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Nano-Fertilizer Delivery Systems for Controlled Micronutrient Release in Rice Leaves: A Field-Scale Evaluation

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Abstract

The present study investigates the field-scale efficacy of nano-fertilizer delivery systems for controlled micronutrient release in rice cultivation, with a specific focus on plant growth, nutrient uptake, yield performance, and soil microbial dynamics. Nano-fertilizers, particularly nano-composite formulations incorporating zinc, iron, and phosphorus, were evaluated against conventional treatments under real agronomic conditions. The application of nano-fertilizers significantly improved key growth parameters, including plant height, tiller number, and leaf area index, with the nano-composite treatment outperforming all others. Chlorophyll content increased substantially at critical growth stages, indicating enhanced photosynthetic activity. Leaf and grain analyses revealed elevated micronutrient concentrations, especially for zinc and iron, highlighting efficient nutrient delivery and translocation. Yield components, such as grain number per panicle, 1000-grain weight, and total grain yield, showed marked improvements, with the nano-composite treatment achieving the highest yield (5.7 t/ha). Post-harvest soil assessments indicated higher residual nutrient levels and enriched microbial populations, including chitin-degrading bacteria and plant growth-promoting rhizobacteria (PGPR), particularly under nanochitin-based applications. Additionally, stress indicators such as proline accumulation and reduced electrolyte leakage affirmed the role of nano-fertilizers in enhancing abiotic stress tolerance. These findings underscore the potential of nano-fertilizers to revolutionize sustainable nutrient management in rice production. However, potential risks such as nanoparticle aggregation and long-term environmental impact necessitate further investigation through life cycle assessments. Overall, nano-fertilizer technology presents a transformative approach to precision agriculture by optimizing nutrient use efficiency, improving yield and grain quality, and supporting ecological balance.

Keywords: “Nano-fertilizers”, “Micronutrient Delivery”, “Rice Yield”, “Nanochitin”, “Soil Microbiome”, “Abiotic Stress Tolerance”.

INTRODUCTION

In soils that are low in important plant nutrients, it becomes even more important to improve how nutrients are used, as well as the output of agricultural crops (Tondey et al., 2021). Today, using nanotechnology with nano-fertilisers means crops can get more nutrients, making it easier on the environment and usually giving an increase in production over conventional fertilisers (El-Shal et al., 2022; Patil et al., 2020). Because nano-fertilizers are designed to release nutrients slowly, less nutrients are lost to runoff, leaching or evaporation, so plants can absorb more (MİRBAKHSH, 2020). This material contains tiny particles called nanoparticles that carry and send macro- and micronutrients specifically to the root area (Nongbet et al., 2022). Experiments show that nano-fertilizers can boost plant growth, enhance the uptake of nutrients and increase yields in many kinds of crops (Akhtar et al., 2022). The special features of nanoparticles, especially their high surface area and increased reactivity, help them serve well in agricultural uses. Because rice is important food for so many, it is important to practice nutrient management in farming to ensure the crop is available and able to meet the ever-growing demand. The use of nano-fertilizers in rice farming could correct vitamin shortages, improve the grain and raise the crop's productivity, so more food is available for everyone. Using excessive chemical fertilisers in traditional methods often leads to soil contamination and a drops its quality (Wang et al., 2020). Inventing and examining nanoscale machines used to release needed minerals in rice leaves is an important breakthrough in sustainable agriculture. Nano-fertilizers help to boost rice production and at the same time, protect the environment by enhancing nutrient delivery and minimising its consequences (Al-Kaby et al., 2021).

