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REVIEW ARTICLE

The potential of nano fertilizers in modern crop nutrition: Advancement, efficiency and challenges in sustainable agriculture

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Abstract

Nano fertilizer has emerged as a promising innovation in modern agriculture, the traditional methods of crop nutrition. This review explores the significance of crop nutrition in the context of nanotechnology applications in agriculture. It delves into the importance of nano fertilizers, highlighting their distinct advantages over conventional counterparts. The discussion encompasses various sources of nano fertilizers for crop nutrition, elucidating their modes of action and efficiency compared to commercial soil-applied fertilizers. Furthermore, this article provides a comprehensive analysis of the effects of nano fertilizers on the growth and yield components and yield of different agricultural crop plants. Through a comparative study, it evaluates the dosage requirements and agronomic use efficiency of nano fertilizers, shedding light on their potential to enhance crop productivity while minimizing environmental impact. Moreover, the limitations and challenges associated with nano fertilizers are critically examined, offering insights into future research directions and practical implications. By synthesizing existing literature and empirical evidence, this review aims to provide a holistic understanding of nano fertilization in modern agriculture, paving the way for sustainable and efficient crop production practices.

Keywords: challenges; crop nutrient; efficiency; nano fertilizer and sustainable agriculture

Introduction

Nutrient management is a key component of agricultural productivity, significantly influencing global food security and the stability of food systems, particularly as they face the growing human population and challenges of climate change. By optimizing nutrient use, crops can achieve sustainable yields, improve food availability and bolster resistance to various environmental pressures (1, 2). Recent progress in nanotechnology has revolutionized agricultural practices, particularly through the intro-duction of advanced, targeted nutrient delivery systems. These technologies improve crop yields by enhancing nutrient absorption and utilization, while also minimizing environmental degradation and boosting plants' ability to withstand stress (3, 4). Nano fertilizers have become a key innovation in agriculture, enhancing nutrient delivery and boosting crop productivity. They not only improve the efficiency of nutrient absorption but also offer environ-mental advan-tages, helping agriculture meet sustain-ability goals (5, 6). Nano fertilizers, engineered at the nanoscale, offer distinct advantages over conventional fertilizers by enhancing nutrient uptake and utilization efficiency in plants (7). The development of nano fertilizers has enabled precise nutrient targeting within plants, addressing nutrient deficiencies and supporting sustain-able yield improvements by optimizing nutrient uptake efficiency and reducing environmental impact (5). However, the diverse sources of nano fertilizers and their varying compositions pose challenges in understanding their modes of action and optimal application methods for crop nutrition (8). In comparison to commercial soil-applied fertilizers, nano fertilizers demonstrate superior efficacy in terms of nutrient release kinetics and targeted delivery mechanisms (9). This has sparked interest in evaluating the dosage requirements and agronomic use efficiency of nano fertilizers across different crop species and environmental conditions (10). Moreover, the effects of nano fertilizers on growth components, such as root development, leaf morphology and nutrient assimilation, vary among various crop plants, necessitating a compre-hensive analysis to elucidate their impact on crop productivity (11). Furthermore, the influence of nano fertilizers on yield and its components, including grain size, weight and nutritional quality, remains a subject of intensive research and debate within the agricultural community (12). Understanding the agronomic implications of nano fertilization is crucial for optimizing nutrient management strategies and mitigating environ-mental risks associated with excessive fertilizer application (13). However, despite their potential benefits, the adoption of nano fertilizers in mainstream agriculture is hindered by various limitations, including cost-effective-ness, regulatory constraints and concerns regarding nanoparticle toxicity and environmental persistence (14). Addressing these limitations requires interdisciplinary collaboration and innovative approaches to ensure the safe and sustainable deployment of nano fertilizers in agricultural systems (15). In light of these considerations, this review aims to critically analyze the role of nano fertilizers as a gateway to future crop production and its aftermath. By synthesizing existing literature and empirical evidence to provide insights into the importance of crop nutrition, the application of nanotechnology in agriculture and the potential benefits and limitations of nano fertilization for sustainable crop production.

