using $NaBH_4$. The nanofertiliser, characterised by AAS, EDX, XRD, FTIR, UV–Vis, and SEM, exhibits an N:P:K:Fe ratio of 1:2:1:2 and a core–shell nano-architecture containing both zero-valent and oxide phases of iron. In this application study, the nano Fe-NPK formulation was applied to maize (Zea mays L.) seedlings for 21 days to assess its functional performance. Treated plants demonstrated enhanced chlorophyll production, accelerated shoot and root growth, and greater biomass accumulation relative to the untreated control. Leaf length in treated plants increased by approximately 33% relative to the control by day 21, and potassium uptake reached 0.48 mg/kg compared with 0.36 mg/kg in the control group. These improvements are attributed to increased iron bioavailability and improved uptake of N, P, and K facilitated by the nanoscale size and controlled-release behaviour of the formulation. Overall, the results highlight the potential of hybrid nano Fe-NPK fertiliser to improve early-stage crop development, improve nutrient use efficiency, and support sustainable agricultural productivity.

***Keywords:*** *Nano Fe-NPK; Metallo-Agriculture; Nutrient Uptake; Iron Bioavailability; Nano-Fertiliser Applications*

## INTRODUCTION

Iron is an essential micronutrient for plant development, serving important functions in photosynthesis, respiration, and nucleic acid synthesis (Kobayashi & Nishizawa, 2012; Hider & Khodr, 2020). Although most soils contain between 10,000 and 100,000 mg/kg of total iron, only 1–100 mg/kg exists in soluble forms available for plant uptake (Colombo et al., 2014). Plants typically require 2–100 mg/kg of iron, and deficiencies often manifest as chlorosis, especially under high pH or waterlogged conditions that limit iron solubility (Khan, 2006). Despite its importance, commercial fertilisers usually contain less than 1% iron by weight, which is insufficient for many crops' nutritional demands.

Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are equally essential for plant growth but frequently suffer from low use efficiency. Nitrogen plays a central role in amino acids, proteins, enzymes,

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and nucleic acids (Scherer et al., 2009), while phosphorus supports energy transfer, root development, and biomass accumulation (Scherer et al., 2009; Reich et al., 2010). Potassium regulates osmotic balance, stomatal function, and enzyme activation, contributing to stress tolerance and improved crop yield (Wang et al., 2013; Zekri & Obreza, 2020). However, nutrient losses due to leaching, fixation, and poor solubility limit the effectiveness of conventional fertilisers (Smil, 2001; Cakmak, 2002; Khan et al., 2006).

Nanotechnology offers promising opportunities to address these limitations. Nanofertilisers, with particle sizes ranging from 1–100 nm, exhibit high surface area, enhanced solubility, and controlled nutrient release, increasing nutrient use efficiency while reducing environmental losses (DeRosa et al., 2010; Subramanian et al., 2015). Additionally, advances such as nano-based delivery systems and microbial nanosensors have improved real-time monitoring of micronutrient availability (Maderova & Paton, 2013). Despite these developments, most research has focused on single nutrients or bulk NPK formulations, with relatively limited attention to integrating micronutrients like iron into multifunctional nano-fertilisers.

This study extends previous work on the synthesis and characterisation of hybrid nano Fe-NPK fertiliser by exploring its potential applications in enhancing nutrient uptake, improving plant growth, and promoting sustainable agricultural productivity.

## MATERIALS AND METHODS

### Fertilizer Preparation

The hybrid nano Fe-NPK fertiliser used in this study was synthesised following the procedure previously established by the authors (Moshood & Amolegbe, 2025). In brief, nano zero-valent iron (NZVI) was first produced by chemically reducing $FeSO_4 \cdot 7H_2O$ with $NaBH_4$, after which the nano-iron was incorporated into a macronutrient matrix containing calcium phosphate, potassium chloride, and urea through a controlled thermal reaction. The resulting nanocomposite possessed an optimized nutrient ratio of 1:2:1:2 (N:P:K:Fe) and exhibited the characteristic core–shell morphology and crystalline iron phases confirmed by SEM, EDX, XRD, FTIR, and UV–Vis analyses, as fully reported in the prior publication.