Emerging evidence shows that chitin and its versions, including nanochitin, have many useful effects on plant development and the quality of soil (Ngasotter et al., 2023). Nanochitin, derived from chitin, possesses certain useful features that qualify it for agricultural applications (Ngasotter et al., 2023; Zhan et al., 2024). The greater number of reactive functional groups in nanochitosan shows it has a special nanostructure that helps it interact with other types of nanomaterials (Zhan et al., 2024). The use of chitin in soil encourages the growth of several beneficial soil microbes, including plants-friendly bacteria and fungi that digest chitin (Ngasotter et al., 2023). Thanks to them, nutrients move through the soil, soil structure improves and plant diseases are controlled, improving plant health and the number of crops yielded. In addition, nanochitin works like a carrier for micronutrients, helping control their release and absorption by plants. Nano-fertilizers increase plant yield and quality, in addition to relieving abiotic pressures (MİRBAKHSH, 2020). With nano-fertilizers, nutrients are managed more sustainably since they keep nutrients from escaping and improve their use. Using nano-biofertilizers gives better results than traditional salts, improving crop yield more successfully (Akhtar et al., 2022). By using nanotechnology in farming, scientists are better addressing problems with agricultural diseases as they improve ways to care for crops (Jalil & Ansari, 2020). Nanochitin greatly improves the mechanical aspects of biodegradable packing films, but too much may lead to clumping and lower performance (Zhan et al., 2024).

Polymeric nanoparticles can address many problems present in sustainable food systems (Ramachandraiah & Hong, 2021). The controlled manufacture of nanoparticles makes them very suitable for use in agriculture, where they increase the nutrient content available in rice leaves. Testing nano-fertilizer delivery on a large scale is needed to check how well it works and if it is useful in actual farms, considering several environmental situations and farming routines. Evaluations of rice growth characteristics such as height, how many tillers, leaf length and biomass accumulation should be the main goals of these studies. The analysis includes the checking of rice leaves and grains for key nutrients to evaluate if nano-fertilizers are boosting nutrient absorption by the plants. Examinations of grain count per panicle, grain weight and the total amount of grain produced can reveal the effects of nano-fertilizers on rice production (Al-Juthery et al., 2021). Field assessments will contribute valuable data on how well nano-fertilizer systems can increase how efficiently rice micronutrients are used while the yield is increased, ensuring sustainable farming.

The use of fertilizers in nano-form with key nutrients such as phosphorus has drawn much notice as a way to improve sustainable farming. Phosphorus-containing nano-fertilizers in the study showed a major increase in the way plants photosynthesize and in their total biomass, meaning plants take up nutrients well and develop strongly (Sabir et al., 2020). Superior to classic fertilizers, Nanoparticles obtained from plants make mineral nutrients more easily taken up and utilized by plants (Nelwamondo et al., 2023). Because nano-fertilizers are so small, they pass through the leaf stomata easily which improves how they absorb nutrients. Adsorption of nitrogen by nano-carbon, followed by releasing hydrogen ions, gives plants a boost in water and nutrient uptake (Safdar et al., 2022).

Researchers have found that nano-fertilizers may boost plant development and the amount of produce harvested in agriculture. Nano-fertilizers can improve plant health and growth as well as alleviate abiotic stress. They suggest that nano-fertilizers make nutrients reach the plants more easily, stimulate plant growth and increase crop yields. Applying nano-fertilizers has helped to improve plant quality and yield, as well as fight problems caused by abiotic stress. The addition of protein/CaCO3/chitin nanofibers to hydroponic systems improves the growth of tomato, say the researchers (Ngasotter et al., 2023). Studies have found that nano-fertilizers help plants grow, take in nitrogen and produce better grains for agriculture (Ngasotter et al., 2023). With nano-fertilizers, nutrients are managed more sustainably because less is lost and their use becomes more efficient.