Importance of nano fertilizer

Nanotechnology is a prospective field with multiple applications across various areas of modern science, including physics, pharmacology, chemistry, computer science, agriculture and engineering (16). The distinct physical, chemical and biological properties of nano-particles (NPs) give them the ability to modify typical chemicals and devices (17). Nano particles are defined as natural and artificial materials with at least one dimension ranging from 1 nm to 100 nm and these materials can be organic, inorganic or polymeric compounds (18). Nano fertilizers, designed primarily through encapsulation with nanoparticles are typically categorized into macronutrient and micronutrient types. These advanced fertilizers enable targeted and controlled nutrient release, enhancing uptake and efficiency while minimizing environmental impact (19, 20). Macronutrients such as carbon (C), nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), sulfur (S) and magnesium (Mg) have been encapsulated by different nano materials to improve crop absorption of fertilizers and decrease fertilizer outflow (21).

Nano fertilizers have emerged as a pivotal tool in modern agriculture, offering targeted and efficient delivery of nutrients to crops (4). Nano-urea particles, generally sized between 20-50 nm are designed to release nutrients gradually, facilitating efficient nitrogen uptake, minimizing environmental losses and supporting improved plant growth (22). Nano fertilizers possess the capability to overcome soil nutrient imbalances, thereby promoting balanced nutrient uptake by crops (6). It offers a promising solution for enhancing crop productivity in nutrient-deficient soils, particularly in regions with limited access to conventional fertilizers (12). Their nanoscale formulations facilitate efficient nutrient transport within plants, leading to improved physiological processes and resilience to environmental stresses (11). Compared to traditional fertilizers, the nano fertilizers exhibit enhanced efficacy in promoting crop growth and development (9). The tailored nutrient delivery provided by nano fertilizers addresses specific plant requirements, optimizing resource utili-zation and minimizing wastage (10). The precise control over nutrient release provided by nano fertilizers allows for tailored nutrient management strategies, optimizing crop growth and development (14). Furthermore, nano fertilizers contribute to reducing the ecological footprint of agriculture by minimizing nutrient leaching and runoff, thus safeguarding water quality and ecosystem health (15). Fig. 1 illustrates the significance of nano fertilizer.

Different sources of nano fertilizer for crop nutrition

Different sources of nano fertilizers contribute to enhancing crop nutrition through diverse mechanisms. Metal-based nanoparticles, such as zinc oxide (ZnO) and iron oxide (Fe_2O_3), offer essential micronutrients to plants while exhibiting controlled release properties (23). Carbon-based nanomaterials, including carbon nanotubes (CNTs) and graphene oxide (GO), serve as carriers for nutrient delivery, facilitating efficient uptake by plant roots (24). Polymer-based nanocomposites, such as

