Review Article

Effect of Nanofertilizers in Wheat Crop Nutrition: A Review

Abstract

The use of ~~nanofertilizers~~ nano fertilizers in wheat cultivation represents a promising approach to overcoming some of the inefficiencies and environmental challenges associated with conventional fertilizer practices. Traditional fertilizers often suffer from low nutrient use efficiency, leading to excessive application, nutrient runoff, and environmental harm. ~~Nanofertilizers~~Nano fertilizers, due to their nano-scale size and enhanced reactivity, improve nutrient uptake by plants, leading to better growth, higher yields, and reduced nutrient wastage. Studies show that ~~nanoformulations~~Nano formulations of both macronutrients (such as nitrogen, phosphorus, and potassium) and micronutrients (like zinc and iron) can significantly enhance wheat productivity. ~~Nanofertilizers~~Nano fertilizers not only increase crop yield but also reduce the overall cost of fertilizer application by minimizing nutrient loss and improving absorption by the plants.

Introduction

Wheat is one of the earliest domesticated and most important staple food crops globally. It is believed to have been domesticated around 10,000 years ago in the Fertile Crescent, a region spanning Western Asia and North Africa (de Sousa et al., 2021). Currently, wheat is grown on an area of 242.39 million hectares (~~mha~~MHA) worldwide, producing approximately 895.18 million tonnes (~~mT~~MT) of grain (FAOSTAT, 2022). Wheat provides 85% of the energy and 82% of the protein requirements for the global population (Al-Juthery et al., 2022). In India, wheat ranks second only to rice, with a cultivation area of 31.12 ~~mha~~ MHA and a production of 109.58 mT (Indiastat, 2022). The major wheat-producing nations include China, India, the United States, and Canada. As the world population is projected to reach 10 billion by 2050, there is an urgent need to increase wheat production to meet the rising demand for energy and protein. Historically, the rate of wheat production growth has fluctuated. After the Green Revolution, the growth rate increased from 2.1% between 1966 and 1977 to 3.0% between 1977 and 1985. However, this rate declined to 1.3% from 1985 to 1997, which was lower than the pre-Green Revolution growth rate of 1.5% (Tandon and Sethi, 2006). More recently, wheat production growth has slowed to just 0.9% (Salim, 2020). Understanding and addressing the root causes of this decline is essential for reversing the trend and increasing production sustainably. Several factors have been attributed to the reduction in wheat yields, including heat stress, declining soil health due to intensive cropping and tillage practices, and increasing biotic stress (Jasrotia et al., 2018). Crop nutrition remains a crucial aspect of wheat production. Before the Green Revolution, fertilizer use in wheat farming was minimal. However, the introduction of high-yielding dwarf wheat varieties during the Green Revolution led to the widespread use of fertilizers and irrigation to maximize yields. Over time, the gap between input costs and returns has widened, reducing the profitability of wheat farming (Dhanda et al., 2022). Revisiting nutrient management and adopting more efficient and sustainable practices,

~~such~~ Such as nanofertilizers, could help address these challenges and improve wheat productivity in the face of growing global demand. Nanofertilizers are a novel approach to nutrient management in agriculture. They consist of either ~~nutrients~~nutrient in the form of nanomaterials, nutrients encapsulated within nanomaterials, or nanomaterials that act as carriers or additives for minerals (Usman et al., 2020). These nanoformulations have several advantageous properties, including **controlled and timely nutrient release**, **enhanced solubility and effectiveness**, improved **stability**, **targeted delivery** at desired concentrations, and safer, more environmentally friendly disposal with reduced toxicity (Pramanik et al., 2020).

Nanostructured materials such as **chitosan**, **zeolites**, **~~nanohydroxyapatites~~nanohydroxyapatite**, and **clay minerals** can be employed to develop fertilizers for soil or foliar ~~application~~applications. These materials facilitate better interaction with nutrients. For instance, urea modified with nanohydroxyapatite particles can act as a **slow-release fertilizer**, supplying nutrients to crops for up to 60 days (Chippa, 2019; Pramanik et al., 2020; Usman et al., 2020). Today, various natural and synthetic polymers, such as **biodegradable chitosan nanoparticles** and **kaolin**, are used as coatings for slow-release fertilizers (Duhan et al., 2017). The slow release of nutrients is particularly beneficial when dealing with **nitrogen fertilizers**, which can be lost through volatilization, leaching, or denitrification, and **phosphate fertilizers**, which may revert to less available forms. Potassium fertilizers also face issues of leaching and fixation, depending on soil texture (Dhillon et al., 2019; Dianjun et al., 2022). The slow-release formulation of these nutrients minimizes such losses, improving efficiency. In soils with lower pH, where many micronutrients become less available, nanoparticle-based foliar sprays can be particularly effective. Nanomaterials bind nutrients more strongly due to their higher surface tension, resulting in improved nutrient absorption by plants (Pramanik et al., 2020). Additionally, some nanomaterial additives, like **nano silica** and **nano titanium dioxide**, enhance plant resistance to both **biotic** (pathogens) and **abiotic** (environmental) stresses (Duhan et al., 2017), providing a further advantage in promoting plant health and productivity. The adoption of ~~nanofertilizers~~ nano fertilizers can thus lead to more efficient nutrient management, minimizing environmental losses while enhancing crop resilience and productivity.