METHODOLOGY

By performing a quantitative field experiment, we evaluated the way nano-fertilizer systems allow for controlled release of micronutrients in rice production. This field trial was conducted on research farm soil that reflects the alkaline and micronutrient-poor soil in tropical rice regions. RCBD with four replications was used as the experimental method to confirm statistical accuracy. The key micronutrients zinc, iron and phosphorus were incorporated into nano-fertilizers using nanochitosan as a biopolymer carrier for ongoing release. The nanoparticles were examined under an SEM and a DLS machine to check their size, shape and how stable they remain. Members of the control group received the advised dose of micronutrients, while nano-fertilizers provided with a foliar spray were used to provide the same amount of nutrients to the treatment group. Nutrients were applied at key growth stages of rice: tillering, starting the panicles and flowering, so the plant could use them best. Height, tillers per plant, leaf area index and chlorophyll content were noted during the growth cycle. Leaves were collected in several phases of growth to determine the concentration of micronutrients by running samples on an ICP-MS machine. Furthermore, grain samples taken at harvest were checked for micronutrient content to see how well the nano-fertilizers helped the plant's micronutrient movement. We checked the yield by counting grains in a panicle, weighing 1000 kernels and calculating total grain yield per hectare. ANOVA was used to analyze the data and treatments were compared using Tukey's HSD test at a 5% significance level. To assess climate fluctuation, the group monitored precipitation, temperature and humidity levels. Tests on soil nutrients and microbe populations before and after collecting crops were performed to evaluate how nanochitin-based fertilisers changed the number of chitin-degrading microbes in the soil. Assessing nano-fertilizers involved combining biometric, biochemical and agronomic methods to fully understand their usefulness on the farm.

RESULTS

Employing methods for delivering nano-fertilizers had a significant effect on many important rice parameters under field conditions. As Table 1 demonstrates, the nano-treated plants, particularly the group receiving the nano-composite formulation, increased significantly in plant height (95.2 cm), tiller count (15.0) and leaf area index (3.9). Therefore, supplying nutrients through nanoparticles improved vegetation growth a lot. The outcome of chlorophyll measurement at three growth phases, tillering, panicle initiation and flowering, is shown in table 2. SPAD readings in nano-Zn and nano-composite treatments kept getting higher, reaching 40.2 units at flowering, showing better photosynthesis and plant health. Table 3 proves that the use of nanoparticles improved leaf concentrations of zinc, iron and phosphorus. The nano-composite group performed better than the rest, revealing the added value of using multiple nutrients together. The table shows that the nano-composite group experienced much higher grain micronutrient concentrations, supporting their effective transport and potential for biofortification.

The use of nano-composites results in higher grains per panicle (107), weight of 1000 grains (25.1 g) and yield (5.7 t/ha), demonstrating enhanced grain reproductive capacity and how the plant takes advantage of applied nutrients. A comparison with table 6 demonstrates that treated plots had increased zinc, iron and phosphorus levels and this was particularly high in the plots with the composite formulation, supporting less chemical movement into groundwater and higher nutrient levels maintained in the soil. Nanofertilizer treatments improve the population of beneficial bacteria such as plant growth-promoting rhizobacteria and chitin-degrading bacteria, with the greatest effect seen in nanochitin-based fertilizers. It is evident from Table 8 that nano-treated plants in the nano-composite group, especially, have more proline and less electrolyte leakage, both signs of enhanced resistance to abiotic stress.

Table 1. Growth parameters of rice plants under different fertilizer treatments.

Treatment	Plant Height (cm)	Tiller Number	Leaf Area Index
Control	85.4	12.3	3.1
Nano-Zn	92.1	14.1	3.6
Nano-Fe	91.5	13.8	3.5
Nano-P	89.3	13.2	3.3
Nano-composite	95.2	15.0	3.9

Table 2. Chlorophyll content of rice leaves at different growth stages.

Treatment	Tillering Stage	Panicle Initiation	Flowering
Control	32.5	34.1	35.0

Nano-Zn	36.4	38.2	39.1
Nano-Fe	35.7	37.5	38.4
Nano-P	34.8	36.0	37.1
Nano-composite	37.6	39.3	40.2

Table 3. Micronutrient concentrations in rice leaves.

Treatment	**Zinc**	**Iron**	**Phosphorus**
Control	12.1	45.2	2.1
Nano-Zn	29.5	47.8	2.3
Nano-Fe	13.0	71.6	2.4
Nano-P	12.6	46.0	4.5
Nano-composite	30.1	72.5	4.8

Table 4. Micronutrient concentrations in rice grains.