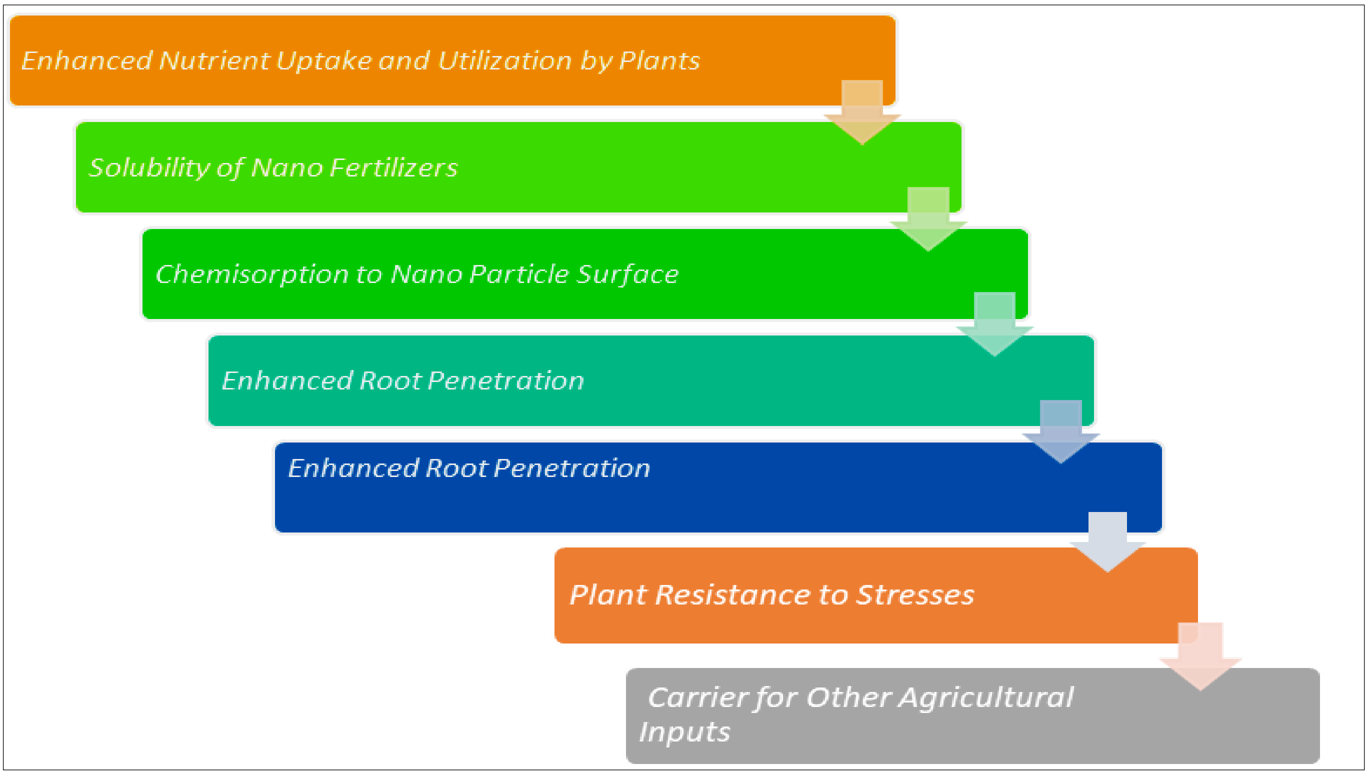

Fig. 1. Significance of nano fertilizer.

chitosan nano-particles and polymeric micelles, as effective in enabling controlled nutrient release and reducing nutrient loss through leaching in soil. These systems provide a sustain-ned nutrient supply, which is particularly beneficial for promoting plant health and reducing environmental impacts associated with nutrient runoff (25, 26). The utilization of these diverse nano fertilizers underscores their potential to address specific nutrient deficiencies and improve overall crop productivity in agricultural systems.

Mode of action

The mode of action of nano fertilizers in crop production involves intricate mechanisms that contribute to enhanced nutrient uptake and utilization by the plants. Nano fertilizers typically exhibit improved solubility, allowing nutrients to be readily available for plant uptake (23). Nanoparticles enter plant leaves primarily through stomatal openings or cuticles, with smaller particles often penetrating more effectively than larger ones. Studies show that nanoparticles under 50 nm can pass through both stomatal and cuticular pathways, while larger particles tend to enter primarily through stomata. Once inside, nanoparticles may travel via apoplastic and symplastic pathways, distributing within vascular systems and potentially moving between cells depending on size and composition (27, 28). Nano fertilizers can enhance nutrient uptake by plants through chemisorption, where nutrients are bound to the surface of nanoparticles and released gradually for uptaking plant nutrients (8). The small size of nano fertilizers facilitates the penetration of plant cell walls, enabling direct delivery of nutrients into plant cells and promoting metabolic processes essential for growth and development (10). Nano fertilizers can interact with plant root exudates, promoting symbiotic relationships with beneficial microorganisms in the rhizosphere that aid in nutrient acquisition and plant health (9). Nano fertilizers also have the potential to enhance plant resistance to biotic and abiotic stresses by inducing systemic acquired resistance mechanisms and modulating plant hormone signaling pathways (12). The unique physicochemical properties of nano fertilizers enable them to serve as carriers for other agricultural inputs, such as pesticides and growth regulators, enhancing their efficacy and reducing environmental impact (14). These multifaceted mechanisms highlight the significant potential of nano fertilizers in optimizing nutrient management and promoting sustainable crop production practices.

A comparision of nano vs commercial soil applied fertilizers

Recent research has focused on comparing the efficacy of nano fertilizer doses with traditional commercial soil-applied fertilizers in crop production. Results indicate that nano fertilizers often outperform conventional fertilizers in terms of nutrient uptake efficiency and crop yield improvement (29). Fig. 2 shows nutrient use efficiencies of conventional fertilizers (30).

