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Evaluating the Effect of Fe-Oxide Nanoparticles on Maize Yield, Bio-fortification and Fe Use Efficiency

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ABSTRACT

Micronutrient deficiencies, particularly iron (Fe) deficiency, affect over 2 billion people globally, with staple cereal crops such as maize (Zea mays L.) contributing significantly to dietary Fe intake in developing countries. Agronomic bio-fortification through nanotechnology offers a promising strategy to enhance grain Fe concentration while improving crop productivity. A field experiment was conducted during the 2024 cropping season at the Research Farm of The University of Agriculture, Peshawar, Pakistan, to evaluate the effect of Fe_3O_4 nanoparticles (NPs) seed priming on maize yield, bio-fortification, and Fe use efficiency. The experiment was laid out in a randomized complete block design (RCBD) with three replications. Treatments comprised seed priming with Fe_3O_4-NPs at 0 (control), 1, 2, 4, and 6 mg L^{-1}, with a basal application of 120 kg N ha^{-1} as urea. Maize variety "Azam" was sown at 20 cm plant-to-plant and 70 cm row-to-row spacing in 3 × 3 m plots. Results revealed that seed priming with 4 mg L^{-1} Fe_3O_4-NPs significantly ($p \leq 0.05$) enhanced plant height (157.7 cm), cob weight (212.0 g), thousand grain weight (227.7 g), grain yield (3260 kg ha^{-1}), and biological yield (10023.7 kg ha^{-1}) compared with the control. The same

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treatment recorded the highest N (0.84% straw; 1.81% grain), P (0.36% straw; 0.55% grain), K (0.66% straw; 1.12% grain), and Fe (90 mg kg^{-1} straw; 60 mg kg^{-1} grain) concentrations. Iron uptake (9.0 kg ha^{-1}) and Fe use efficiency (7.2%) were also maximized at 4 mg L^{-1} Fe_3O_4-NPs. Concentrations above 4 mg L^{-1} (6 mg L^{-1}) resulted in a slight decline in most parameters, indicating a hormetic dose-response. These findings demonstrate that seed priming with 4 mg L^{-1} Fe_3O_4-NPs is an effective, sustainable strategy for enhancing maize productivity, grain nutrient density, and iron bio-fortification under field conditions.

Keywords: Fe_3O_4 Nanoparticles, Seed Priming, Maize (Zea mays L.), Bio-Fortification, Iron Use Efficiency, Grain Yield, Nutrient Uptake, Nanofertilizer

Introduction

Micronutrient deficiencies, commonly referred to as "hidden hunger," remain a major public health concern in developing countries, particularly in Sub-Saharan Africa and South-East Asia. Deficiencies in vitamins (especially vitamin A and B9) and minerals (Fe and Zn) have been linked to underdevelopment, mental retardation, reproductive disorders, and even mortality (Bailey et al., 2015; de Benoist et al., 2008). Iron deficiency is the most prevalent micronutrient disorder, affecting approximately 24.8% of the world population equivalent to 1.6 billion cases globally (McLean et al., 2009). The daily dietary requirement of Fe ranges between 8–18 mg, increasing to 27 mg during pregnancy.

Iron is the fourth most abundant element in the Earth's crust, accounting for approximately 5% of its composition (Adriano, 2001). In soil, Fe exists primarily as aluminum silicate iron minerals and can be converted to nano Fe oxides through weathering. Iron oxides have historical significance beyond their role as primary ore for the iron and steel industry; nano-magnetite (Fe_3O_4) served as a catalyst in the Haber-Bosch process, which revolutionized nitrogen fertilizer production in the last century (Erisman et al., 2008). Plant uptake of Fe is governed by valence changes and soil pH. Acidic conditions (pH < 5.0) and low redox potential (Eh < 0.4 V) enhance ferrous ion (Fe^{2+}) concentration, while neutral to alkaline pH and high Eh (> 0.6 V) favor ferric hydroxides.

Agriculture faces increasing challenges in sustaining crop productivity under conditions of nutrient depletion, soil degradation, and climate variability. To address these issues, innovative approaches are being explored, among which nanotechnology has emerged as a promising frontier. Recent advances in nanoscience have opened new avenues in agriculture, particularly through the development of nanopesticides and nanofertilizers that offer enhanced efficiency, targeted delivery, and reduced environmental impact (Rizwan et al., 2017; Munir et al., 2018).

Among various nanomaterials, iron nanoparticles (Fe-NPs) have attracted considerable attention due to their unique physicochemical properties, including high surface area, catalytic reactivity, and the ability to function as slow-release nutrient sources. These attributes make Fe-NPs particularly suitable for improving nutrient uptake and utilization efficiency in crops. Previous studies have demonstrated their potential to positively influence plant growth, physiology, and biochemical processes. For example, Elanchezhian et al. (2017) reported that Fe-NPs enhanced plant

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morphology and physiological traits compared with conventional Fe salts. Similarly, Iannone et al. (2016) showed that citric-acid-coated Fe_3O_4-NPs (up to 20 ppm) improved enzymatic activity in wheat under hydroponic conditions without adverse effects on growth. Liu et al. (2016) further observed that Fe-NPs (1–20 ppm) promoted seed germination and root elongation in lettuce, highlighting their beneficial role in early plant development.

Despite these encouraging findings, the application of Fe-NPs in field crops remains underexplored, particularly in staple cereals such as maize. Maize (Zea mays L.) is a globally important crop, serving as a source of food, feed, and industrial raw material. Enhancing its nutrient uptake efficiency is critical for sustainable production. Seed priming with nanoparticles represents a novel strategy to improve germination, vigor, and nutrient assimilation; yet systematic evaluations of Fe_3O_4-NPs priming effects on maize growth and yield are limited.