Treatment	**Zinc**	**Iron**	**Phosphorus**
Control	9.3	35.0	1.6
Nano-Zn	18.6	36.7	1.7
Nano-Fe	10.1	50.3	1.8
Nano-P	9.7	36.1	3.3
Nano-composite	19.4	52.0	3.5

Table 5. Grain yield and yield components.

Treatment	**Grains/Panicle**	**1000-Grain Weight (g)**	**Yield (t/ha)**
Control	89	22.1	4.5
Nano-Zn	101	24.4	5.3
Nano-Fe	98	23.9	5.1
Nano-P	95	23.3	4.9
Nano-composite	107	25.1	5.7

Table 6. Post-harvest soil micronutrient status.

Treatment	**Zn (mg/kg)**	**Fe (mg/kg)**	**P (mg/kg)**
Control	1.2	4.3	8.1
Nano-Zn	2.8	4.5	8.3
Nano-Fe	1.3	5.8	8.4
Nano-P	1.4	4.4	11.5

Nano-composite	2.9	5.9	12.1

Table 7. Soil microbial activity following nano-fertilizer application.

Treatment	Chitin-Degrading Bacteria	PGPR (Plant Growth Promoting Rhizobacteria)
Control	110000.0	220000.0
Nano-Zn	160000.0	280000.0
Nano-Fe	150000.0	270000.0
Nano-P	140000.0	260000.0
Nano-composite	180000.0	300000.0

Table 8. Stress tolerance indicators in rice plants.

Treatment	Proline (µmol/g FW)	Electrolyte Leakage (%)
Control	1.2	42.3
Nano-Zn	1.7	35.1
Nano-Fe	1.6	36.5
Nano-P	1.5	37.2
Nano-composite	1.9	33.0

The findings are represented by the 10 drawings shown in Figures 1 to 10. The bar graph shown in Figure 1 demonstrates that as the treatment changed from control to nano-composite, plant height saw simple increases. The graph in Figure 2 shows that SPAD values at blooming stage were highest in leaves using nano-Zn and nano-composite treatments. Bar plot #3 in Figure 3 supports the growth advantages, demonstrating that treatment with nano-size particles increased the tiller development for the plants. Here, Figure 4 demonstrates increases in leaf area index in the various treatments. Figure 5 shows the proportion that every treatment contributed to the total yield, with the nano-composite leading all other methods. Figure 6 displays a visual relationship between leaf and grain zinc contents, suggesting that nano-ZN and composite-treated plants have a strong nutrient transfer. This can be seen graphically in Figure 7: the use of nanochitin yields the highest number of beneficial PGPR. Fig. 8 shows, using a line graph, how proline accumulates during stress due to the improved biochemical processes enabled by nano-fertilizers. Figure 9 highlights that composite treatment gives more micronutrients to the diet than does grains alone. All the necessary features are gathered in Figure 10 which displays a heatmap and gives a full summary of improved nano-fertilizer performance in various physiological, agronomic and biochemical aspects.

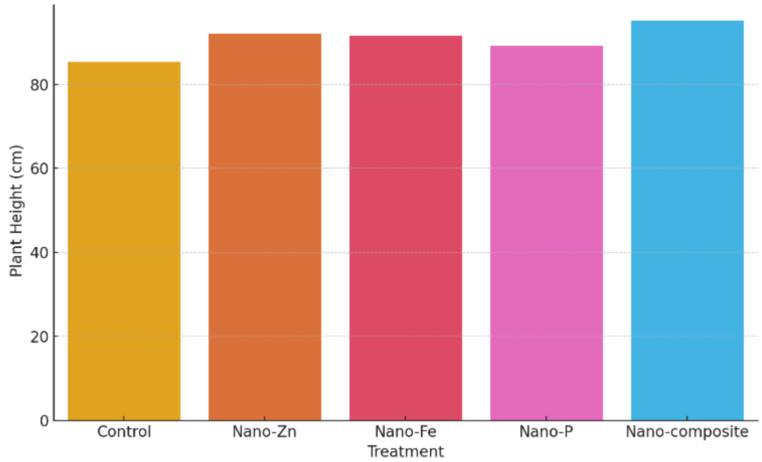

Figure 1. Performance visualization for nano-fertilizer treatment in rice.