The controlled release properties of nano fertilizers allow for better nutrient utilization by plants, leading to higher agronomic efficiency and reduced nutrient losses through leaching or volatilization. Furthermore, nano fertilizers can be applied at lower doses compared to traditional fertilizers while achieving comparable or even higher yields, thus offering cost savings and environmental benefits (10). However, more research is needed to fully understand the long-term effects and potential risks associated with the widespread adoption of nano fertilizers in agricultural systems. Fig. 3 exhibits comparison between nanotechnology-based formulations and traditional fertilizers (31).

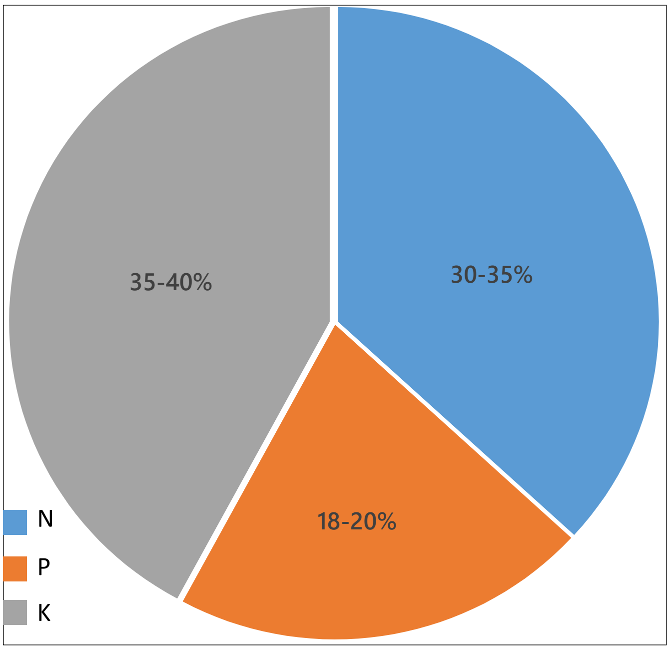

Fig. 2. Nutrient use efficiencies of conventional fertilizers.

Effect of nano fertilizer on growth characteristics of various crop

Nano fertilizers play a crucial role in physiological and biochemical processes by enhancing nutrient availability, which in turn boosts metabolic activities, promotes meristematic growth and increases apical growth and photosynthetic leaf area. Recent studies have demonstrated that foliar applications of nano formulations of NPK and micronutrients significantly improve the plant height and branch number in crop such as black gram (32, 33). Foliar application of nano NPK fertilizers significantly enhances leaf growth in crops like wheat, owing to improved nutrient bioavailability and efficient penetration through stomata. This method allows for targeted delivery during gas exchange, promoting better leaf expansion and dry weight. In peppermint, foliar nano nitrogen application increased leaf dry weight by upto 165 %, illustrating the potential for similar growth responses across diverse plant species. These findings suggest that nano fertilizers can support more robust and efficient nutrient uptake, bolstering overall plant growth (34-36).

Effect of nano fertilizer on yield and components of various crop plants

Nano fertilizers are proving highly effective for enhancing crop yields, with foliar sprays that improve nutrient uptake and support healthier plant growth. Studies show that applying nano NPK as foliar sprays in wheat significantly boosts yield by increasing nutrient efficiency and offering controlled nutrient release, which reduces nutrient loss and improves productivity. Applying nitrogen and phosphorus nano fertilizers during key growth phases has notably increased wheat's grain yield and biomass compared to traditional methods, leading to greater productivity and economic returns for farmers (37, 38). Foliar application of NPK nano fertilizers has been demonstrated to significantly improve the yield and yield components of

