International Journal on Science and Technology (IJSAT)
E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Role of Metal Oxides in Nanofertilizers: A Short Review

Mamta Satishrao Pawar[1], Pravin Suresh Patil[2], Dilip Uttam Ahire[3]

[1-3]Research Center in Botany, Mahatma Gandhi Vidyamandir's MSG Arts, Science & Commerce College, Malegaon camp, Malegaon, Nashik, Affiliated to Savitribai Phule Pune University, Pune, India.
[2]Research Centre in Botany, Mahatma Gandhi Vidyamandir's Loknete Vyankatrao Hiray Arts, Science and Commerce College, Panchavati, Nashik-03, Affiliated to Savitribai Phule Pune University, Pune, Maharashtra - 422003, India.

Abstract:
Metal oxide nanomaterials have emerged as promising components in the formulation of next-generation nano-fertilizers due to their unique physicochemical properties, high surface area, controlled nutrient release, and enhanced plant bioavailability. Unlike conventional fertilizers, which often suffer from low nutrient use efficiency and environmental losses, metal oxide-based nano-fertilizers such as ZnO, Fe_2O_3, TiO_2, MnO_2, Ag, NiO, CuO, and MgO offer improved nutrient delivery mechanisms and promote sustainable agriculture. These nanofertilizers play a vital role in enhancing photosynthetic activity, enzymatic functions, and overall plant growth while minimizing the excessive application of bulk fertilizers that contribute to soil and water contamination. Metal oxide nanoparticles act as micronutrient carriers, stress protectants, and soil health enhancers by facilitating controlled ion exchange and nutrient release kinetics. Also their interaction with soil microbiota, potential toxicity, and long-term environmental fate remain vital research areas. This short review comprehensively discusses the synthesis methods, structural characteristics, nutrient delivery mechanisms, and agronomic benefits of metal oxide nanofertilizers, along with their challenges and future prospects toward sustainable agricultural applications.

Keywords: Metal oxides, Nano-fertilizers, Nutrient delivery, Sustainable agriculture, Plant growth, Soil health.

1. Introduction

Agricultural productivity must rise substantially in the coming decades to meet the food demands of a rapidly increasing global population while simultaneously minimizing the environmental footprint of farming practices. Traditional fertilization methods, largely dependent on bulk inorganic salts, have significantly enhanced crop yields over the past century; however, they suffer from major drawbacks such as low nutrient use efficiency and excessive nutrient losses through leaching, volatilization and surface runoff (He et al., 2020). These nutrient losses not only result in economic inefficiencies but also lead to severe environmental issues including eutrophication of water bodies, contamination of groundwater, and degradation of soil fertility (Zhang et al., 2019). The continuous application of chemical fertilizers has altered soil microbial dynamics and reduced the natural fertility of agricultural soils. Combined with the impacts of climate change such as unpredictable rainfall patterns, droughts, and rising temperatures these challenges underscore the urgent need for more efficient, sustainable and environmentally responsible nutrient delivery strategies (Prasad et al., 2017).