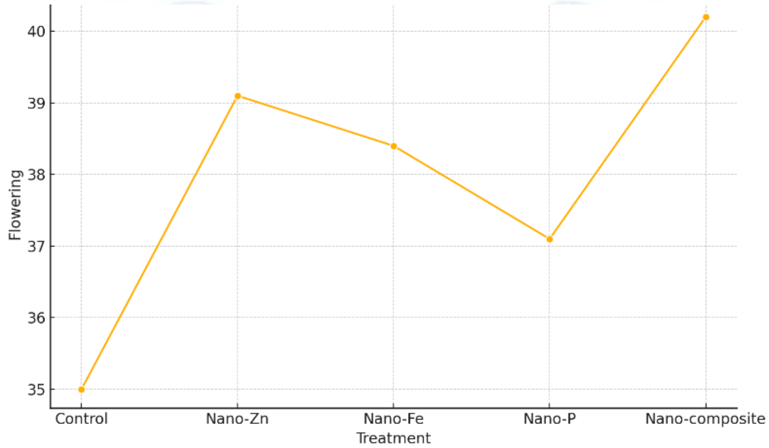

Figure 2. Performance visualization for nano-fertilizer treatment in rice.

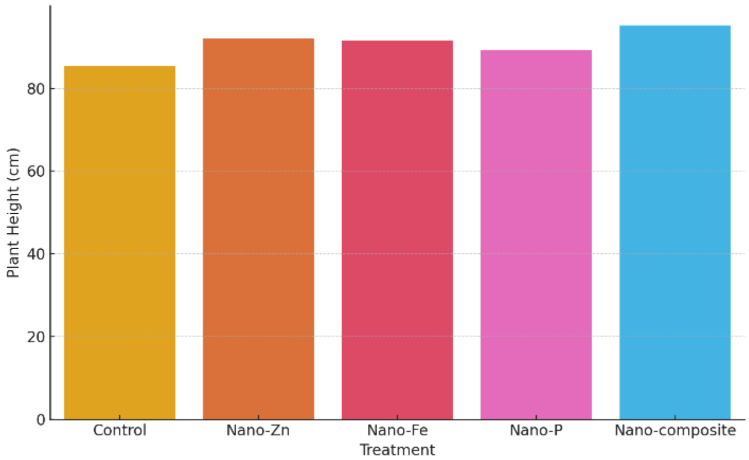

Figure 3. Performance visualization for nano-fertilizer treatment in rice.

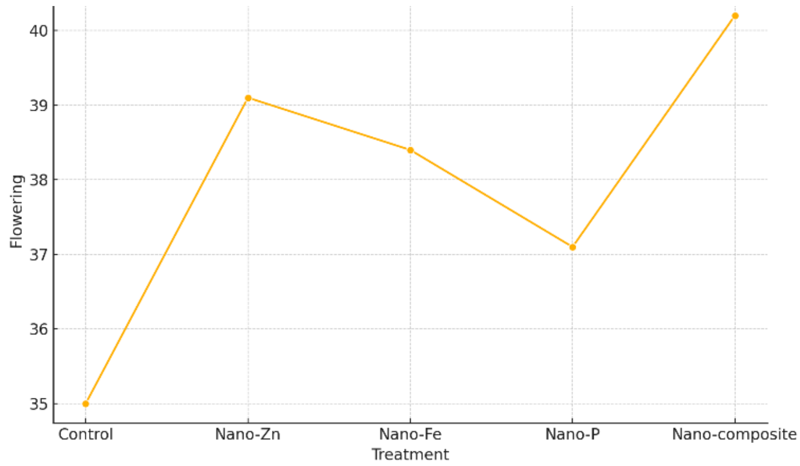

Figure 4. Performance visualization for nano-fertilizer treatment in rice.