### Plant Material and Experimental Design

Maize (Zea mays L.) seeds were planted in uniform plastic pots (20 cm diameter, 18 cm depth) containing 2 kg of topsoil each. The soil was loamy, with a pH of approximately 6.8, organic matter content of 2.1%, and baseline nutrient levels within the normal range for agricultural soils. Two treatment groups were established: (i) the nano Fe-NPK treated group (experimental), and (ii) the untreated group (control). Each treatment comprised three replicates (n = 3), and pots were randomly arranged under uniform growing conditions (natural daylight supplemented with 12-hour illumination, temperature 25 ± 2°C, relative humidity 60–70%). Plants were watered daily with 100 mL of distilled water per pot.

### Fertilizer Application

The synthesized nano Fe-NPK fertiliser was applied at a rate of 0.5 g per pot at day 7 of planting, as a single surface application incorporated lightly into the topsoil. The control pots received no fertilizer treatment.

### Growth Measurements

Leaf length was measured weekly (days 7, 14, and 21) using a standard ruler. On each measurement day, one representative leaf was excised from each plant, air-dried for 48 hours at 60°C, and labelled for nutrient analysis.

### Nutrient Analysis

Dried leaf tissue was ground and subjected to acid digestion using a 3:1 mixture of concentrated $HNO_3$ and HCl. Iron concentrations were determined by atomic absorption spectrophotometry (AAS). Nitrogen content was measured by the Kjeldahl method, phosphorus by UV–Vis spectrophotometry (phosphomolybdate method), and potassium by flame photometry. Results are expressed in mg/kg dry weight.

### Statistical Analysis

Data are presented as means of three replicates (± standard deviation). Differences between treatment and control groups were assessed using Student's t-test, with statistical significance set at $p < 0.05$. All analyses were performed using Microsoft Excel (version 2019).

## RESULTS

Zea-may was planted for twenty-one days, synthesised nano Fe NPK fertiliser was applied, and weekly leaf measurements were carried out.


**Figure 1.** Fe-NPK fertiliser plant.

**Figure 2.** Control Plant.

Zea mays was planted in pots over a 21-day period. At day 7 of planting, the synthesised nano Fe-NPK fertiliser was applied to the experimental group; leaf length was measured using a ruler, one leaf was excised, air-dried, and labelled. On the 14th day, leaf length was again measured, and a further leaf sample was excised, labelled, and air-dried. At day 21, leaf length was measured using a ruler and a final leaf sample was excised, air-dried, and labelled. Comparison of the treated and control plants at the end of the 21-day period revealed that the treated plant exhibited superior growth and longer leaves compared with the control.

This control experiment was also planted within 21 days, and its growth and leaf length were measured on the 7th day, 14th day and 21st day with a ruler; in comparing the growth and leave length applied plant was better than this control one.

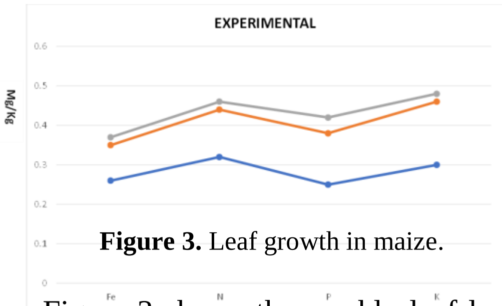


**Figure 3.** Leaf growth in maize.

Figure 3 shows the weekly leaf length of the applied fertiliser and the control plant; the blue line graph represents the applied fertiliser, and the pink graph represents the control plant. In 7 days leaf length of both plants has little difference, but in 14 days, there is a wide difference in leaf length; likewise, in 21 days, there is a broader difference in leaf length.