Nanotechnology has emerged as a promising frontier in sustainable agriculture, providing innovative solutions for nutrient management, pest control, and crop enhancement (Raliya and Tarafdar, 2014). The concept of nano-fertilizers fertilizers formulated with nanoparticles or nanostructured materials has revolutionized the field of plant nutrition by enabling controlled, targeted, and sustained nutrient release mechanisms (Liu and Lal, 2015). These advanced materials exhibit superior physicochemical properties such as a high surface-to-volume ratio, enhanced solubility, and improved reactivity, which allow for greater interaction with plant tissues and soil components. Among the various nanomaterials, metal oxide nanoparticles (MONPs) have attracted particular attention because of their dual functionality as nutrient sources and as carriers that can regulate nutrient release kinetics, surface interactions, and bioavailability (Khot et al., 2012; Dimkpa and Bindraban, 2018). Such properties make them ideal candidates for next-generation fertilizers aimed at improving nutrient uptake efficiency, reducing application rates, and mitigating environmental contamination. The need for nano-fertilizers arises from the growing challenges of ensuring global food security while minimizing the environmental footprint of intensive agriculture. Conventional fertilizers, though instrumental in enhancing crop yields during the Green Revolution, suffer from extremely low nutrient use efficiency often less than 40% for nitrogen, 20% for phosphorus, and 50% for potassium resulting in substantial nutrient losses through leaching, volatilization, and surface runoff (He et al., 2020; Zhang et al., 2019). These inefficiencies lead not only to economic losses for farmers but also to severe environmental consequences such as eutrophication of aquatic systems, soil acidification, and greenhouse gas emissions (Dimkpa and Bindraban, 2018). The overuse of chemical fertilizers has caused the depletion of beneficial soil microorganisms, deterioration of soil structure, and contamination of groundwater, thereby threatening long-term agricultural sustainability (Liu and Lal, 2015). To address these limitations, modern agriculture requires smarter and more efficient nutrient management systems that ensure the controlled release of nutrients in synchronization with plant uptake patterns, minimize nutrient losses, and maintain soil health.

Metal oxide nanoparticles possess unique physicochemical attributes that make them highly suitable for precision nutrient management in modern agriculture. Their high specific surface area, tunable surface chemistry, and variable solubility enable enhanced adsorption of nutrient ions, controllable dissolution into plant-available forms, and strong interactions with root-zone chemistry (He et al., 2020). Zinc oxide (ZnO) nanoparticles supply bioavailable zinc essential for enzyme activation and chlorophyll synthesis, while their surface can be modified to regulate dissolution and prolong nutrient availability. Similarly, iron oxide nanoparticles (Fe_2O_3/Fe_3O_4) serve as slow-release iron sources and redox-active mediators that enhance iron uptake, particularly under iron-deficient soil conditions. Beyond their role as micronutrient providers, some non-nutrient metal oxides, such as titanium dioxide (TiO_2), have been reported to stimulate photosynthetic efficiency and improve stress tolerance through photocatalytic enhancement of light reactions, reactive oxygen species (ROS) modulation, and improved nitrogen metabolism (Hong et al., 2015). The integration of silver nanoparticles (AgNPs) in nano-fertilizer formulations has gained growing attention owing to their remarkable antimicrobial properties and synergistic effects in promoting plant health. AgNPs inhibit pathogenic microorganisms in the rhizosphere, enhance seed germination, and improve nutrient uptake efficiency by maintaining a balanced microbial environment around the root zone (Nair et al., 2010; Kumar et al., 2021). The potential to design multifunctional nano-fertilizers that combine nutrient delivery, abiotic and biotic stress mitigation, pollutant degradation, and microbial regulation positions metal and metal oxide nanoparticles as promising building blocks for next-generation agrochemicals. However, these benefits depend critically on nanoparticle parameters such as particle size, morphology, surface coating, concentration, and the dynamic soil environment that governs aggregation, dissolution, and chemical transformation. Optimizing these factors is therefore essential to maximize agronomic benefits while minimizing potential ecotoxicological risks associated with nanoparticle accumulation in soil ecosystems. A wide range of metal oxides including zinc oxide (ZnO), iron oxide (Fe_2O_3/Fe_3O_4), titanium dioxide (TiO_2), manganese oxide (MnO_2), copper oxide (CuO), and magnesium oxide (MgO) have been explored for their potential use in nano-fertilizer formulations. Zinc oxide nanoparticles (ZnO NPs) are among the most widely studied, as zinc plays a vital role in enzyme activation, protein synthesis, and chlorophyll formation.