Effect of Nano-forms on wheat

Macronutrient

The application of nutrients in nano form can significantly reduce costs while improving nutrient use efficiency in wheat cultivation (El-Saadony et al., 2021). Research has demonstrated that the use of nano nutrients leads to yield advantages, with superior performance across various parameters compared to conventional nutrient application methods. Application of a multinutrient mixture in nano form resulted in a **15% increase in yield**, a **15% increase in chlorophyll content**, and a **6% increase in protein content** compared to conventional fertilizer application. Even the use of only nano NPK led to an **8.5% increase in yield** over conventional ~~multinutrient~~ multi nutrient mixtures (Al-Juthery et al., 2018). The combination of ~~nanofertilizers~~ nano fertilizers with amino acids significantly enhanced all vegetative growth parameters, yield, protein content, nutrient uptake, and agronomic efficiency. This combination outperformed the use of mineral fertilizers with amino acids or the use of nanofertilizers alone (Kandil et al., 2017; Al-Juthery et al., 2019a). Additionally, a combination of **~~nano chelated~~nano-chelated NPK**, **nano micronutrients**, and yeast extract produced a synergistic effect, leading to a substantial increase in wheat yield and nutrient uptake (Al-Juthery et al., 2020). A nano formulation of **lithovit**, rich in calcium, magnesium, and silica, when sprayed at 400 ppm, resulted in a significantly higher durum wheat yield. This effect was amplified when combined.

~~with~~ With increased nitrogen fertilizer doses, particularly under deficit irrigation conditions (Morsey et al., 2018). Lower concentrations of **chitosan-Nano NPK** increased vegetative and reproductive parameters, yield, and total phosphorus (P) and potassium (K) content in grains. The application of these nanoforms reduced the life cycle of the wheat crop by **23.5%** compared to higher concentrations and conventional NPK application (Abdel-Aziz et al., 2016; 2018). **Three sprays** of nano phosphorus (P), potassium (K), and zinc (Zn) combined with **75% RDF** led to an **average yield gain of 16%** compared to one spray with 100% RDF (Meena et al., 2021). Abdelsalam et al. (2019) also found that using **75% Nano NPK + 25% mineral NPK** resulted in higher yield and yield-attributing characteristics compared to using 100% of either alone or 50% of each in combination. **Nutrient Use Efficiency**: Nano formulations of **NPK fertilizers**, applied with varying levels of fertilizers, resulted in significantly higher nitrogen, phosphorus, and potassium use efficiencies compared to using RDF alone in wheat crops (Mehta and Bharat, 2019). The use of **chitosan nanoparticles** with nano nitrogen significantly boosted grain yield and yield attributes compared to doubling the dose of mineral nitrogen (Saad et al., 2022). Under drought stress, the use of **chelated ~~nano nitrogen~~nanonitrogen** resulted in higher grain yields even with lower nitrogen doses (Astaneh et al., 2018). **Biofertilizers loaded on nanoparticles** allowed for comparable NPK uptake even when using half the recommended dose, showing similar results to full-dose fertilizer applications (Hasan and Saad, 2020). When **nano zinc** and **nano nitrogen** were applied along with organic nutrient sources, a yield gain of **5.35%** was reported compared to the conventional NPK plus zinc application (Kumar et al., 2022). The application of nutrients in nano form offers clear advantages in wheat cultivation, including higher yield, improved nutrient use efficiency, and enhanced crop quality. Nano nutrients not only outperform conventional fertilizers but also reduce input costs and improve stress resilience, making them a promising solution for sustainable agriculture.

