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Nanofertilizers in maize (*Zea mays* L.): Enhancing nutrient efficiency and sustainability

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Abstract

The advancement of nanotechnology in modern agriculture has created a sustainable tool which offers a new emerging technique to boost the productivity and sustainability of the crop. In this current study, it explores the potentiality of nanofertilizers application in maize (*Zea mays* L.) which optimizes on their significance in improving nutrient efficiency, minimising the impact on environment and paving the way for sustainability in agricultural activities. In contrast to conventional fertilizers, nanofertilizers has emerged significantly in enhancing nutrient uptake by assuring and promoting the population of bioavailability and it results in reducing losses through the process of volatilization and leaching and made it proper system of nutrient delivery to the plants. This study analyses different aspect of nanofertilizers formulations and their effect on various parameters of maize like soil health, growth, grain quality and yield, as well as their potentiality in mitigating the nutrient deficiency in crop. Similarly, this review paper also examines the environmental impact by the utilization of nano based fertilizers and highlighting their ability minimize fertilizer application and ecological pollution. This paper also highlights the contributions and development of sustainable fertilization practices while optimizing the proper nutrient uptake, improving crop performance and promotes ecologically and authorized system of agriculture.

Keywords: Maize, productivity, sustainability, nutrient use efficiency, Nanofertilizers, volatilization, leaching

1. Introduction

Among all the cereal crops grown globally, maize accounts for 3rd position in worldwide following wheat and rice and it holds fourth rank in India in terms of production after rice, wheat, and sorghum (FAO, 2021) [4]. The production and productivity of maize is closely related to efficient nutrient while securing optimum yield. Utilization of conventional fertilizers have generally led to maximum nutrient losses by various process like leaching, volatilization and fixation (Singh *et al.*, 2020) [25]. Additionally, the extreme application of chemical fertilizers causes soil deterioration as well as hazardous impact on environment.

The rise of food security globally has necessitated the integration and adoption of new emerging agriculture techniques to increase crop productivity while ensuring less risk on the environment. Maize (*Zea mays* L.) crop, the most extensively grown staple food worldwide in cereal crop is a major source of industrial raw material (FAO, 2021) [5]. Despite the major staple food worldwide, the application of conventional fertilizers often progresses in low nutrient efficiency (NUE), maximum nutrient losses through leaching and volatilization and it also contributes environmental pollution, soil degradation and water contamination (Chen *et al.*, 2018) [2]. To mitigate these ongoing challenges and as well as alternative to conventional fertilizers in agriculture system, nanotechnology has proved a boon for the farming community in creating sustainable methods with nanofertilizers which offers a precise solution, efficient application and eco- friendly approach.

Nanofertilizers are synthesized, manipulated and designed at a nano scale range of 1-100nm which significantly improves the nutrient availability, uptake and utilization by plants while enhancing nutrient use efficiency (NUE) and minimizing the losses of fertilizers (Rai *et al.*, 2021) [18], (Rai *et al.*, 2019) [17]. The exceptional physical and chemical nature of nanofertilizers exhibit various properties like high surface area to volume ratios, precise and efficient release

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mechanism with superior solubility, contributing and making them superior performance as it is compared to traditional fertilizers (Shang *et al.*, 2019) ^[21]. There are various forms of nanofertilizers which are available like nanoscale nutrient carriers, nanocomposites, and bio-nanofertilizers and have shown immense potential in enhancing maize production and productivity and creating stress resilience to the crops while minimizing the environmental footprint of agriculture fertilization (Singh *et al.*, 2022) ^[24].

The utilization, integration and adoption of nanofertilizers in maize production present a significant role in building sustainable agriculture by enhancing nutrient management, boosting soil fertility, and reducing the negative effects of excessive agrochemical use for our crop production (Khan *et al.*, 2020) ^[9]. Despite having potential benefit for our crop production by utilizing these innovative methods, it also faces several rigorous challenges such as nanoparticle stability, soil-plant interactions, risk of potential toxicity and several mandates and policies must be addressed through rigorous research and scientific approach (Kah *et al.*, 2018) ^[8].

However, this study approaches the effective application of nanofertilizers in creating use of optimum nutrient on maize productivity and ensuring sustainable practices in agriculture systems. This study investigates the role of different nanofertilizers formulations, and it focusses on maize physiology and yield with the development of innovative strategies and eco-friendly approach of fertilization for modern maize production.