Agronomic bio-fortification through soil application, foliar spray, seed priming, or seedling immersion offers a cost-effective approach to enhance micronutrient density in staple crops (Dimkpa and Bindraban, 2016). This technique has been successfully used to fortify rice, wheat, maize, barley, and sorghum with Zn and Fe (Ramzani et al., 2016). Seed priming, in particular, is a low-cost, farmer-friendly technology that enables controlled nutrient delivery during germination, promoting uniform seedling establishment and early vigor. Despite the potential of Fe_3O_4-NPs, limited field-based evidence exists on their optimal concentration for maize production and grain Fe bio-fortification under alkaline calcareous soil conditions. Therefore, This study evaluated the effects of Fe_3O_4-NPs seed priming on maize growth and yield, as well as on tissue concentrations of N, P, K, and Fe, and overall Fe uptake and use efficiency.

Materials and Methods

Experimental Site and Soil Characteristics

The field experiment was conducted during the 2024 cropping season at the Research Farm of The University of Agriculture, Peshawar, Pakistan (**Figure 1**). The experimental soil was silt loam in texture with the following physicochemical properties: sand 14.35%, silt 72.03%, clay 13.62%, and pH 7.73 (1:5), EC 0.24 dS m^{-1} (1:5), organic matter 0.66%, and AB-DTPA extractable Fe 1.9 mg kg^{-1} (Table 1). The soil was slightly alkaline, non-saline, and low in organic matter and available Fe.

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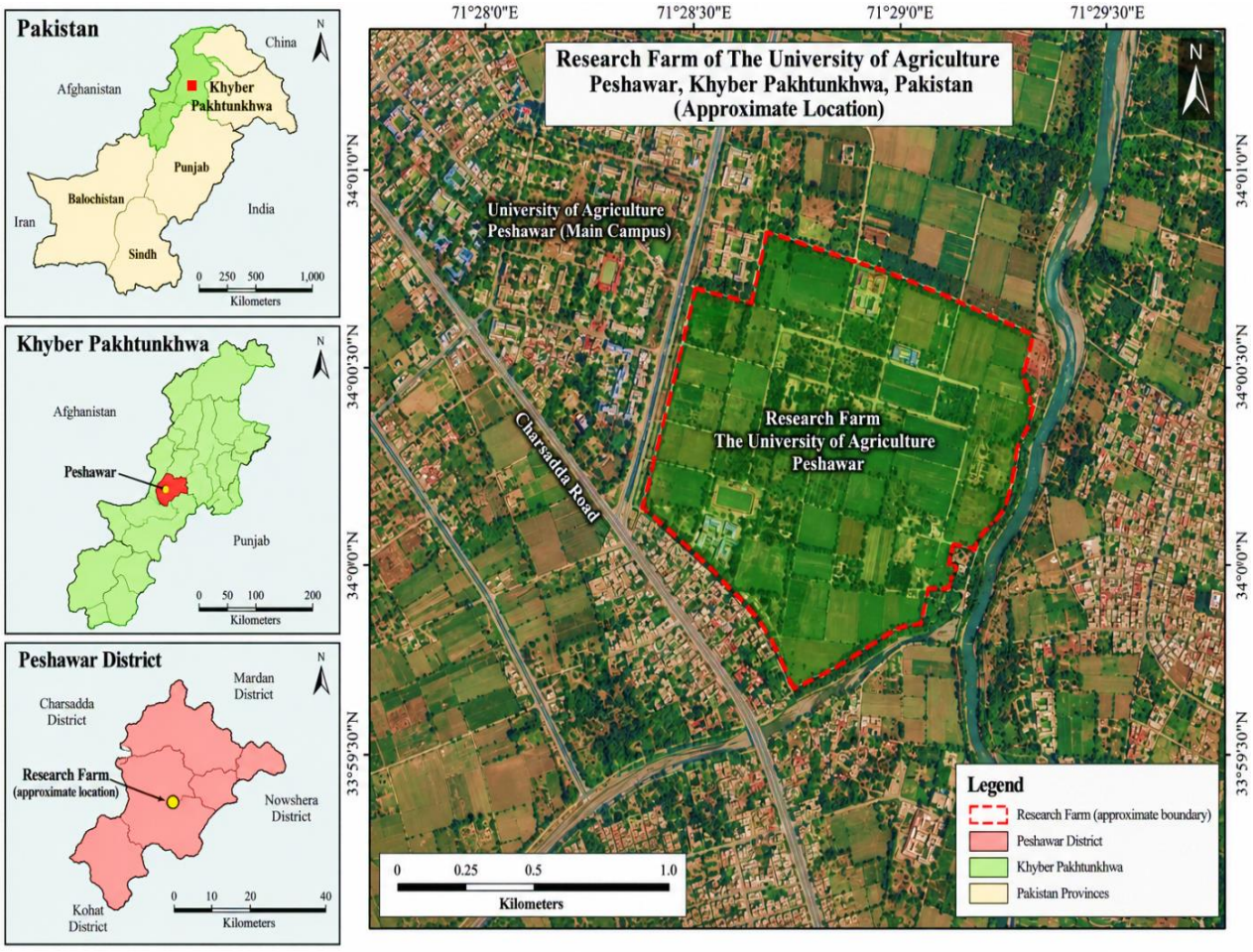


Figure 1: Geographical location of the experimental site at the Research Farm of The University of Agriculture, Peshawar, Pakistan.