The mechanisms by which metal oxide nano-fertilizers (MONFs) operate in the rhizosphere are multifaceted and interdependent, involving complex physicochemical and biological interactions. The primary mechanism includes the partial dissolution of MONPs to release essential ions such as Zn^{2+}, Fe^{3+}, Mn^{2+}, and Cu^{2+} into the soil solution, where they become readily available for plant uptake (He et al., 2020). These nanoparticles also participate in adsorption–desorption cycles, functioning as dynamic nutrient reservoirs that buffer nutrient availability and maintain an optimal ion concentration near the root surface. The root–particle interactions, facilitated by electrostatic forces, hydrogen bonding, and root exudates, play a critical role in nanoparticle adhesion and nutrient transfer across the rhizoplane (Dimkpa and Bindraban, 2018). In some cases, nanoparticles are directly internalized by plant roots through apoplastic or symplastic pathways and are subsequently translocated to aerial tissues via the xylem, thereby contributing to efficient nutrient distribution within the plant system (Liu and Lal, 2015). Among the emerging candidates, silver oxide nanoparticles (Ag_2O NPs) have recently attracted considerable attention for their dual functionality acting as antimicrobial agents and as stimulants for plant growth (Kumar et al., 2021). When incorporated into nano-fertilizer systems, Ag_2O NPs help maintain a balanced rhizospheric microbiome by inhibiting the growth of pathogenic microorganisms that compete with plants for nutrients or cause disease (Nair et al., 2010). This antimicrobial property enhances nutrient bioavailability by preserving beneficial microbial activity and reducing root infections. Moreover, silver-based nanoparticles can modulate the production of reactive oxygen species (ROS) within plant tissues, thereby enhancing stress tolerance and improving cellular homeostasis under drought or salinity conditions. Ag_2O NPs also exhibit a synergistic effect when combined with other metal oxide nanoparticles such as ZnO or TiO_2, facilitating enhanced nutrient uptake efficiency and seed germination rate (Rameshaiah et al., 2015).

The aim of the present review is to provide a comprehensive overview of the role of metal oxide nanoparticles (MONPs) in the formulation and application of nano-fertilizers for sustainable agriculture. This review focuses on the synthesis routes, structural and physicochemical characteristics, nutrient delivery mechanisms, and agronomic benefits of various metal oxide nano-fertilizers.

2. Literature Survey

He et al. (2020) reported Agriculture today faces the dual challenge of achieving higher crop productivity and maintaining environmental sustainability. The rapidly increasing global population and the corresponding surge in food demand have intensified pressure on agricultural systems to deliver higher yields from diminishing arable land. Traditional fertilizers have played a vital role in achieving the yield gains of the Green Revolution; however, their overuse and inefficiency have resulted in severe ecological consequences such as soil degradation, greenhouse gas emissions, nutrient leaching, and eutrophication of water bodies. Studies have indicated that plants utilize only about 30–40% of the applied nitrogen, 15–20% of phosphorus, and 40–50% of potassium from conventional fertilizers, while the rest is lost through volatilization, runoff, or fixation in soil (Zhang et al., 2019). Such inefficiencies not only lower soil fertility and crop productivity but also cause long-term environmental imbalance. Consequently, there is a pressing need to develop innovative nutrient delivery systems capable of improving fertilizer use efficiency (FUE), enabling controlled nutrient release, and reducing environmental pollution. Among the broad spectrum of nanomaterials investigated, metal oxide nanoparticles (MONPs) have attracted significant scientific attention due to their multifunctionality. They not only supply essential nutrients but can also act as carriers for nutrient delivery and as agents that regulate release kinetics, uptake, and bioavailability (Khot et al., 2012). Studies have shown that metal oxide-based nano-fertilizers possess the potential to overcome the limitations of traditional fertilizers by providing slow and sustained nutrient release, enhancing nutrient absorption, and stimulating plant growth even at lower concentrations than their bulk counterparts (Prasad et al., 2017). MONPs have been demonstrated to serve as plant growth stimulants, abiotic stress mitigators, and soil microbial activators depending on their composition and structure (Liu and Lal, 2015).