2. Types of Nanofertilizers Used in Maize Production

2.1 Nano Urea

Nano urea is a modern nano-based fertilizer which is synthesized to improve nitrogen use efficiency (NUE) in crops as compared to conventional fertilizers. Compared to conventional fertilizers, nano urea offers more precise and targeted applications while reducing the nitrogen losses through leaching and volatilization. The features of nano urea due to its nano particle size, it gets easily absorbed by foliar application methods through its cell membrane and resulting in minimal dependence on soil application and nitrogen losses. Due to its precise application, it aims to improve chlorophyll synthesis, protein formation, and enzymatic activity, leading to enhance plant growth and higher yield potential. As per recent studies, it has been observed that application of nano urea enhances NUE and crop productivity restricting to the use of conventional urea. As a research conducted at various SAUs and research centres by IFFCO, it is recommended to apply nano urea at a concentration of 4 ml per litre of water by foliar application methods during critical maize growth stages, e.g., vegetative stage and reproductive stage to obtain optimum results (IFFCO, 2021) ^[7]. Adopting these techniques ensures and enhance better nitrogen uptake utilization to the crops which contributes sustainable agricultural system while reducing the hazardous impact of nitrogen fertilization on the environment.

2.1.1 Nano Zinc

Among the nano fertilizers developed, nano zinc is most advanced fertilizer that promotes the bioavailability in the

plants. It plays a significant role in enzyme activation, chlorophyll formation and plant growth. Zinc is a such type of important micronutrient which participates in various physiological process of the plants like protein synthesis, hormone regulation and antioxidant mechanism. The nano particulate fertilizers permits better translocation and absorption of nutrients within the plant, providing the necessity of zinc for metabolic functions. As per the recent research conducted, the application of the nano zinc has promoted stress resilience in the plants to combat against drought and disease by cellular defense mechanism while promoting strong root and shoot systems. It is suggested to apply foliar application of zinc at a concentration of 2 ml per litre of water during maize vegetative and reproductive to obtain maximum outputs (Kumar *et al.*, 2022) ^[11]. This approach of targeted application supports and promotes nutrient efficiency and its utilization which ultimately enhances health, stress tolerance and yield potential of the crop.

2.1.2 Nano Copper

As a promising micronutrient fertilizer, nano copper performs key role in promoting photosynthetic efficiency and activating enzymatic reactions which plays significant role in metabolic activities. It also activates various plant health and resilience by contributing to electron transport, lignin synthesis and oxidative process. It has been synthesized by manipulating its characters, helps the plant to improve its resistance against disease and by supporting defense mechanism while mitigating various bacterial and fungal infections. The properties of nano copper at its nanoscale formulation improves its absorption and movement of nutrients within the plant tissues, allowing it to progress the efficacy of nutrients. To achieve the optimum outcomes, it has been recommended to perform foliar application of nano copper at a concentration of 2 ml per litre of water before the initiation of the flowering stages which ensures healthy growth and improved yield potential by uptaking and utilization of the nutrients in the plants (Patel *et al.*, 2020) ^[14].

2.1.3 Nano Phosphorus

With its manipulating characters, nano phosphorus serves and ensures better root development, energy metabolism, and formation of seed in crops. As it has been formulated as a vital source of macronutrient, phosphorus significantly plays a key role in ATP synthesis, formation of nucleic acid, and promoting enzymatic activities that improves plant growth and productivity. As per the utilization of the conventional fertilizers in crops which often leads to fix the nutrients in the soil and readily available to plants, but nano phosphorus due to its characterization, it increases the bioavailability, leading to efficient uptake and utilization. Nano phosphorus due to its nano scale formulation, it improves better absorption and translocation, enabling to reduce the loss of nutrients and boosting maximum phosphorus use efficiency. Maximizing its optimum benefits, it has been approached to apply as foliar application at a concentration of 2-4 ml per litre of water during the early vegetative stage, which ensures proper root establishment and vigorous growth in plants (Sharma & Mehta, 2021) ^[22].

Parameters	Conventional fertilizers	Nanofertilizers
Environmental impact	High (Soil degradation, runoff)	Low (Less leaching & Volatilization) (Singh <i>et al.</i> , 2021) ^[26] .
Nutrient Use Efficiency	Low (20–30%)	High (40–60%) (Patel & Sharma, 2020) ^[15] .
Yield Improvement	Moderate (nutrient loss reduces efficiency)	Higher (enhanced absorption) (Kumar <i>et al.</i> , 2019) ^[12] .
Cost-effectiveness	Lower initial cost but high wastage	High in long term (low application rates) (Mehta <i>et al.</i> , 2022) ^[13] .