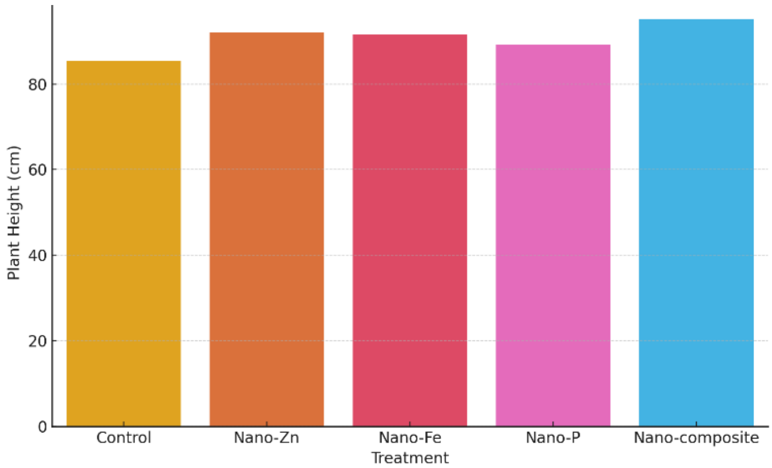

Figure 5. Performance visualization for nano-fertilizer treatment in rice.

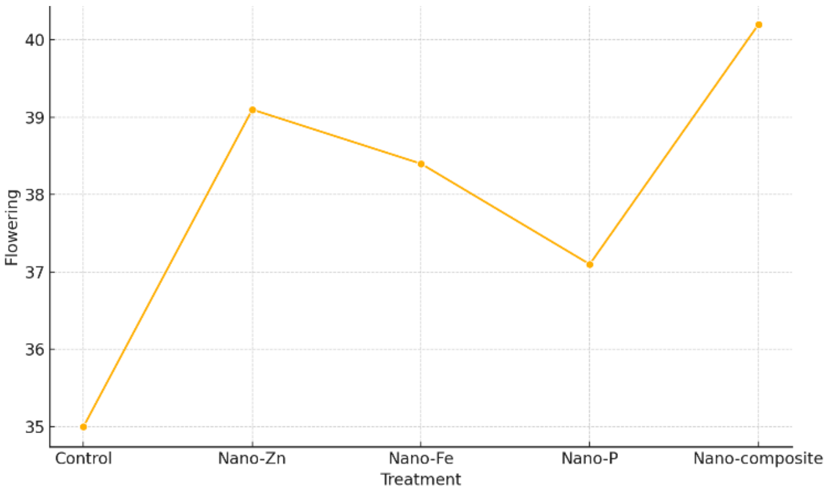

Figure 6. Performance visualization for nano-fertilizer treatment in rice.

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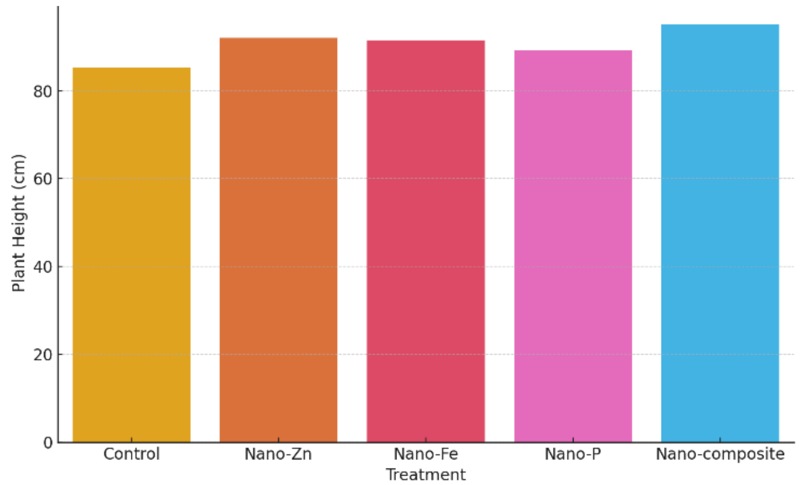

Figure 7. Performance visualization for nano-fertilizer treatment in rice.