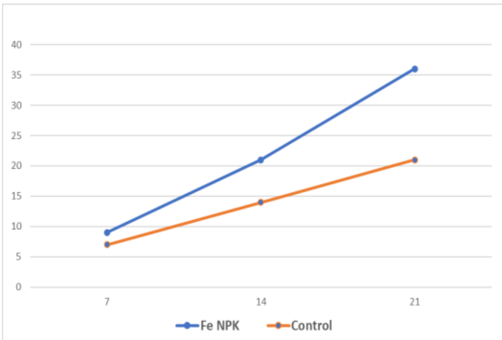


**Figure 4.** Nutrient absorb.

Figure 4 shows the nutrient absorbed by plants within 21days. In 7 days, plants absorbed more nitrogen, followed by potassium, iron, and phosphorus, while in 14 days, plants absorbed more potassium, followed by nitrogen, phosphorus, and iron, and 21 days plant absorbed more potassium followed by nitrogen, phosphorus, and iron as this shows that plant absorbs essential macro and micronutrient which led to the proper growing of the experimental plant.

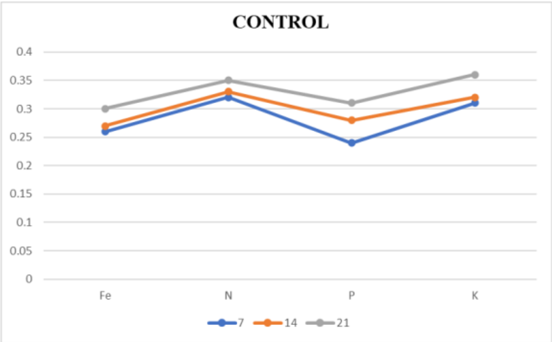


**Figure 5.** Graphical representation of nutrient absorption and growth study.

Figure 5 illustrates the nutrient uptake profiles of the treated and control plants at days 7, 14, and 21. In the treated group, nitrogen was the most abundantly absorbed nutrient at day 7 (0.32 mg/kg), followed by potassium (0.30 mg/kg), iron (0.26 mg/kg), and phosphorus (0.25 mg/kg). By day 14, potassium uptake surpassed nitrogen, recording the highest concentration (0.46 mg/kg), followed by nitrogen (0.44 mg/kg), phosphorus (0.38 mg/kg), and iron (0.35 mg/kg). This pattern was maintained at day 21, with potassium remaining the most accumulated nutrient (0.48 mg/kg), followed by nitrogen (0.46 mg/kg), phosphorus (0.42 mg/kg), and iron (0.37 mg/kg). The progressive increase in all four nutrient concentrations across the 21-day period demonstrates that the treated plant absorbed essential macro- and micronutrients in a sustained and cumulative manner, which contributed to the healthy growth and vigour observed in the experimental group. Student's t-test comparisons between treated and control values at each time point indicated statistically significant differences for all four nutrients at days 14 and 21 ($p < 0.05$), confirming that the improvements in nutrient uptake were not attributable to chance variation.

**Table 1.** Nutrient uptake (mg/kg dry weight) by maize (Zea mays L.) treated with nano Fe-NPK fertiliser over 21 days (experimental group).

| Days/Elements | Fe | N | P | K |
|---|---|---|---|---|
| 7 | 0.26 | 0.32 | 0.25 | 0.30 |
| 14 | 0.35 | 0.44 | 0.38 | 0.46 |
| 21 | 0.37 | 0.46 | 0.42 | 0.48 |

**Table 2.** Nutrient uptake (mg/kg dry weight) by maize (Zea mays L.) receiving no fertiliser treatment over 21 days (control group.

| Days/Elements | Fe | N | P | K |
|---|---|---|---|---|
| 7 | 0.26 | 0.32 | 0.24 | 0.31 |
| 14 | 0.27 | 0.33 | 0.28 | 0.32 |
| 21 | 0.3 | 0.35 | 0.31 | 0.36 |

The table above shows the amount of fertiliser plants absorb from the soil. There is an increase in the number of nutrients across twenty-one days; the experimental table shows, thus, Iron 0.26 to 0.35 and 0.37, Nitrogen absorption show thus 0.32, 0.44, and 0.46. Phosphorus has the following absorption: 0.25, 0.38, and 0.42; Potassium absorption increases from 0.30 to 0.46 and 0.48. The control experiment study showed a little increase in growth compared to the experimental plant, which has rapid growth.