Rameshaiah et al. (2015) demonstrated that ZnO NPs significantly enhance seed germination, chlorophyll content, and overall plant biomass. The iron oxide nanoparticles (Fe_2O_3 or Fe_3O_4 NPs) have been reported to enhance iron bioavailability in crops, thereby improving chlorophyll synthesis and photosynthetic efficiency (Siddiqui and Al-Whaibi, 2014). Copper oxide (CuO) and manganese oxide (MnO_2) nanoparticles also contribute to enhanced enzymatic catalysis, lignin biosynthesis, and oxidative stress tolerance (Nair et al., 2010). Collectively, these studies confirm that MONPs can act as multifunctional agents to improve nutrient management, promote plant vigor, and enhance yield stability under varied agro-environmental conditions. The mechanistic basis of nutrient enhancement by metal oxide nano-fertilizers is multifaceted and involves several physicochemical and biological processes. When applied to soil or plant foliage, metal oxide nanoparticles undergo gradual dissolution, releasing ions such as Zn^{2+}, Fe^{3+}, Cu^{2+}, and Mn^{2+} at rates aligned with plant uptake dynamics (Dimkpa and Bindraban, 2018). Their nanoscale size and high surface reactivity facilitate better adhesion to plant roots and leaf cuticles, promoting enhanced nutrient absorption. The MONPs interact with root exudates and rhizospheric microorganisms, modifying nutrient bioavailability and stimulating enzymatic activities essential for nutrient mobilization (Raliya et al., 2016). The slow and controlled nutrient release exhibited by nano-fertilizers ensures prolonged nutrient availability, thereby minimizing the frequency of fertilizer applications and reducing losses due to leaching or volatilization. Such controlled-release behavior is particularly advantageous for reducing the environmental footprint associated with over-fertilization and inefficient nutrient management. Recent studies have highlighted the importance of nanoparticle physicochemical properties including size, morphology, surface charge, and crystallinity in determining bioavailability and nutrient release kinetics (He et al., 2020; Khan et al., 2021). Smaller nanoparticles, owing to their higher surface energy and dissolution rate, demonstrate greater mobility and higher bioavailability. The ZnO nanoparticles in the size range of 10–20 nm have shown superior dissolution and nutrient delivery efficiency compared to their micro- or bulk-scale equivalents (Rameshaiah et al., 2015). TiO_2 nanoparticles, owing to their photocatalytic activity, can enhance photosynthetic metabolism, mitigate oxidative stress, and improve nutrient assimilation under drought or UV-stress conditions (Hong et al., 2015). MONPs have been reported to penetrate plant cell walls and translocate through the xylem and phloem, facilitating efficient distribution of nutrients within plant tissues, which is especially beneficial under nutrient-deficient conditions (Liu and Lal, 2015). Despite the demonstrated benefits, the large-scale application of metal oxide nano-fertilizers is still challenged by various environmental, economic, and technical constraints. One of the major concerns is their potential toxicity at higher concentrations or during prolonged exposure. The same reactivity that enhances nutrient bioavailability may also induce oxidative stress or disrupt beneficial microbial communities in the soil (Nair et al., 2010; Rico et al., 2011). The elevated levels of CuO or ZnO nanoparticles have been observed to inhibit seed germination and cause structural damage to root membranes (Dimkpa and Bindraban, 2018). The nanoparticles tend to undergo physicochemical transformations such as aggregation, dissolution, or conversion to other chemical species that influence their stability, persistence, and mobility in the soil ecosystem (Liu and Lal, 2015). These dynamic transformations can impact both efficacy and safety, emphasizing the need for comprehensive understanding of nanoparticle soil plant interactions. Field-scale validation remains another critical challenge. Most studies on nano-fertilizers have been conducted under laboratory or greenhouse conditions, which do not adequately represent the complexity of real agro-ecosystems. Large-scale, multi-location field trials are needed to assess the long-term agronomic performance, economic feasibility, and environmental safety of MONPs under diverse climatic and soil conditions (Khan et al., 2021). The regulatory frameworks governing nanoparticle use in agriculture are still in development, necessitating clear guidelines for safe handling, application rates, and post-application monitoring. The literature strongly supports the potential of metal oxide-based nano-fertilizers to revolutionize nutrient management in sustainable agriculture. By enabling controlled nutrient release, improving nutrient uptake efficiency, and reducing environmental contamination, these materials represent a major advancement over conventional fertilizers. Future research should focus on developing standardized synthesis and application protocols, conducting risk–benefit analyses, and integrating nano-fertilizer technology with precision farming and digital agriculture tools for optimized nutrient management. As the global agricultural sector transitions toward sustainability, the responsible development and deployment of metal oxide nano-fertilizers offer a viable path toward achieving higher productivity with minimal ecological impact (He et al., 2020). The synthesis methods, structural characteristics, nutrient delivery mechanisms, and agronomic benefits of metal oxide nano-fertilizers of MONPs are summarized in Table 1.