Table 1. Physicochemical properties of the experimental soil

Soil Property	Unit	Value
Sand	%	14.35
Silt	%	72.03
Clay	%	13.62
Soil Texture	—	Silt Loam
pH (1:5)	—	7.73
EC (1:5)	dS m^{-1}	0.24
Organic Matter	%	0.66
AB-DTPA extractable Fe	mg kg^{-1}	1.9

Experimental Design and Treatments

The experiment was laid out in a randomized complete block design (RCBD) with three replications. The net plot size was 3 × 3 m (9 m^2). Treatments comprised seed priming with Fe_3O_4-NPs at five concentrations: 0 (control, no priming), 1, 2, 4, and 6 mg L^{-1}. A basal dose of 120 kg N ha^{-1} (as urea), 90 kg P ha^{-1} (as single super

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phosphate), and 60 kg K ha^{-1} (as potassium sulfate) was applied uniformly to all plots.

Fe_3O_4 Nanoparticles and Seed Priming

Fe_3O_4 nanoparticles (average particle size < 50 nm, purity > 98%) were obtained from [commercial supplier]. Seed priming was performed by soaking maize seeds in aqueous suspensions of Fe_3O_4-NPs at the respective concentrations for 16 hours at room temperature. Following soaking, seeds were air-dried back to their original moisture content under shade before sowing (Azmat et al., 2020).

Crop Husbandry

Maize variety "Azam" was collected from the research farm. Seeds were surface-sterilized with 95% ethanol for 2 minutes and 5% sodium hypochlorite for 1 minute, followed by thorough rinsing with distilled water. Seeds were drilled sown at a depth of 1.5 inches in rows spaced 70 cm apart, with plant-to-plant spacing of 20 cm maintained through thinning. All standard agronomic practices—including irrigation, weeding, and pest management were followed uniformly across all plots.

Soil Analysis

Soil samples were collected from 0–20 cm depth before sowing. Soil pH and EC were determined in 1:5 soil-water suspensions using a calibrated pH meter and conductivity meter, respectively (McLean, 1982; Richard, 1954). Soil texture was determined using the Bouyoucos hydrometer method (Saxton et al., 1986). Organic matter was estimated by the dichromate oxidation method (Nelson and Sommer, 1982). AB-DTPA extractable Fe was determined according to Soltanpour and Schwab (1977) and analyzed using atomic absorption spectrophotometry.

Agronomic and Yield Parameters

Plant height (cm): Measured at physiological maturity from the base to the tip of the tassel for five randomly selected plants per plot. Cob weight (g): Five randomly selected cobs per plot were weighed using an electronic balance, and the average was recorded. Thousand grain weight (g): One thousand grains were randomly counted from each plot and weighed. Grain yield (kg ha^{-1}): Grains were separated from cobs, weighed, and converted to kg ha^{-1} using the formula: Grain yield (kg ha^{-1}) = Weight of harvested grain (kg) / Area of field (ha). Biological yield (kg ha^{-1}): Two plants per plot were harvested at maturity, sun-dried, and weighed using a spring balance.

Plant Nutrient Analysis

Plant samples (straw and grains) were washed with distilled water, air-dried, and ground. Samples (0.5 g) were digested using the wet acid digestion method (Ryan, 2000) with HNO_3 and $HClO_4$. Concentrations of N, P, K, and Fe were determined using standard analytical procedures. Fe concentration was measured by atomic absorption spectrophotometry. Fe uptake (kg ha^{-1}) was calculated as: Fe uptake = (Fe concentration × dry matter yield) / 1000. Fe use efficiency (FeUE, %) was calculated according to Longnecker et al. (1986): FeUE = [(Total uptake − Control uptake) × 100] / Applied fertilizer.

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Statistical Analysis

Data recorded for all agronomic and yield parameters (plant height, cob weight, thousand grain weight, grain yield, and biological yield) as well as plant nutrient analysis (N, P, K, and Fe concentrations, Fe uptake, and Fe use efficiency) were subjected to analysis of variance (ANOVA) using Statistix 8.1 software. Before analysis, data were checked for normality and homogeneity of variance to ensure that the assumptions of ANOVA were met. The ANOVA was performed to determine the significance of differences among treatments for each parameter. Treatment means were compared using the least significant difference (LSD) test at 5% probability level (Steel et al., 1997). Differences among treatment means were considered statistically significant at $p \leq 0.05$. Results were presented as means, and where appropriate, standard errors of the means were calculated and reported alongside the treatment means to indicate the variability within treatments

Results

Analysis of Agronomic Parameters.

Seed priming with Fe_3O_4-NPs significantly ($p \leq 0.05$) influenced maize plant height (**Figure 2**). The tallest plants (157.7 cm) were recorded at 4 mg L^{-1} Fe_3O_4-NPs, representing a 26.1% increase over the control (125.0 cm). The 6 mg L^{-1} treatment produced plants of 155.3 cm, statistically at par with 4 mg L^{-1} (LSD = 3.20). Plant height increased progressively from 1 mg L^{-1} (132.0 cm) to 4 mg L^{-1} before a marginal decline at the highest concentration. Cob weight was significantly affected by Fe_3O_4-NPs priming (Table 2). The highest cob weight (212.0 g) was recorded at 4 mg L^{-1}, which was significantly superior to all other treatments (LSD = 1.79). The control recorded the lowest cob weight (112.3 g), representing an 88.8% improvement at the optimal concentration. The 6 mg L^{-1} treatment produced cobs of 201.0 g, significantly lower than 4 mg L^{-1} but higher than the 2 mg L^{-1} treatment. Thousand grain weight (TGW) showed a highly significant response to Fe_3O_4-NPs priming (Table 2). The maximum TGW (227.7 g) was obtained at 4 mg L^{-1}, compared with 174.0 g in the control a 30.9% increase. All treatment means were statistically distinct (LSD = 0.52), with TGW values of 186.0, 198.0, 227.7, and 220.7 g recorded for 1, 2, 4, and 6 mg L^{-1}, respectively.