Micronutrient

The application of micronutrients in nano form, particularly iron, zinc, and copper, has shown significant benefits in wheat cultivation, including enhanced yield, improved nutrient uptake, and stress resilience. Nanofertilizers offer more efficient and targeted nutrient delivery, making them superior to conventional fertilizers. These benefits extend to biofortification, where the nutritional quality of wheat grains, especially in terms of micronutrient content, can be substantially improved. By integrating nanotechnology, wheat production can be optimized, contributing to sustainable agricultural practices and addressing global food and nutrition security challenges.
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The combined application of **iron (Fe)**, **zinc (Zn)**, and **copper (Cu)** in nanoform has led to a significant increase in **vegetative parameters**, **yield-attributing characteristics**, **grain yield**, and **chlorophyll content** (Al-Juthery et al., 2019b). **Iron oxide nanoparticles** (20–40 nm) were highly effective in wheat, leading to improved uptake, translocation, biomass production, and chlorophyll content (Al-Amri et al., 2020). Increasing concentrations of **iron nanofertilizers** have been linked to higher grain yields and improved yield components (Hanon Mohsen et al., 2022). Under **semi-arid conditions** in Iran, an **iron nanochelated fertilizer** applied at 2.5 kg per 1000 liters of water significantly increased yields in wheat, even outperforming higher concentrations (Rezaeei et al., 2014). **Seed treatment followed by foliar application** of zinc nanoparticles has been shown to significantly increase grain yield and yield-contributing traits compared to either method applied alone or the use of conventional zinc sulfate (Prajapati et al., 2018). **Nano zinc** at 400 mg/L, applied along with the recommended nitrogen dose, stimulated plant growth and ~~yield~~ yielded better than a higher dose of 600 mg/L (Seadh et al., 2020). Application of **nano zinc** showed no antagonistic interaction with phosphorus at the highest doses and improved protein and carbohydrate content in wheat grains (Abdelaziz et al.,

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2020). Zinc oxide nanoparticles also demonstrated the ability to alleviate **salinity stress** in wheat, improving yield, chlorophyll content, and vegetative parameters (Adil et al., 2022). Combined application of **nano iron** and **nano zinc**, or each applied individually, significantly improved wheat yields under severe **water-limiting conditions** (Seyed Sharifi et al., 2020). ~~Use~~ The use of **Zn + Fe + Mn nanochelates**, together with one supplementary irrigation, increased grain yield by 86% compared to using irrigation alone (Moitazedi et al., 2022). **Enzymatic activity** (catalase and polyphenol oxidase) and grain yield were improved by applying iron and zinc oxides under **saline conditions**, helping wheat to better cope with stress (Babaei et al., 2017). **Chitosan zinc nanoparticles** applied with urea resulted in increased grain zinc, iron, and protein content, even at concentrations **10 times lower** than conventional zinc sulfate, showing great potential for biofortification (Dapkekar et al., 2018). **Seed priming with ZnO nanoparticles** led to an increase in grain zinc concentration, suggesting its effectiveness for **biofortification** in wheat (Munir et al., 2018). Lower concentrations of **nano iron oxide** were more effective than traditional iron sources (iron chelates or iron sulfate) in increasing grain iron and protein content (Ghafari and Razamjoo, 2013). Applying a combination of **nano iron, nano zinc, and other micronutrients** resulted in synergistic effects, such as improved growth, yield, and nutrient content, especially under stress conditions such as drought and salinity.

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Future research potential in nano nutrition of wheat

The future research potential in **nano nutrition of wheat** offers a promising frontier in improving crop productivity, nutrient use efficiency, and sustainability. Several areas of advancement and exploration are outlined below:

1. Development of Intelligent Nanofertilizers

The next step in ~~nanofertilizer~~ nano fertilizer research is the creation of **intelligent fertilizers** that can sense and respond to environmental and physiological stimuli. These fertilizers would detect **nutrient deficiencies** in the plant or soil and release nutrients accordingly, enhancing nutrient use efficiency.

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- For instance, intelligent fertilizers could respond to signals like **ethylene production** or **rhizosphere acidification**, which occur when plants experience nutrient deficiencies (Usman et al., 2020).
- This approach would minimize overuse and wastage of fertilizers, improving both environmental sustainability and economic viability.

2. Real-Time Monitoring with Nanosensors

Nanosensors offer the potential to revolutionize precision agriculture by enabling **real-time monitoring** of nutrient levels in plants and soils.

- **Gold nanoparticles**, **copper nanoparticles**, **carbon nanotubes**, and **silver nanoparticles** are being studied for their potential as sensors to track plant health, growth, and nutrient uptake (He et al., 2019).
- These sensors could optimize the timing and dosage of nutrient application, further enhancing fertilizer efficiency and crop yield.

3. Biofortification via Nanofertilizers

Biofortification through nanofertilizers presents a cost-effective, efficient alternative to traditional breeding and biotechnological approaches.

- **Nanofertilizers** can be tailored to increase the concentrations of essential micronutrients (such as **iron**, **zinc**, and **selenium**) in wheat grains, contributing to improved human nutrition (Al Juthery, 2022).
- This agronomic strategy is quicker and more scalable compared to lengthy genetic modifications or selective breeding processes.

4. Improved Uptake and Translocation

Further research is needed to improve the **uptake and translocation** of nanofertilizers within plants. One promising avenue involves the **magnetization of nanofertilizers**.