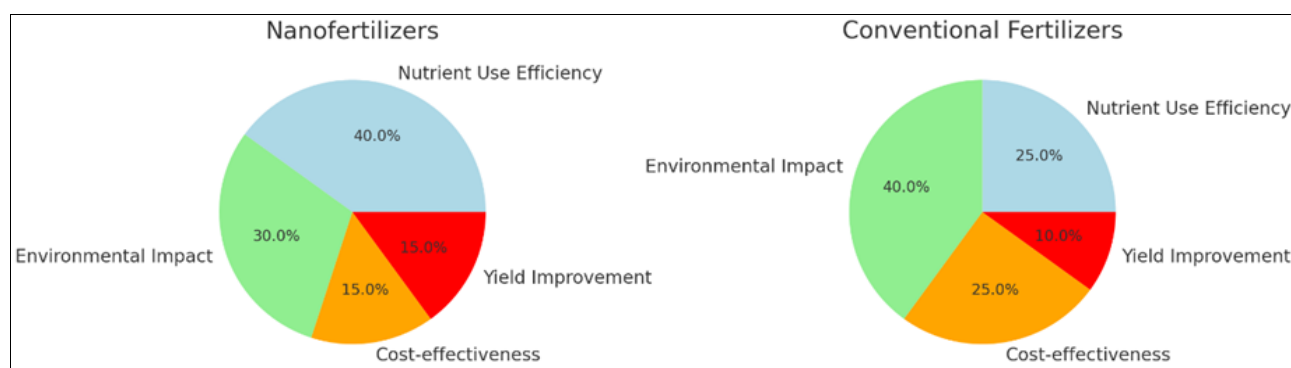


Fig 1: Illustrating and exploring the use of nanofertilizers and conventional fertilizers

3. Mechanism of Action:

Nanofertilizers performs through various mechanisms to ensure proper nutrient efficiency and plant growth:

Increased Surface Area: The nanoscale nature of nanofertilizers results in a significantly larger surface area, promoting enhanced interaction with plant roots and facilitating improved nutrient absorption (Raliya *et al.*, 2016)^[20].

Sustained Nutrient Release: Application of conventional fertilizers in plants induces rapid release of nutrients, while in case of nanofertilizers which show the mechanism of slow release and ensuring a quick action of nutrients reducing leaching and volatilization.

Improved Solubility and Uptake: Unlike conventional fertilizers, nanofertilizers facilitates and move more quickly through the soil and plant tissues due to its superior solubility characters, enabling efficiency of absorption and translocation of nutrients (Das *et al.*, 2018)^[31].

4. Importance of Nanofertilizers in Maize Production:

Due to nano scale characteristics of nano fertilizers, which plays a crucial role in up taking the nutrient efficiency by increasing the concentration of bioavailability and absorption and transportation of vital nutrients in crops. Modifying nanofertilizers enables penetration and uptake of nutrients in plants cell improving optimum utilization of nutrients in crops. Improved efficiency of nanofertilizers reduces overall fertilizer requirements while preserving high crop yields and establishing nanofertilizers as a sustainable approach to traditional fertilizers (Singh & Prasad, 2021)^[23].

Through precise application of nanofertilizers, it delivers proper nutrient use efficiency and significantly contributing to less environmental risk. Their targeted nutrient delivery approach helps in minimizing losses such as leaching, runoff, and volatilization- a common issue which is frequently associated with traditional fertilizers. Reduction of nutrient wastage and preventing pollution of water bodies and ground water surfaces by the application of nanofertilizers help to combat various environmental pollution and strongly supports friendly approach for agricultural activities (Rajput *et al.*, 2019)^[19].

Additionally, nanofertilizers application in crops enhances grain quality and yield. By activating vital metabolic processes, nanofertilizers improve protein content, nutrient composition as well as overall crop productivity. This in contrast it makes nanofertilizers a important tool in modern agriculture, wherein maximizing both quality and yield for sustainable food production.

The several advantages of nanofertilizers are like their cost-

effectiveness and due to greater nutrient use efficiency and controlled release properties of nanofertilizers, lower concentration rates as compared to conventional fertilizers are recommended. This character lead to reduction in input costs and benefitting farmers less dependency on large scale fertilizer use and in result maintaining or even promoting maximum crop performance (Khan *et al.*, 2020)^[10]. Integration of advanced nanotechnology, nanofertilizers evolved as smarter tool and more economical solution towards enhancement of agricultural productivity and sustainability.

5. Challenges and Limitations

In spite of having numerous benefits of nanofertilizers in maize crop production, various challenges encounter the widespread adoption. The primary obstacles are cost effective materials associated with their manipulation and formulation. The synthesis and production of nanotechnology using advanced techniques like specialized equipment enabling certain characteristics like precise control makes them more expensive than that of conventional fertilizers. Due to their cost-effective nature, there is a major concern for the availability and affordability among the small-scale farmers (Prasad *et al.*, 2019)^[16].

The government has not made standardized regulations and guidelines for the applications and safety of nano fertilizers, creates critical challenge regarding their adoption. Due to less concern on global level about the permissible limits, risk assessment protocols, or standard application, leading to uncertainty among farming community, researchers and policy makers. Due to uncertain regulations and frameworks, the large-scale commercialization and adoption of nanofertilizers remain constraints, leaving its major footprint on environmental safety still exists.