Grain yield was significantly influenced by Fe_3O_4-NPs priming (**Figure 2**). The maximum grain yield (3260 kg ha^{-1}) was recorded at 4 mg L^{-1}, significantly higher than all other treatments (LSD = 1.05). The control recorded the minimum grain yield (2917 kg ha^{-1}), representing an 11.8% yield reduction. Grain yield increased progressively up to 4 mg L^{-1} and declined at 6 mg L^{-1} (3146.3 kg ha^{-1}) but remained higher than the control. Biological yield was significantly affected by Fe_3O_4-NPs priming (Table 2). The highest biological yield (10023.7 kg ha^{-1}) was recorded at 4 mg L^{-1}, significantly superior to all other treatments (LSD = 2.15). The control recorded the lowest biological yield (8100.3 kg ha^{-1}), representing a 23.7% increase at the optimal concentration. The treatment ranking for biological yield followed the order: Control < 1 < 2 < 6 < 4 mg L^{-1}.

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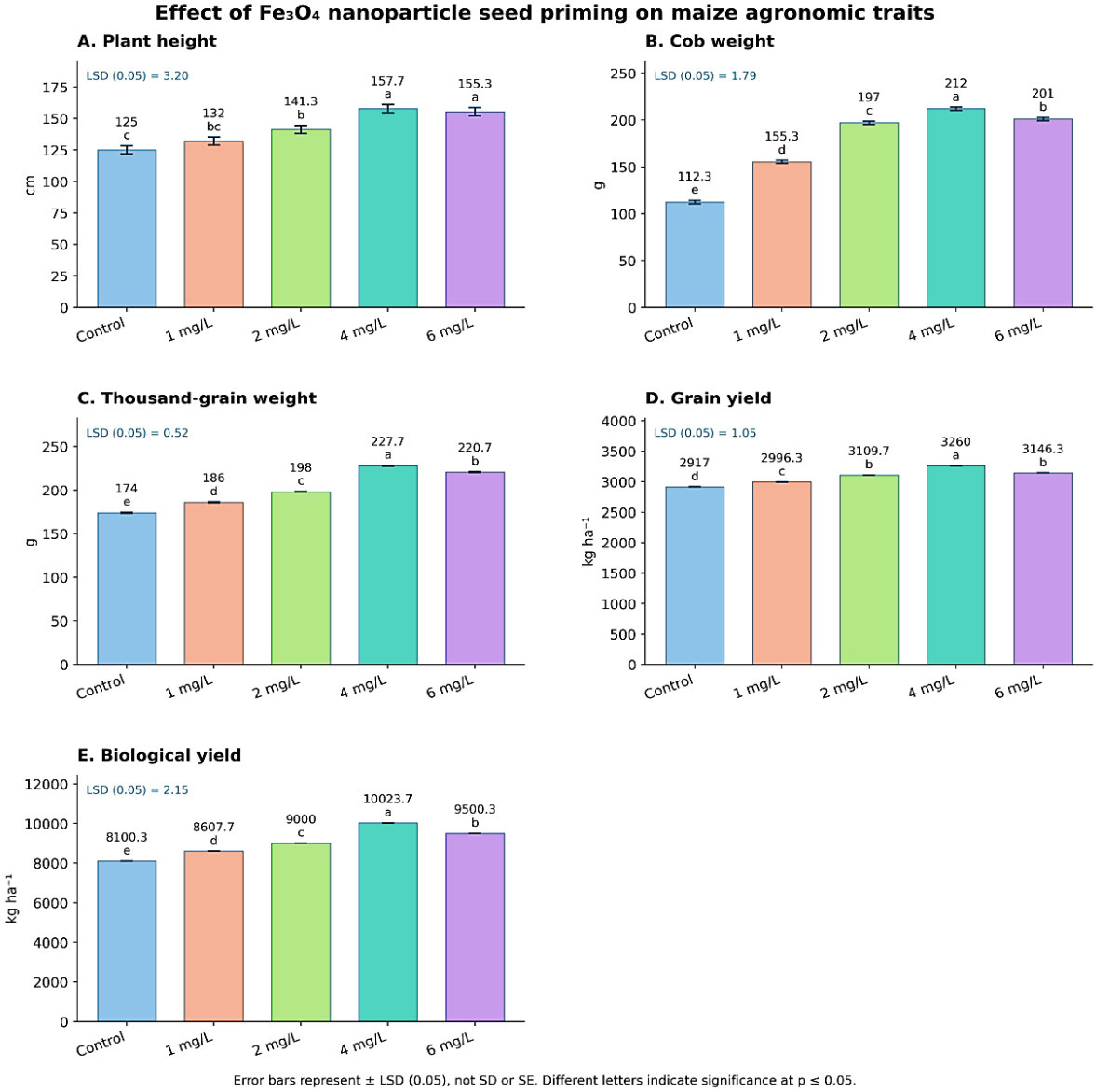


Figure 2: Effects of Fe_3O_4 nanoparticle seed priming on (A) plant height, (B) cob weight, (C) thousand-grain weight, (D) grain yield, and (E) biological yield of maize. Different letters indicate significant differences among treatments at $p \leq 0.05$.