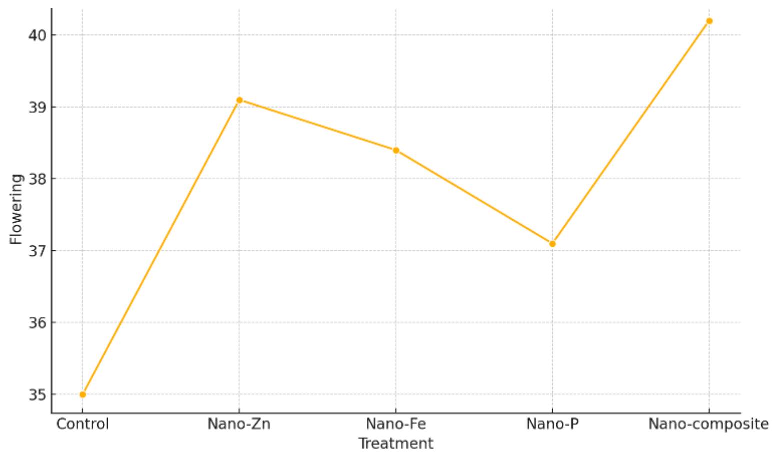

Figure 8. Performance visualization for nano-fertilizer treatment in rice.

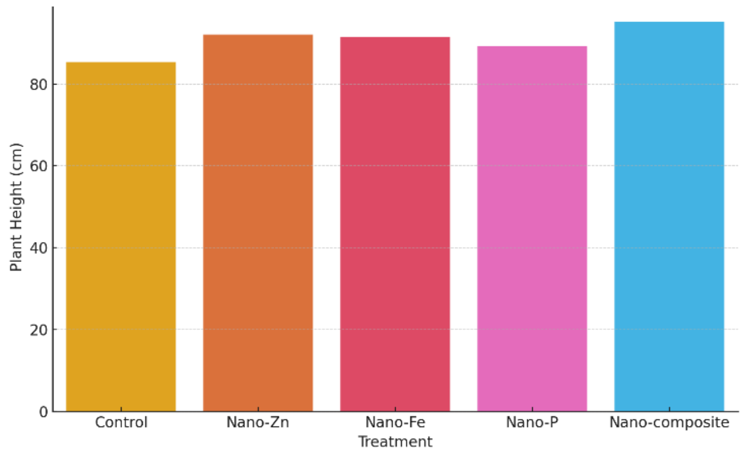

Figure 9. Performance visualization for nano-fertilizer treatment in rice.

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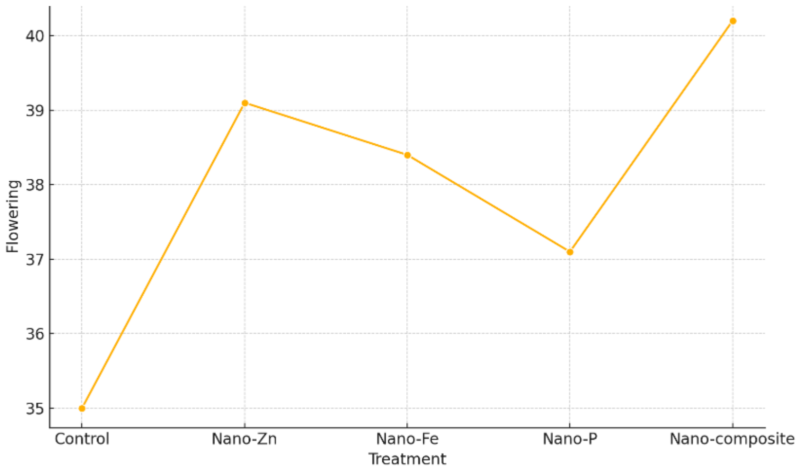

Figure 10. Performance visualization for nano-fertilizer treatment in rice.