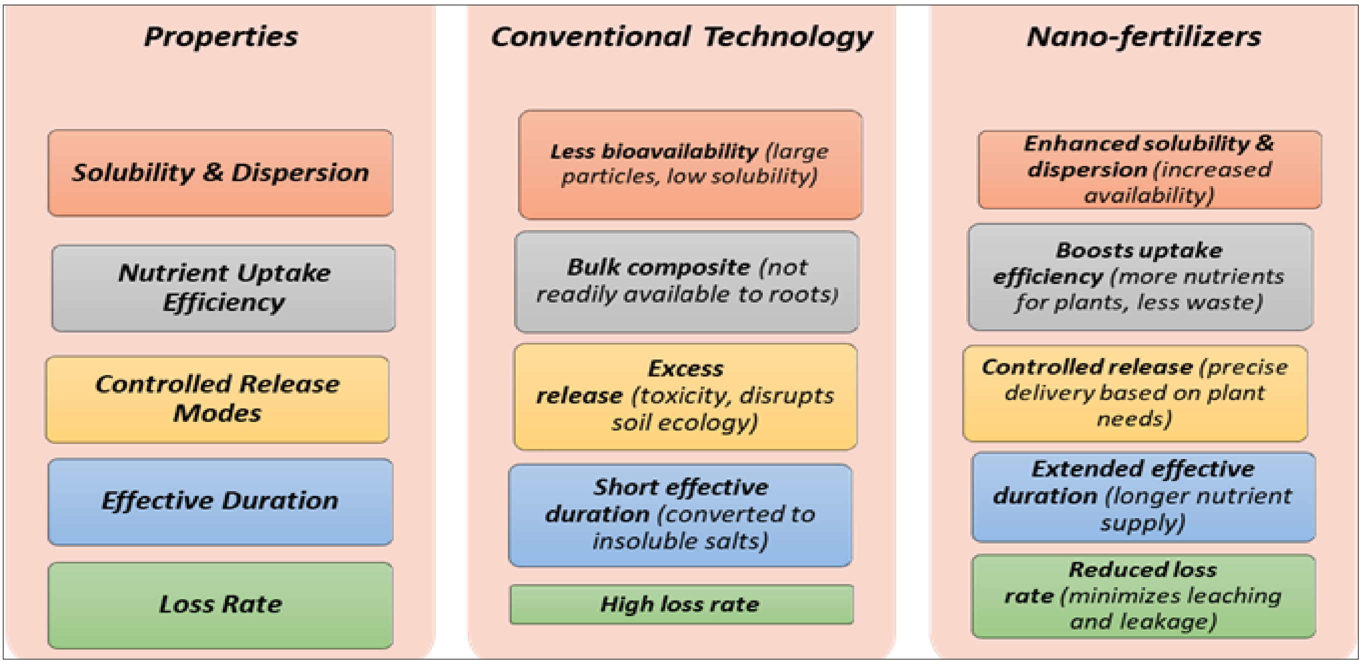

Fig. 3. Comparison of nanotechnology-based formulations and conventional fertilizers applications.

chickpea by enhancing growth hormone activity and speeding up metabolic processes, which subsequently boosts flowering and grain filling. Further-more, the application of nano fertilizers in cotton not only increases yield but also lowers fertilizer costs, thus reducing environmental pollution. Recent research has shown that foliar applications of nano iron, zinc and NPK effectively stimulate chickpea growth, resulting in better yield outcomes (39-41). Fig. 4 highlights the impact of nano fertilizers (NFs) on crops.

Nano fertilization on agronomic use efficiency

Nano fertilization is gaining recognition as an effective method for improving agronomic efficiency in agricultural practices. A variety of studies have repeatedly demonstrated that nano fertilizers can enhance the uptake and utilization of nutrients by crop plants, leading to increased yields and overall productivity (42-44). The distinct nanoscale features of these fertilizers allow for precise nutrient delivery, which ensures that plants effectively absorb and utilize the nutrients for their growth and development. Moreover, nano fertilizers have been shown to significantly lower nutrient losses due to leaching and runoff, contributing to reduced environ-mental pollution and promoting sustainability (41, 42, 39). By optimizing nutrient management practices and promo-ting more efficient use of resources, nano fertilization holds great potential to contribute to the advancement of sustainable agriculture and address global food security challenges. The nano fertilizers release nutrients slowly into the crops and thus increase their