Plant Nutrient Analysis

Nitrogen and Phosphorus Content

Nitrogen concentration in maize straw and grains was significantly ($p \leq 0.05$) enhanced by Fe_3O_4-NPs priming (**Figure 3**). The highest straw N (0.84%) and grain N (1.81%) was recorded at 4 mg L^{-1}, representing increases of 86.7% and 64.5% over the control, respectively. The 6 mg L^{-1} treatment was statistically at par with 4 mg L^{-1} for both parameters. A clear dose-dependent trend was observed, with values increasing progressively up to 4 mg L^{-1} before a non-significant decline at 6 mg L^{-1}.

Phosphorus concentration in straw and grains was significantly influenced by Fe_3O_4-NPs priming (**Figure 3**). The highest straw P (0.36%) and grain P (0.55%) was

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recorded at 4 mg L^{-1}, representing increases of 100% and 120% over the control, respectively. The 6 mg L^{-1} treatment produced straw P of 0.33% and grain P of 0.50%, significantly lower than 4 mg L^{-1} for grain P.

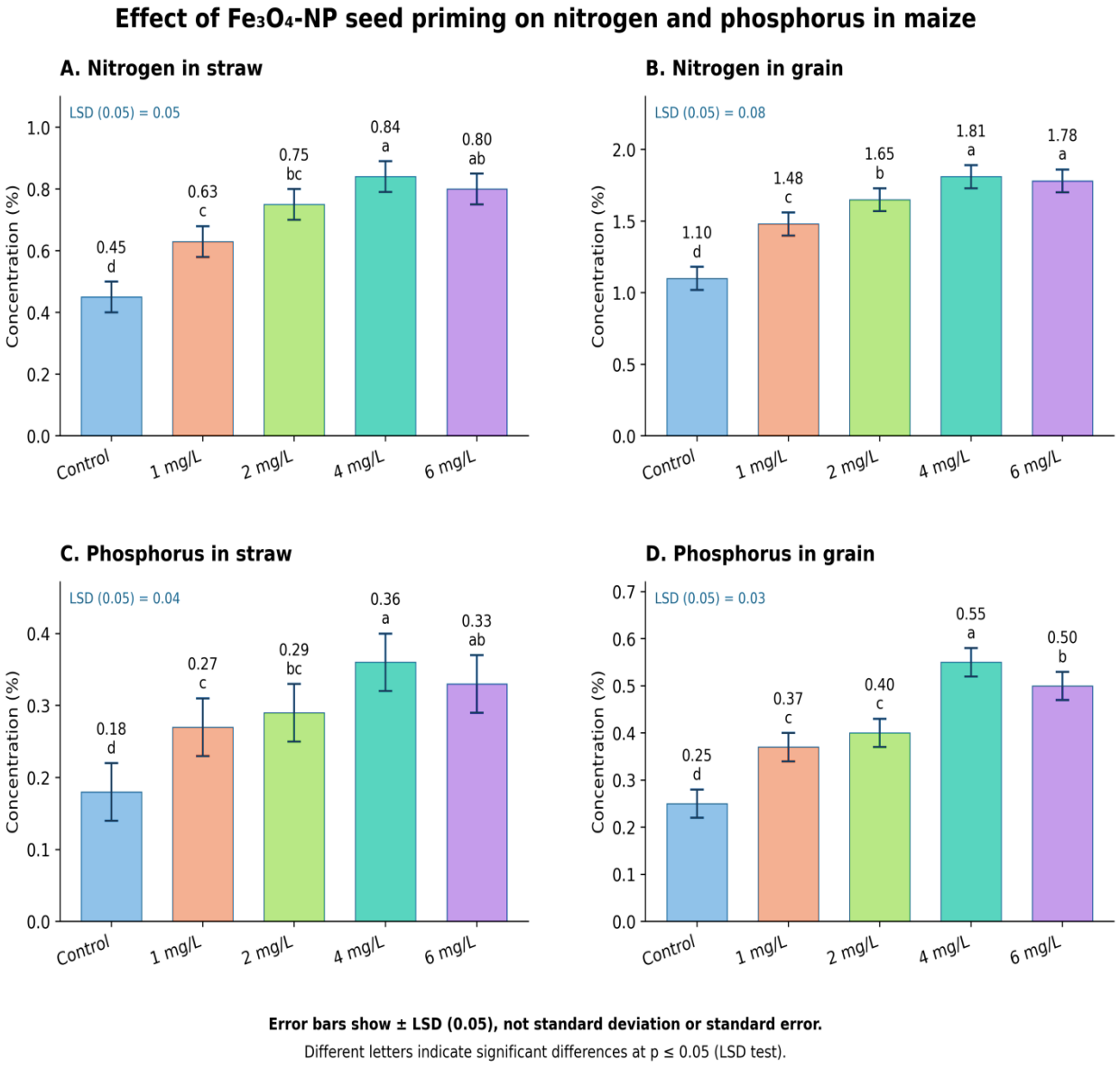


Figure 3. Effect of Fe_3O_4 nanoparticle seed priming on (A) nitrogen concentration in maize straw, (B) nitrogen concentration in maize grain, (C) phosphorus concentration in maize straw, and (D) phosphorus concentration in maize grain. Bars represent treatment means, and error bars indicate ± LSD (0.05). Different letters above the bars indicate significant differences among treatments at $p \leq 0.05$ according to the LSD test.

