Zinc Oxide Nanoparticles as Novel Nanofertilizers: A Comprehensive Agricultural Perspective

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Abstract

Nano-biotechnology has emerged as a transformative platform for developing next-generation fertilizers capable of delivering nutrients to plants in a controlled, targeted, and highly efficient manner. Nanoparticle-engineered fertilizers provide several advantages over conventional formulations, including improved nutrient bioavailability, sustained and slow-release behaviour, enhanced uptake efficiency, and reduced nutrient losses to the environment. Zinc oxide nanoparticles (ZnO NPs) and their derivatives have gained significant attention as promising nano fertilizers due to their large surface area, controlled nutrient-release capabilities, and demonstrated physiological benefits to crops. The application of Zn ONPs as nanofertilizers can strengthen plant tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity thereby promoting crop resilience and yield stability. The evolving research landscape indicates that ZnO nanofertilizers can serve as highly effective alternatives to conventional zinc salts when formulated and applied with appropriate consideration for dose optimization, safety, and environmental stewardship. This review critically synthesizes recent advances in ZnO nano fertilizer research, encompassing their synthesis routes, physicochemical characteristics, mechanisms of uptake and translocation in plants, and agronomic efficacy across diverse cropping systems. Additionally, it examines their interactions within soil–plant systems, potential toxicity and environmental risks, and future directions for developing safe, sustainable, and nano-enabled agricultural practices.

Keywords: Zinc oxide nanoparticles, Nanofertilizers, Green synthesis, Plant bioavailability, Sustainable agriculture.

1. Introduction

Zinc (Zn) is an essential micronutrient required for enzyme activation, metabolic regulation, and protein synthesis in plants. Conventional Zn fertilizers such as zinc sulfate often exhibit low use efficiency due to leaching, adsorption to soil colloids, and poor mobility. Nanotechnology offers an opportunity to overcome these limitations by reformulating Zn into nanoscale fertilizers that improve absorption efficiency and crop response.[1][2] Zinc oxide nanoparticles (ZnO NPs) are among the most studied metal oxide nanofertilizers because of

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Published: 20/04/2024
DOI: https://doi.org/10.70558/IJST.2024.v1.i2.241014

their stability, catalytic activity, slow-release characteristics, and compatibility with diverse agricultural systems. Their derivatives including doped ZnO NPs, composite nanoparticles, surface-functionalized ZnO, and biopolymer-encapsulated ZnO systems show additional advantages such as reduced toxicity and enhanced nutrient delivery. [1][3][4]

Nanotechnology has been increasingly applied across diverse fields such as health and agriculture to meet growing global demands. Among various nanomaterials, zinc oxide nanoparticles (ZnO-NPs) have emerged as promising tools in modern agriculture, particularly in plant nutrition and crop management. With advances in nanotechnology-based production, ZnO-NPs are being developed and tested under controlled conditions, where they have begun to play significant roles as novel nanofertilizers. [1][3] Compared to conventional zinc fertilizers, ZnO-NPs offer multiple advantages, including enhanced crop productivity, improved nutrient uptake, and reduced reliance on chemical fertilizers. Their unique physicochemical properties such as high surface area, controlled release behavior, and superior bioavailability make them more efficient and environmentally sustainable. Moreover, ZnO-NPs enable applications involving eco-friendly, biocompatible, and relatively low-toxicity formulations, providing more effective solutions for micronutrient management.[4][5][6] This chapter discusses the key properties of ZnO-NPs, their applications in agriculture as nanofertilizers, their uptake and utilization pathways in plants, and their potential positive and negative impacts on plant growth parameters and yield attributes. This review paper sequentially provides an overview concerning the possible use of Zinc oxide nano-enabled fertilizers in various crops, their impact on the nutritional quality and stress tolerance of crops, a possible destination in the environment, and their potential effects on ecosystems. In this paper, the properties of ZnO-NPs, applications in agriculture as nano fertilizers, and positive and negative impacts on plant growth parameters and yield properties were discussed.