Furthermore, the potential risks of nanotoxicity presents vital concerns. The application of nano-fertilizers enhances nutrient efficiency and according to the research its long-term effects on soil health, microbial activity, environmental stability remains limited. As per the research studies conducted excessive or continued use of nano materials may hamper soil microbial population and alter plant-microbe interactions. Still it is uncertain about the potential accumulation in plants tissue and the consequences for food safety. Further more a rigorous research is necessary to assess and explore their long-term impact on environment ensuring sustainable use while mitigating potential risks (Ghorbani *et al.*, 2021)^[6].

If proper integration and utilization of nanofertilizers into modern agricultural practices, these evolving challenges must be addressed through continued scientific research, cost effective production and through well-defined regulatory policies.

6. Future Prospects

Utilizing the complete potentiality of nanofertilizers in maize production, researchers along with government should frame a policy which focus on crucial areas that promotes their effective application, safety towards environment and ensuring large scale adoption. It is need of the current situation extensive field trial should be conducted to validate laboratory findings. As per the various research demonstrated, it has been observed the significant benefits of nanofertilizers under controlled conditions as well as large scale trials must be performed essentially to assess their performance under various diverse environmental situations (Singh & Prasad, 2021) ^[23]. Conducting these trials will help the farming community to optimize application methods, analyse the most effective doses and which will study the long-term impacts on soil health, crop yield and nutrient efficiency (Patel & Sharma, 2020) ^[15]. As per the research, it is also necessary to develop multifunctional nanofertilizers. While assimilating multiple essential nutrients like nitrogen, phosphorus, and micronutrients can enhance overall plant health and growth. Adopting this multifunctional approach leads to the improvement of nutrient uptake efficiency and support resistance in plants to stress conditions and further strengthen sustainable system of agriculture (Rai *et al.*, 2019) ^[17]. Adopting and utilizing the advanced formulations supply specific nutrients of maize at different growth stages, further researchers can exploit the agronomic benefits of nanofertilizers (Sharma & Mehta, 2021) ^[22]. Furthermore, a proper mandate should be proposed for the commercial production of the nanofertilizers. In recent time due to lack of standard guidelines there is a very less production and application of nanofertilizers and due to safety concerns among policy makers, farmers, and consumers, it has not been completely commercialized (Ghorbani *et al.*, 2021) ^[6]. The regulating agency must perform towards its acceptable limits, safety assessment protocols along with proper guidelines should be established to evaluate the impact on environment. If such mandates are proposed, will ensure the judicious use of nanofertilizers while reducing potential risk on human health and ecosystems (Rajput *et al.*, 2019) ^[19].

A well-established regulatory framework will also boost investor confidence, facilitate large-scale production, and accelerate the widespread adoption of nanofertilizers in modern agriculture (Chaudhary *et al.*, 2022) ^[1]. Addressing and overcoming these critical challenges through future research and policy can emerge a strong foundation for nanofertilizers to become transformative tool for enhancing nutrient efficiency and ensuring sustainability in maize production.

7. Conclusion

The use of nanofertilizers in maize (*Zea mays* L.) presents a significant strategy to agricultural performance and promoting sustainable practices of agriculture. Unlike conventional fertilizers various issues like wastage and leaching of nutrients, nanofertilizers offers targeted delivery minimizing nutrient losses and improve microbial availability resulting in optimum plant growth and higher yields. Up-taking the optimum essential nutrients like nitrogen, phosphorus, zinc and copper nanofertilizers contribute to photosynthesis, enzymatic activities, stress tolerance and overall crop health.

Additionally, nanofertilizers play a vital role in overcoming potential environmental risks associated with fertilizer loss, including soil degradation, water contamination and green house gas emissions. Their controlled approach of nutrients delivery, reduces nutrient runoff and leaching, ensuring efficient utilization while sinking the ecological footprint of fertilization.

Although nanofertilizers offers several benefits, several challenges must be addressed to enable the widespread adoption. Various issues such as stability of nanoparticle, potential toxicity, cost effectiveness and regulatory uncertainties require rigorous research. It is essential to conduct a long-term study to evaluate their impacts on soil health, microbial diversity, and food safety.

Integrating nanofertilizers into modern agriculture systems, high cost-effective production techniques and developing standardized protocols regarding the applications must be formulated and implemented further.

Overall, the development of nanofertilizers offers a ground-breaking innovation in maize production, alternative approach to conventional fertilization methods. Their implementation pointedly improves nutrient efficiency, contributing to worldwide food security and promoting ecologically farming systems. As nanotechnology and agronomic research, nanofertilizers have potential to transform modern agriculture contributing to further sustainable future.

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