Potassium and Iron Content

Potassium concentration in straw and grains was significantly ($p \leq 0.05$) affected by

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Fe_3O_4-NPs priming (Figure 4). The highest straw K (0.66%) and grain K (1.12%) was recorded at 4 mg L^{-1}, representing increases of 57.1% and 45.5% over the control, respectively. The 6 mg L^{-1} treatment recorded straw K of 0.60% and grain K of 1.08%, with grain K statistically at par with 4 mg L^{-1}. Iron concentration in straw and grains showed highly significant responses to Fe_3O_4-NPs priming (Figure 4). The highest straw Fe (90 mg kg^{-1}) and grain Fe (60 mg kg^{-1}) were recorded at 4 mg L^{-1}, representing 18-fold and 15-fold increases over the control, respectively. The 6 mg L^{-1} treatment recorded straw Fe of 80 mg kg^{-1} and grain Fe of 46 mg kg^{-1}, both significantly lower than 4 mg L^{-1}. Notably, grain Fe responded significantly even at 2 mg L^{-1} (16 mg kg^{-1}), indicating preferential partitioning of Fe to reproductive sinks at lower concentrations.

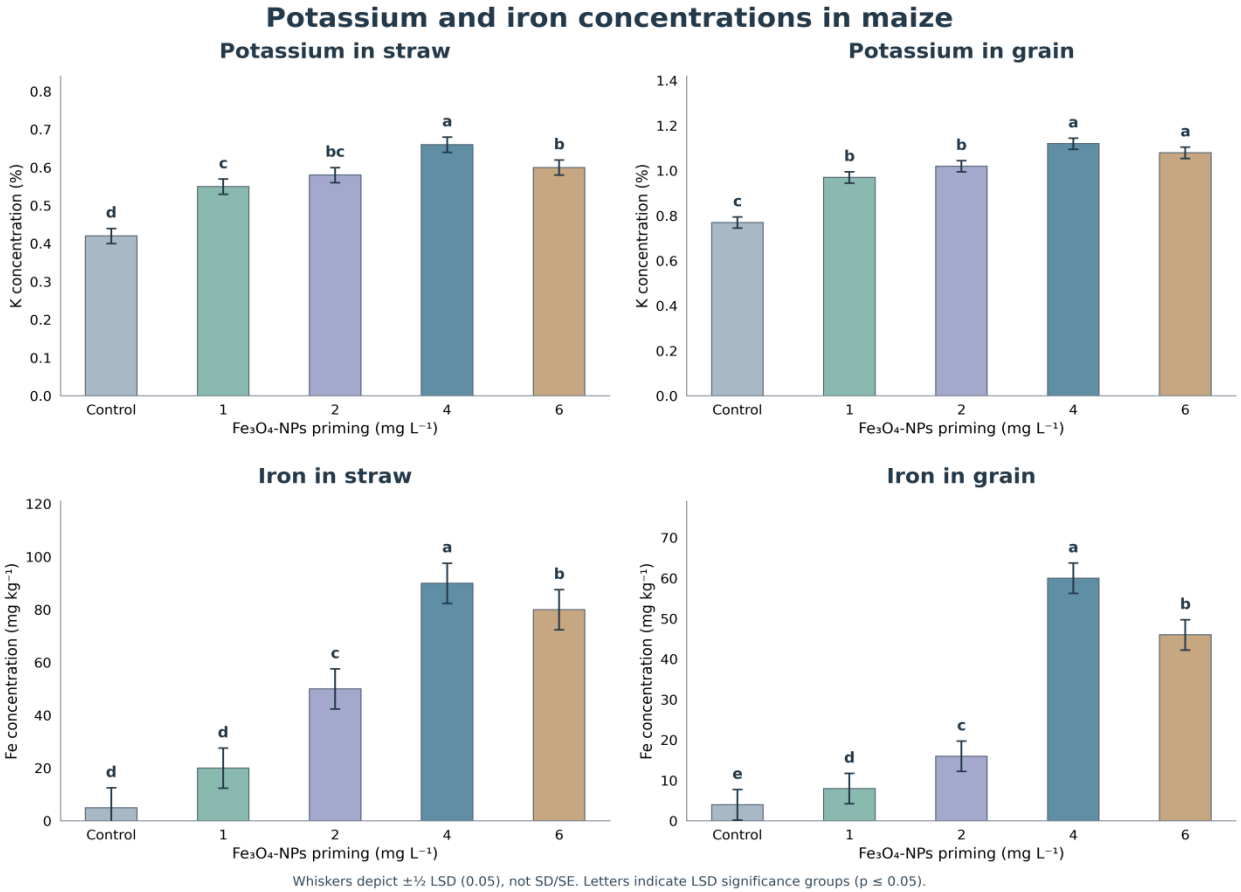


Figure 4: Effects of Fe_3O_4 nanoparticles (Fe_3O_4-NPs) seed priming at different concentrations (0, 1, 2, 4, and 6 mg L^{-1}) on potassium (K) and iron (Fe) concentrations in maize straw and grains. (A) K concentration in straw (%), (B) K concentration in grains (%), (C) Fe concentration in straw (mg kg^{-1}), and (D) Fe concentration in grains (mg kg^{-1}). Different lowercase letters above the bars indicate statistically significant differences among treatments at $p \leq 0.05$ (LSD test). Error indicators represent ±½ LSD (0.05) and should not be interpreted as standard

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deviation or standard error.