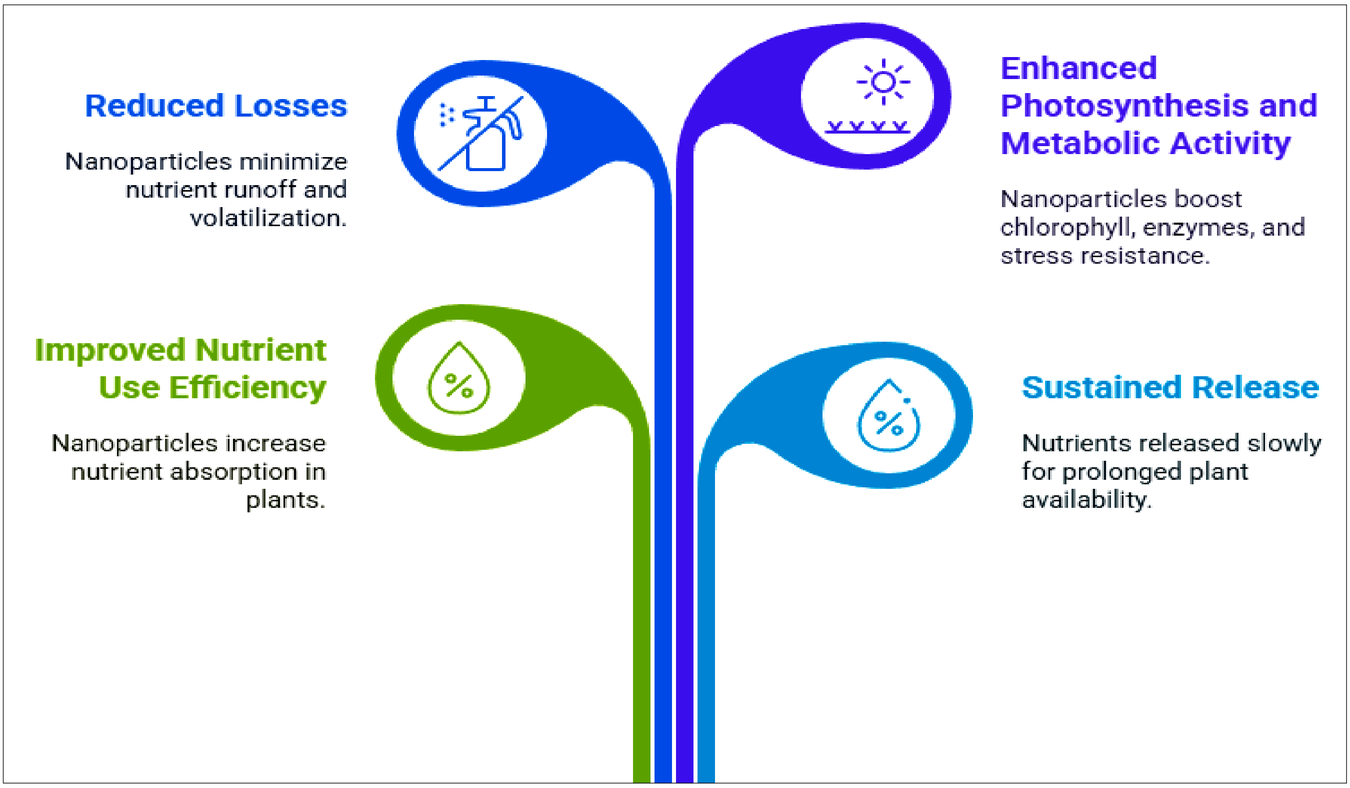

Fig. 4. Impact of Nano fertilizers (NFs) on crops.

availability over the entire growing cycle. This is an important mitigation measure as it prevents loss of nitrogen through the process of denitrification, volatilization, leaching and fixation in the soil particularly into nitrate (NO_3^-) and nitrite (NO_2^-) forms of nitrogen (29). Recent investigations indicate that applying foliar sprays of nano NPK and comparable nano fertilizers can significantly boost growth and yield in maize. The implementation of nano-based nutrients such as nano urea has demonstrated benefits, including enhanced plant height, improved grain yields and better nutrient absorption particularly when administered at critical growth phases (45, 46).

Chlorophyll content

Chlorophyll content in leaves (measured in SPAD units) was assessed using a portable SPAD-502 chlorophyll meter (Konica Minolta, Japan) which provides a rapid and accurate estimation of leaf chlorophyll levels in real-time field conditions (47).

Plant height

Plant height (in meters) was recorded using a tape measure, extending from the soil surface to the tallest part of the plant at the time of full flowering. This technique offers a simple and effective way to accurately measure plant height in field settings (48).