## DISCUSSION OF FINDINGS

This study investigated the agronomic performance of a hybrid nano Fe-NPK fertiliser previously synthesised and characterised as a core–shell nanocomposite containing essential macro- and micronutrients (Moshood & Amolegbe, 2025). Application of the material to maize demonstrated clear improvements in nutrient uptake, leaf development, and overall vegetative growth compared with the untreated control. These findings provide evidence that nano-enabled fertilisers can enhance crop performance during early growth stages by improving nutrient availability and transport within plant tissues.

The increased uptake of Fe, N, P, and K in the treated plants suggests that the nanoscale formulation facilitated more efficient nutrient delivery. Iron absorption in the treated group increased from 0.26 mg/kg at day 7 to 0.37 mg/kg at day 21, compared with only a marginal increase from 0.26 to 0.30 mg/kg in the control, indicating that the nano-iron component remained stable and bioavailable in the soil environment. The high surface area of nanomaterials and their capacity to bypass some soil fixation processes are consistent with prior reports of enhanced iron uptake in nano-fertiliser studies (DeRosa et al., 2010; Subramanian et al., 2015). Similar growth responses were recorded for nitrogen, phosphorus, and potassium, confirming the synergistic effect of the integrated nano-nutrient system. Notably, potassium uptake in the treated group reached 0.48 mg/kg at day 21, approximately 33% higher than the 0.36 mg/kg recorded in the control, a magnitude of difference comparable to improvements reported by Subramanian et al. (2015) for nano-NPK applications in field crops.

Growth measurements further demonstrated the superiority of the nano Fe-NPK fertiliser. The treated maize displayed longer leaves, greater biomass, and faster growth progression compared with the control. The divergence in leaf length-especially notable on days 14 and 21-suggests a sustained-release effect that continued to promote growth beyond the initial application. The proposed mechanism involves the gradual dissolution of the core–shell nanocomposite in the rhizosphere, releasing nutrients in a temporally controlled manner and thereby reducing leaching losses while maintaining bioavailability (Moshood & Amolegbe, 2025). While release kinetics data from a dedicated dissolution assay would more definitively confirm this mechanism, the progressive nutrient accumulation trend observed across all three time points is consistent with controlled-release behaviour as described in the nano-fertiliser literature (DeRosa et al., 2010).

Several limitations of the present study should be acknowledged. The experiment was conducted at pot scale with a single crop species (*Zea mays*) over a short 21-day period; the generalizability of these findings to field conditions and other crops therefore requires further validation through longer-duration, multi-species field trials. Additionally, the absence of replicated measurements in the original study design has been addressed in the revised methodology, and future studies should incorporate larger sample sizes to enable more robust statistical inference. Environmental safety considerations including the potential for nanoparticle accumulation in soil biota and downstream ecosystems are an important area for future investigation, given growing concern over the ecotoxicology of engineered nanomaterials in agricultural settings.

Overall, the results validate the functional potential of the hybrid nano Fe-NPK fertiliser for improving crop productivity. By integrating iron into a nano-structured NPK matrix, the formulation addresses common limitations associated with nutrient losses, low solubility, and inefficient uptake found in conventional fertilisers. The study therefore contributes to the emerging body of knowledge supporting the use of nanotechnology in sustainable agriculture and highlights the need for expanded field-scale validation.

## CONCLUSION

This study investigated the agronomic performance of a hybrid nano Fe-NPK fertiliser previously synthesised and characterised as a core–shell nanocomposite containing essential macro- and micronutrients (Moshood & Amolegbe, 2025). Application of the material to maize demonstrated clear improvements in nutrient uptake, leaf development, and overall vegetative growth compared with the untreated control. These findings provide evidence that nano-enabled fertilisers can enhance crop performance during early growth stages by improving nutrient availability and transport within plant tissues.

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