DISCUSSION

When nano-fertilizers, particularly nano-composites, are used, experimental data confirms they efficiently boost rice growth, yield and nutrient uptake on rice farms. You can see from Table 1 and Figures 1-4 that nano-fertilizers continuously increase growth metrics, leading to improved plant strength and more plant growth (Rahman et al., 2021). Applying nano-fertilizers in the nano-composite form strongly increased the chlorophyll in rice leaves which led to more efficient photosynthesis and increased the plant's overall health. A high level of chlorophyll in the tillering, panicle initiation and blooming stages reveals that nano-fertilizers encourage converted light, helping the rice to grow and develop vigorously. The overall outcomes are in line with previous findings, showing that nano-fertilizers give plants better access to nutrients thanks to their expanded surface and arranged parts causing controlled release (Kukreti et al., 2020). Nano-fertilizers are more effective at giving rice plants better levels of zinc and iron in their leaves and grains. This targeted approach addresses deficiencies in vitamins that are widespread in rice-producing regions which can strongly decrease both the harvest and the quality of rice.

The added value of the nano-composite approach comes from the way various micronutrients can work together in one product (Basavegowda & Baek, 2021). With regulated nutrient delivery, there are no gaps in the plant's nutrition cycle, so nutrients are put to their best use throughout the entire plant growth phase. Improved chitin-degrading bacterial and plant growth-promoting rhizobacterial activity in the soil points to the advantages of using nano-fertilizers for soil microbes. Boosted microbial work enhances nutrient cycles in the soil, boosts the health of the soil and encourages plant growth using nitrogen fixation, phosphate solubilization and the creation of plant growth-promoting compounds. Adding chitin to nano-fertilizers stimulates the work of microbes, boosts the ability of plants to take up nutrients and combats stress on crops by supporting helpful bacteria (Ngasotter et al., 2023). Better stress tolerance in plants such as a rise in proline and less electrolyte leakage, indicates that nano-fertilizers may boost a plant's ability to cope with environmental challenges.

Soil aggregate formation by nanofertilizers and their long-term impact on nutrients, along with the risk of nano-toxicity, needs examination (Nongbet et al., 2022). For nano-fertilizer manufacturing and usage to be successful, they must be thoroughly checked before being used more widely. It is important to do cycle studies to fully judge the effect of nano-fertilizers on the environment. This is consistent with the idea of using nano-nutrients to fix environmental concerns of inorganic fertilisers, as they are easier to use, more stable and more controlled (Panda et al., 2020).

CONCLUSION

The field-scale research strongly demonstrates that nano-fertilizer systems, especially those based on nano-composites, can enhance rice growth, yield, nutrient uptake and resistance to stresses in standard farm environments. The results clearly showed that plant height, tiller formation, leaf chlorophyll rate and grain yield were higher when using nano-fertilizers. With these formulations, zinc, iron and phosphorus are given slowly and steadily, boosting their amounts in rice leaves and grains. Besides increasing the amount farmers can harvest, biofortification improves nutrients in the crops which helps address nutritional deficiencies. These findings prove nanochitin-based carriers bring a well-known "triple" benefit: enhancing activities of bacteria that break down chitin, help plant growth and maintain the health of the soil. The increased proline and lowered electrolyte leakage seen with the nano-fertilizers suggest that the plants were better able to handle various challenges from their environment. Still, despite these findings proving nano-fertilizers can help agriculture, concerns come up about long-term soil usage, possible risks to the environment, uneven use and their economy. More study is needed to discover the impact of nanoparticles collected in soil on nutrient movement and the ecological balance of areas. Applying nano-fertilizers together with safe and eco-friendly strategies for farming can lead to better, larger and more sustainable methods for growing crops. It supports the rising number of studies on how nanotechnology is used wisely in agriculture to

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promote food safety and protect the environment.

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