Fe Uptake and Fe Use Efficiency

Fe uptake increased progressively with increasing Fe_3O_4-NPs concentrations up to 4 mg L^{-1}, reaching a maximum of 9.0 kg ha^{-1} compared with 0.41 kg ha^{-1} in the control (**Figure 5**). The 6 mg L^{-1} treatment recorded a slight decline in Fe uptake (7.6 kg ha^{-1}) but remained higher than the control and lower concentrations. Fe use efficiency followed a similar trend, with the highest value (7.2%) recorded at 4 mg L^{-1} (**Figure 5**). The 1 and 2 mg L^{-1} treatments recorded FeUE values of 4.4% and 6.8%, respectively, while the 6 mg L^{-1} treatment declined to 4.0%.

The close correspondence between Fe uptake and Fe use efficiency indicates that the enhanced Fe accumulation in plant tissues translated efficiently into biomass and grain production, particularly at the optimal concentration of 4 mg L^{-1}(**Figure 5**). The sharp increase in Fe uptake from 0.41 kg ha^{-1} in the control to 9.0 kg ha^{-1} at 4 mg L^{-1} represents a substantial improvement in Fe acquisition, which can be attributed to the enhanced availability and mobility of Fe supplied through Fe_3O_4-NPs priming. The subsequent decline in both Fe uptake and FeUE at 6 mg L^{-1} suggests a threshold beyond which additional Fe supply does not confer further benefits and may even induce mild toxicity or antagonistic effects on nutrient balance. These findings demonstrate that 4 mg L^{-1} Fe_3O_4-NPs was the most effective concentration for maximizing both Fe accumulation and its efficient utilization in maize.

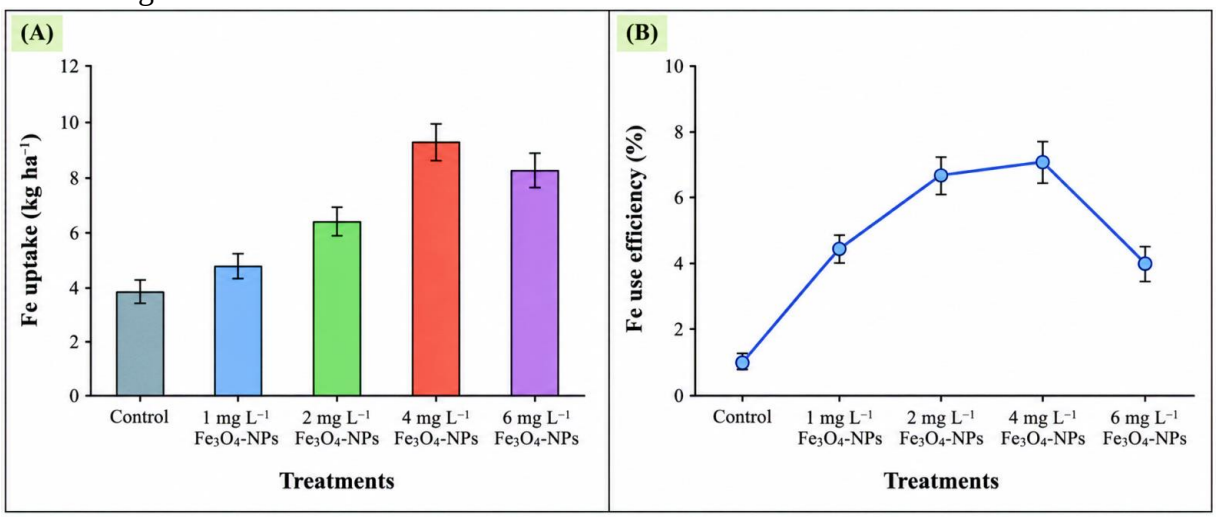


Figure 5: Effects of Fe_3O_4 nanoparticles (Fe_3O_4-NPs) seed priming at different concentrations (0, 1, 2, 4, and 6 mg L^{-1}) on (**A**) iron (Fe) uptake (kg ha^{-1}) and (**B**) Fe use efficiency (%) in maize. Both parameters showed maximum values at 4 mg L^{-1} Fe_3O_4-NPs, followed by a decline at 6 mg L^{-1}.

Discussion

Growth and Yield Enhancement

The significant improvement in maize growth and yield parameters at 4 mg L^{-1} Fe_3O_4-NPs can be attributed to the multifaceted role of Fe in plant physiology. Iron is essential for chlorophyll biosynthesis, electron transport in photosystems I and II, and enzymatic processes governing cell division and elongation (Marschner, 2012).

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Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Nanoparticulate Fe_3O_4 serves as a slow-release, bioavailable source of Fe^{2+}/Fe^{3+} ions that are efficiently taken up by the seed embryo during priming, promoting germination vigor and seedling establishment (Rui et al., 2016). Enhanced activities of α-amylase and protease during germination may further contribute to improved plant height at optimal concentrations by liberating stored starch and protein for meristematic activity.

The increase in cob weight and thousand grain weight at 4 mg L^{-1} reflects improved photosynthetic efficiency and assimilate allocation to reproductive organs. Iron is a key cofactor in the photosynthetic electron transport chain, and its adequate supply as nanoparticles enables optimal photosynthetic capacity during grain filling (Briat et al., 2015). Additionally, Fe-NPs have been shown to stimulate genes involved in sucrose transport and starch biosynthesis in cereal grains, resulting in higher cob fill and grain weight (Delfani et al., 2014). The significant increase in TGW suggests enhanced activity of ADP-glucose pyrophosphorylase and starch synthase—enzymes critical for starch accumulation in the endosperm (Hannah, 2007).