2. Zinc Oxide Nanoparticles: Properties and Synthesis,

Zinc oxide nanoparticles have emerged as one of the most widely used metal oxide nanomaterials due to their unique optical, catalytic, antimicrobial, and physicochemical properties. They are extensively applied in agriculture as nano fertilizer. The properties of ZnO-NPs such as particle size, morphology, crystallinity, and surface charge are strongly influenced by the method of synthesis. Therefore, identifying eco-friendly, cost-effective, and sustainable synthesis routes has become a major research focus. .[6][7]

2.1 Zinc Oxide Nanostructures: Properties

Zinc oxide nanoparticles exhibit a unique combination of physicochemical, optical, electrical, and biological properties that distinguish them from their bulk counterparts. Their nanoscale dimensions provide a significantly enhanced surface-to-volume ratio, which directly influences their reactivity, stability, and functional performance across various applications.[7][9]

ZnO nanoparticles typically crystallize in the hexagonal wurtzite structure, which is thermodynamically stable under ambient conditions. This crystal structure imparts high mechanical strength, anisotropic growth patterns, and robust thermochemical stability. The morphology of ZnO-NPs ranging from spherical and rod-shaped to flower-like or tetrapod structures further affects their surface activity and application-specific behavior. ZnO nanoparticles possess remarkable optical characteristics due to their wide direct bandgap (~3.37 eV) and high exciton binding energy (~60 meV). These features make them highly efficient in absorbing and emitting UV light. ZnO nanoparticles exhibit semiconducting behaviour with notable n-type conductivity, generally caused by intrinsic defects. [10][11][12]

The high surface area of ZnO nanoparticles results in increased surface reactivity and catalytic potential. Zinc oxide nanoparticles hold significant importance due to their wide range of applications, including gas sensors, chemical sensors, biosensors and drug-delivery systems. ZnO is an attractive material for short-wavelength optoelectronic applications because of its wide band gap (3.37 eV), high bond strength, and large exciton binding energy (60 meV) at room temperature. As a wide band gap semiconductor, ZnO is extensively employed in solid-state blue to ultraviolet (UV) optoelectronics, including the development of advanced laser devices. [1][14][15]

2.2 Green Synthesis of ZnO Nanoparticles (Eco-friendly Approach)

Green synthesis of ZnO-NPs uses biological materials to reduce, stabilize, and cap nanoparticles. These materials contain phytochemicals, enzymes, or metabolites that act as natural reducing and capping agents, replacing harmful chemicals commonly used in chemical synthesis. Major biological sources include plants, microorganisms, and biopolymers, each offering unique advantages in nanoparticle. [16][17]

Green synthesis of ZnO-NPs represents an eco-friendly and sustainable approach that utilizes biological resources such as plant extracts, bacteria, fungi, and algae as reducing and stabilizing agents. This method eliminates the need for hazardous chemicals and high-energy processes typically used in conventional synthesis, thereby minimizing environmental pollution and toxicity. Phytochemicals like flavonoids, phenolics, and proteins in plant extracts can effectively reduce zinc salts to ZnO nanoparticles while controlling their size, shape, and dispersion. Green-synthesized ZnO-NPs exhibit enhanced biocompatibility, higher surface reactivity, and potent antimicrobial, antioxidant, and photocatalytic properties, making them suitable for agricultural applications such as nano fertilizers, pest management, and soil health improvement, all while promoting sustainability and reducing ecological impact. Green synthesis of ZnO nanoparticles employs eco-friendly agents such as plant extracts, microbes, or algae to reduce and stabilize zinc ions, producing non-toxic and cost-effective nanoparticles without harsh chemicals. Natural phytochemicals, including phenols and flavonoids, act as reducing and capping agents, making this a sustainable alternative to conventional methods. The resulting ZnO nanoparticles exhibit excellent nutrient delivery, antimicrobial, and antioxidant properties, making them highly effective as nanofertilizers to enhance crop growth and soil health. [9][18][19]

3. Properties of Zinc Oxide Nanoparticles as Fertilizers

Zinc oxide nanoparticles (ZnO-NPs) possess several physicochemical and functional properties that make them highly effective as nano fertilizers in modern agriculture. Their nanoscale dimensions, enhanced solubility, and controlled-release behaviour allow them to deliver zinc more efficiently than conventional bulk fertilizers. [20][21][22]

3.1 Nanoscale Size and High Surface Area

ZnO-NPs exhibit extremely small particle sizes (1–100 nm) with a high surface-to-volume ratio. This property enables faster dissolution of zinc ions in the soil solution and enhances their interaction with plant root surfaces. As a result, plants can absorb zinc more readily, improving nutrient-use efficiency even at lower application rates. [23][24]