- Magnetization has been shown to reduce the number and strength of hydrogen bonds in water, increase surface area, and reduce surface tension and viscosity. This leads to better nutrient absorption through the plant cell walls (Yasir, 2021).
- Such modifications could enhance the efficiency of nutrient delivery, particularly in challenging soil conditions.

5. Addressing Commercialization and Safety Challenges

Although ~~nanofertilizers~~ nano fertilizers offer substantial benefits, several challenges need to be overcome for widespread adoption:

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- **Cost**: The initial cost of developing and producing nanofertilizers is high, but this could be reduced through **economies of scale** as production increases (Cheng et al., 2016).
- **Safety and Regulation**: There are concerns about the potential environmental and health impacts of increased nanoparticle use. For example, some studies report that nanoparticle exposure in wheat may increase **mitotic activity**, leading to **chromosomal aberrations** and abnormal cell development (Abdelsalam et al., 2019). Addressing these safety concerns will require rigorous regulatory frameworks.
- **Consumer Acceptance**: Educating the public about the safety and benefits of nanofertilizers is essential for gaining consumer trust and acceptance.
- **Government Regulations and Intellectual Property**: Clear guidelines regarding the use, commercialization, and intellectual property rights related to ~~nanofertilizers~~ nano fertilizers need to be established to promote research and investment in this field.

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6. Environmental and Ecological Considerations

Further research should explore the **long-term environmental effects** of ~~nanofertilizers~~nano fertilizers, including their interaction with soil ecosystems and the potential for **bioaccumulation** in the food chain.

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- The **biodegradability** of nanomaterials used in fertilizers needs to be assessed to ensure they do not contribute to environmental pollution.

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With a growing global population, the need for increased agricultural productivity is paramount (Araya-Alman et al. 2020). This study's focus on the efficient use of nano-fertilizers to boost crop yields addresses this pressing concern. Nano-fertilizers have the potential to enhance nutrient uptake, leading to improved crop growth and higher yields. The study's emphasis on maintaining sustainability aligns with the urgent need to develop agricultural practices that minimize environmental impact (Hernandez et al. 2018a; Olivares, 2023). Evaluating the sustainability of nano-fertilizers and their effects on soil health, water resources, and the ecosystem contributes to the broader goal of sustainable agriculture (Hernandez et al. 2018b; Hernandez et al. 2020.

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The study capitalizes on the advancements in nanotechnology to address agricultural challenges. Nano-fertilizers have the advantage of delivering nutrients more efficiently to plants, reducing waste, and minimizing nutrient runoff that could contribute to water pollution. Increasing profitability for farmers is a crucial aspect of agricultural research. The study's exploration of how nano-fertilizers can potentially lead to higher crop yields and improved profitability can directly impact the livelihoods of farmers, especially in regions where rice cultivation is a major economic activity (Olivares et al. 2020; Montenegro et al. 2021; Pitti et al. 2021).

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By investigating the application of nano-fertilizers, the study contributes to the adoption of innovative agricultural technologies. Encouraging the adoption of these technologies can lead to increased food production without expanding agricultural land, which is important for conserving natural habitats (Zingaretti et al. 2016; Olivares et al. 2022). The study's comparison with machine learning studies in tropical crops highlights the integration of cutting-edge technologies into agriculture (Rey et al. 2022; Rodriguez et al. 2023). Machine learning can analyze complex data sets to provide insights into optimal planting times, disease prediction, and yield optimization, contributing to more efficient crop management (Olivares, 2022; Vega et al. 2023).

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While the study focuses on crops, the principles and findings can potentially be extended to other tropical crops (Hernandez and Olivares, 2019). This research could serve as a blueprint for optimizing crop production using nano-fertilizers in different agricultural contexts (Hernandez et al. 2018c; Hernandez and Olivares, 2020).

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In conclusion, the study on the efficient use of nano-fertilizers for increasing productivity and profitability in crops, along with its comparison to machine learning studies in tropical crops, has far-reaching implications for sustainable agriculture, technological innovation, economic development, and environmental conservation. It addresses critical global challenges and demonstrates the potential of interdisciplinary research to drive positive change in agriculture.

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Conclusion:

The future of ~~nanonutrition~~ nano nutrition in wheat involves a combination of technological advancements like **intelligent fertilizers** and **nanosensors**, alongside strategies for improving **biofortification** and **nutrient efficiency**. While ~~nanofertilizers~~ nano fertilizers have immense potential to improve yield and sustainability in wheat production, challenges related to **cost**, **safety**, **regulation**, and **consumer acceptance** must be addressed. Research focusing on these areas can further drive the adoption of nanotechnology in agriculture, supporting global food security in the coming decades.

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