The slight decline in growth and yield parameters at 6 mg L^{-1} indicates a hormetic dose-response, where low to moderate concentrations stimulate growth while higher concentrations induce phytotoxicity. Excess Fe accumulation can trigger reactive oxygen species (ROS) generation through Fenton reactions, causing oxidative stress and membrane damage (Sager and Winship, 2019). This pattern is well-documented for nanoparticles in agricultural contexts (Nair et al., 2010; Calabrese and Baldwin, 2003).

Nutrient Accumulation and Bio-fortification

The enhanced N, P, K, and Fe concentrations in straw and grains at 4 mg L^{-1} Fe_3O_4-NPs reflect the critical role of Fe in nutrient assimilation and translocation. Iron is essential for nitrate reductase and nitrite reductase activities, which catalyze the reduction of absorbed nitrate to ammonium for protein biosynthesis (Taiz and Zeiger, 2010). Iron is also a component of ferredoxin and heme proteins that donate electrons to nitrite reductase in the chloroplast stroma, maintaining close coupling between photosynthetic electron transport and N assimilation (Briat et al., 2015). The improved N status, in turn, supports protein synthesis and grain filling, as evidenced by the strong positive correlation between grain N and TGW.

The significant increase in grain Fe concentration (60 mg kg^{-1} at 4 mg L^{-1}) is particularly noteworthy from a nutritional perspective. Iron deficiency anemia remains the most prevalent micronutrient deficiency globally, affecting over 2 billion people, and bio-fortification of staple cereals is a priority for international food security programs (White and Broadley, 2009). The mechanisms governing Fe loading into cereal grains involve long-distance transport of chelated Fe as Fe(III)-nicotinamine and Fe(III)-deoxymugineic acid complexes in the phloem, unloading and deposition in sub-aleurone endosperm cells via vacuolar iron transporters (VIT1), and remobilization of ferritin-bound Fe from senescent tissues (Slamet-Loedin et al., 2015). Fe_3O_4-NPs priming enhances grain Fe loading by increasing the total systemic Fe pool available for phloem transport and upregulating the biosynthesis of nicotinamine and deoxymugineic acid chelators (Marschner, 2012). The significant grain Fe accumulation even at 2 mg L^{-1}, despite no significant straw Fe increase at

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that concentration, suggests that at lower priming doses the plant prioritizes grain Fe loading over vegetative Fe retention—reflecting the fundamental sink priority of developing grains for limiting micronutrients.

The increase in grain P at 4 mg L^{-1} (120% over control) is important for nutritional reasons, as high grain P provides better phosphorus nutrition to consumers. Maize grains contain a high proportion of P in the form of phytate, the major storage form for germination. Adequate plant P status promotes efficient biosynthesis and accumulation of phytate in embryo tissues and aleurone cells (Lott et al., 2000). The enhanced P status in plants and increased capacity for phloem transport of P under Fe_3O_4-NPs treatment explains the improvements in grain P.

Fe Uptake and Use Efficiency

The maximum Fe uptake (9.0 kg ha^{-1}) and Fe use efficiency (7.2%) at 4 mg L^{-1} Fe_3O_4-NPs demonstrate the effectiveness of nano-enabled seed priming for improving Fe acquisition and utilization. The nano-size, high surface area, and enhanced reactivity of Fe_3O_4-NPs improve nutrient solubility and facilitate easier transport of Fe into plant roots and vascular systems (Rizwan Khan et al., 2022). Nanoparticles can also enhance nutrient mobility in soil and improve root surface interactions, leading to greater Fe absorption efficiency. The decline in Fe uptake and FeUE at 6 mg L^{-1} suggests that excessive nanoparticle concentrations may cause aggregation, reducing surface activity and limiting nutrient availability, or may induce mild phytotoxic effects that interfere with root physiological processes (Parvaiz et al., 2021).

Implications for Sustainable Agriculture

The findings of this study have significant implications for sustainable crop production and nutritional security. Seed priming with Fe_3O_4-NPs at 4 mg L^{-1} represents a low-cost, farmer-friendly technology that can enhance maize productivity and grain Fe density under field conditions. Unlike soil application, seed priming avoids Fe-P antagonism in soil and delivers Fe directly to the germinating embryo, promoting early vigor and uniform stand establishment. The improved nutrient use efficiency (FeUE = 7.2%) indicates that nano-enabled priming can reduce fertilizer requirements while maintaining or increasing yields a key goal of sustainable intensification.

Conclusion

The present study demonstrates that seed priming with Fe_3O_4 nanoparticles significantly enhances maize growth, yield, nutrient accumulation, and grain Fe bio-fortification under field conditions. Among the tested concentrations, 4 mg L^{-1} Fe_3O_4-NPs proved most effective, recording the highest plant height (157.7 cm), cob weight (212.0 g), thousand grain weight (227.7 g), grain yield (3260 kg ha^{-1}), biological yield (10023.7 kg ha^{-1}), and N, P, K, and Fe concentrations in straw and grains. Iron uptake (9.0 kg ha^{-1}) and Fe use efficiency (7.2%) were also maximized at this concentration. Concentrations above 4 mg L^{-1} resulted in a slight decline in most parameters, indicating a hormetic dose-response. These findings suggest that nano-enabled seed priming with 4 mg L^{-1} Fe_3O_4-NPs is a promising, sustainable strategy for improving maize productivity and micronutrient enrichment. Future research should evaluate the

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long-term effects of Fe_3O_4-NPs on soil health, microbial communities, and residual effects on subsequent crops, as well as validate these findings across different agro-ecological zones and maize varieties.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

Z.A. conducted the field experiment, collected and analyzed data, and drafted the manuscript. I.A.M. conceived and designed the study, supervised the research, and critically revised the manuscript. Both authors approved the final version.

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