3.2 The physicochemical properties of ZnO nano-fertilizers

The physicochemical properties of ZnO nanoparticles play a decisive role in determining their efficiency and behaviour as nano-fertilizers. Their exceptionally high surface-to-volume ratio greatly enhances zinc dissolution, ensuring faster availability of micronutrients while minimizing losses. The controlled-release kinetics of ZnO-NPs further support sustained and prolonged nutrient availability, thereby improving uptake efficiency over conventional zinc sources. Additionally, variations in particle size and morphology whether spherical, rod-like, or flower-like significantly influence their mobility, root penetration, and internal translocation within plant tissues. Surface charge and chemical functionalization are equally critical, as they determine colloidal stability, aggregation tendencies, and interactions with soil components and plant cell walls. Beyond these, the intrinsic optoelectronic properties of ZnO nanoparticles contribute to reactive oxygen species (ROS) scavenging, thereby enhancing plant stress tolerance and overall physiological resilience under adverse environmental conditions. By enhancing the scavenging of reactive oxygen species (ROS), ZnO-NPs strengthen the plant's intrinsic defence mechanisms, thereby mitigating oxidative damage and improving tolerance to multiple abiotic stress factors, including drought, salinity, and extreme temperature fluctuations. [10][25][26][27]

3.3 ZnO Nano fertilizer: Effects on Plant Growth and Stress Tolerance

ZnO-NPs enhance plant growth by improving nutrient uptake, increasing zinc bioavailability in the soil, and promoting the synergistic absorption of essential nutrients such as nitrogen, phosphorus, and potassium. They stimulate key physiological processes, including chlorophyll synthesis, which boosts photosynthetic efficiency, and enhance enzymatic activities like dehydrogenase and peroxidase that support overall growth. Furthermore, ZnO-NPs promote root and shoot development by stimulating cell elongation and division, resulting in longer roots, greater biomass accumulation, and improved plant vigor. [12][28][29]

ZnO-NPs also stimulate photosynthesis by enhancing chlorophyll biosynthesis through activation of enzymes such as protochlorophyllide reductase, resulting in higher chlorophyll content, better light absorption, and improved energy conversion. In addition, they promote root and shoot development by activating auxin synthesis and other growth hormones, leading to longer roots, increased root surface area, higher shoot length, and greater biomass accumulation in crops like maize, rice, and tomato. Furthermore, ZnO-NPs improve enzymatic activities and metabolic regulation, enhancing the function of over 300 zinc-dependent enzymes, including superoxide dismutase (SOD) for ROS scavenging, catalase

(CAT) for oxidative stress mitigation, and alkaline phosphatase for phosphorus mobilization, collectively supporting stronger and healthier plant growth. [15][22][30]

ZnO-NPs enhance plant stress tolerance through multiple mechanisms. They mitigate abiotic stresses such as drought by improving water-use efficiency and maintaining osmotic balance, salinity by reducing ion toxicity and promoting ionic homeostasis, and extreme temperatures by enhancing membrane stability and preventing heat- or cold-induced damage. Additionally, ZnO-NPs strengthen the plant's antioxidant defence system by upregulating enzymes like superoxide dismutase, catalase, and peroxidase, which scavenge reactive oxygen species (ROS) and reduce oxidative damage. They also modulate the expression of stress-responsive genes, improving signaling pathways and enabling plants to adapt more effectively to adverse environmental conditions. [11][12][31]

Property	Description	Benefit in Agriculture
Nanoscale Size & High Surface Area	Particles sized 1–100 nm with large surface-to-volume ratio	Faster zinc absorption by roots; improved nutrient-use efficiency
Enhanced Solubility	Dissolves more readily than bulk ZnO	Sustained release of Zn^{2+} ions; reduces leaching and nutrient loss
High Bioavailability	Zn^{2+} ions are easily absorbed and translocated in plants	Supports key physiological processes (chlorophyll synthesis, enzyme activation)
Controlled Release	Slow and targeted nutrient delivery	Ensures zinc availability during critical growth stages; reduces over-fertilization
Improved Mobility in Plants	Nanoparticles move efficiently through xylem and phloem	Uniform distribution of zinc in leaves, stems, and grains
Growth & Stress Tolerance Enhancement	Boosts root growth, photosynthesis, and antioxidant activity	Enhances crop yield and resilience against drought, salinity, and heat stress
Eco-friendly & Sustainable	Can be synthesized via green methods; requires lower doses	Reduces environmental impact; compatible with sustainable agriculture
Antimicrobial Activity	Mild suppression of soil-borne pathogens	Promotes healthier roots and soil microflora balance