Biological yield

Biological yield (ton ha^{-1}) was assessed by measuring the weight of the harvested plant material from a designated square meter in each experimental unit after air-drying until a consistent weight was reached. This weight was then converted to tons per hectare, accounting for a moisture content of 14 % (49, 50).

Grain yield

Grain yield (ton ha^{-1}) was calculated by weighing the harvested ears from plants within a specified square meter of each experimental unit. After separating the grains from the cobs, the weight was converted to tons per hectare, considering a moisture content of 14 % (51).

Future challenges and limitations of nano fertilizer application

Current investigations highlight the possible health hazards linked to nanotechnology in agriculture, especially concerning the build-up of nanoparticles in consumable crops. Research shows that nanoparticles such as zinc oxide and iron oxide can accumulate in food items, potentially diminishing food quality and posing notable risks to human health (52). These particles may enter the human system via different exposure methods, including inhalation, resulting in severe health consequences akin to those seen with asbestos (53). While the effects of nanoparticles on human skin are still being investigated, recent studies indicate that various nano materials can penetrate skin layers and elicit biological responses. For example, research has demonstrated that quantum dots can penetrate the skin barrier, with higher levels of penetration observed under UV exposure conditions (54). The potential for nanoparticles to induce inflammatory responses in skin cells highlights the need for further safety assessments in dermatological appli-cations (55). Inhalation of nanoparticles has been found to impair blood vessel function, with recent research demonstrating that exposure to titanium dioxide nanoparticles can cause vascular dysfunction in animal studies (56). Nano particles have been associated with increased blood clotting, suggesting their possible involvement in thrombus development (57). Further investigation is essential to fully comprehend the effects of nanomaterials on the human circulatory system and various organs. Recent findings emphasize the necessity for more data regarding how nanomaterials interact with blood vessels and organs, particularly given their potential to penetrate cells and influence metabolic processes or fetal development. Organs with high blood flow such as the brain, may be especially vulnerable to these effects (58, 55). In the context of sustainable agriculture, recent advancements have demonstrated the effective application of certain nano fertilizers to enhance crop productivity. However, the intentional implementation of this technology in agricultural practices may lead to various unintended and potentially irreversible consequences (59). In this scenario, new environmental and unintended health safety issues can limit the use of this technology in horticultural crops' productivity. Nano-material phytotoxicity is also an issue in this regard since different plants respond differently to various nano-materials in a dose-dependent manner (54). Hence, it is crucial to consider not only the advantages of nano fertilizers, but also their limitations before market implementation (60). Importantly, nanomaterials are very reactive because of their minute size with enhanced surface area (61). Reactivity and variability of these materials are also a concern. This raises safety concerns for farm workers who may become exposed to xenobiotics during their application (62). This includes not only those involved in the manufacturing of nano fertilizer but also those exposed during their application in the field. Considering the anticipated benefits, there is consequently a need to explore the feasibility and suitability of these new smart fertilizers. Indeed, a considerable concern about their transport, toxicity and bioavailability as well as unintended environmental impacts upon exposure to biological systems, limit their acceptance to adoption in sustainable agriculture and the horticulture sectors (63).

Conclusion

The discussion highlighted various aspects of nano fertilization, including its importance in crop production, mode of action, comparison with traditional fertilizers, effects on growth and yield components of various crops and its impact on agronomic use efficiency. Nano fertilizers have emerged as a promising tool in modern agriculture, offering targeted and efficient delivery of nutrients to crops. Their nanoscale formulations enable precise control over nutrient release, ensuring optimal uptake and utilization by plants. Compared to traditional fertilizers, nano fertilizers exhibit enhanced efficacy in promoting crop growth and development. They contribute to enhancing growth components of various crop plants including root development, leaf area, photosynthetic activity and overall growth rates. Furthermore, nano fertilizers enhance agronomic use efficiency by improving nutrient uptake and reducing environmental pollution associated with excessive fertilizer application.

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Authors' contributions

MAAR contributed to the conceptualization and writing of the original draft. MJ, MH, SS, TS and NV contributed to the conceptualization, supervision, validation and writing review and editing.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest to declare.

Ethical issues: None.

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