Table 1: Summarizing the properties of ZnO nanoparticles as nano fertilizers and their benefits. [7][10][20]

ZnO-NPs can modulate the expression of stress-responsive genes, enhancing plant tolerance to adverse conditions. For instance, under drought stress, ZnO-NPs upregulate genes such as

DREB, HSP, and LEA, which are involved in osmotic adjustment, protein protection, and cellular stabilization. Similarly, under salinity stress, ZnO-NPs promote the expression of the NHX1 gene, which regulates ion homeostasis by maintaining the Na^+/K^+ balance in cells. This regulation of stress-responsive genes contributes to improved physiological adaptation, growth maintenance, and survival of plants under challenging environmental conditions. [22][31][32]

4. ZnO-NPs Compatibility with Green and Sustainable Agriculture

ZnO-NPs have emerged as a promising tool for integrating modern nanotechnology with green and sustainable agricultural practices. Their nanoscale size, high surface area, and enhanced solubility allow for precise and efficient delivery of zinc, an essential micronutrient, directly to plants, thereby minimizing excessive fertilizer use and reducing environmental contamination. Compared to conventional zinc fertilizers, ZnO-NPs enable controlled and slow nutrient release, which aligns with the principles of sustainable agriculture by promoting resource efficiency and lowering chemical runoff into soil and water systems. Moreover, ZnO-NPs can be synthesized via eco-friendly "green" methods using plant extracts, microorganisms, or biopolymers, which avoids toxic chemicals and hazardous by-products, further supporting environmentally responsible practices. Their compatibility with organic amendments, biofertilizers, and other natural inputs enhances soil fertility and microbial diversity, fostering a holistic approach to crop nutrition. By boosting nutrient uptake, enhancing stress tolerance, and increasing crop productivity with minimal ecological footprint, ZnO-NPs present a synergistic strategy that harmonizes advanced nanotechnology with the goals of green and sustainable agriculture. [33][34]

5. ZnO-NPs Future Prospects and Research Directions

ZnO-NPs hold significant promise for advancing sustainable agriculture and crop productivity, owing to their unique physicochemical properties, high bioavailability, and multifunctional roles in enhancing plant growth, nutrient uptake, and stress tolerance. Future research is likely to focus on developing environmentally safe and cost-effective synthesis methods, optimizing particle size, shape, and surface functionalization for targeted delivery, and elucidating detailed mechanisms of uptake, translocation, and molecular interactions within plants. Additionally, integrating ZnO-NPs with other nanomaterials or bio-stimulants could further enhance nutrient-use efficiency and resilience to abiotic stresses. Addressing potential ecotoxicological impacts, soil–plant–microbe interactions, and long-term field-level performance will be critical to translating laboratory findings into practical, scalable applications, paving the way for precision nano fertilization strategies and sustainable crop management. [30][34][35]

6. Conclusion

Zinc oxide nanoparticles represent a transformative approach in modern agriculture, combining nanoscale properties with essential micronutrient functionality to enhance plant growth, nutrient use efficiency, and stress tolerance. Zinc oxide nanoparticles represent a rapidly evolving and highly promising class of nanofertilizers that address the limitations of traditional zinc fertilizers. Their unique physicochemical properties, improved nutrient-use efficiency, and potential for crop biofortification make them attractive for sustainable agriculture. Continued research on their environmental safety, long-term effects, and optimized formulations will be essential for their wider adoption. Future research on zinc oxide nanoparticles in agriculture will likely focus on developing multi-nutrient nano fertilizers combining ZnO and advancing sensor-driven precision delivery systems, and conducting long-term field studies to assess soil health, crop productivity, and food safety. Establishing regulatory frameworks and scaling up green, cost-effective synthesis methods will be essential for safe, sustainable, and widespread adoption.

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