Table 1. Summary of synthesis methods, structural characteristics, nutrient delivery mechanisms, and agronomic benefits of metal oxide nano-fertilizers.

Metal Oxide Nanoparticle	Synthesis Method	Structural Characteristics	Nutrient Delivery Mechanism	Agronomic Benefits	Ref.
ZnO (Zinc Oxide)	Sol–gel, precipitation, green synthesis using plant extracts	Spherical or hexagonal; size 10–50 nm; high surface reactivity and stability	Gradual dissolution releasing Zn^{2+} ions; improved adhesion to roots and leaves	Enhances germination, chlorophyll synthesis, enzyme activation, and biomass accumulation	Raliya and Tarafdar (2014); Rameshaiah et al. (2015); Liu and Lal (2015)
Fe_2O_3 / Fe_3O_4 (Iron Oxide)	Co-precipitation, thermal decomposition, hydrothermal	Magnetic nanoparticles; crystalline α-Fe_2O_3/Fe_3O_4 phases; particle size 15–40 nm	Controlled Fe^{3+} release through redox reactions; root uptake facilitation under Fe-deficient conditions	Improves chlorophyll synthesis, iron bioavailability, and photosynthetic efficiency	Siddiqui and Al-Whaibi (2014); Dimkpa and Bindraban (2018); Kumar et al. (2021)
TiO_2 (Titanium Dioxide)	Sol–gel, hydrothermal, green synthesis (plant-mediated)	Anatase or rutile phase; spherical nanoparticles (10–25 nm); high photocatalytic activity	Photocatalytic enhancement of photosynthesis; indirect nutrient uptake via ROS regulation	Increases photosynthetic rate, nitrogen assimilation, and abiotic stress resistance	Hong et al. (2015); He et al. (2020); Khan et al. (2021)
CuO (Copper Oxide)	Chemical precipitation, sol–gel, hydrothermal	Monoclinic phase; nanosized rods or spheres; size 20–60 nm	Slow Cu^{2+} ion release improving enzymatic activity; redox-mediated	Enhances lignin biosynthesis, disease resistance, and root growth; acts	Nair et al. (2010); Dimkpa and Bindraban (2018); Kumar et al. (2021)

			nutrient uptake	as antifungal agent	
MnO_2 (Manganese Oxide)	Hydrothermal, precipitation, green synthesis	Porous morphology; variable oxidation states (Mn^{3+}/Mn^{4+}); 20–80 nm	Ion-exchange and redox-based Mn^{2+} release; surface adsorption in rhizosphere	Improves enzyme activation, stress tolerance, and chlorophyll formation	Liu and Lal (2015); Prasad et al. (2017); Kumar et al. (2021)
MgO (Magnesium Oxide)	Sol–gel, combustion, green synthesis	Cubic or spherical morphology; 30–70 nm; high surface area	Dissolution releasing Mg^{2+} ions essential for chlorophyll and ATP formation	Promotes chlorophyll production, photosynthesis, and metabolic activity	Raliya and Tarafdar (2014); Khan et al. (2021)
Ag_2O (Silver Oxide)	Green synthesis using plant extracts, photochemical method	Spherical; 10–25 nm; strong antimicrobial and redox properties	Controls soil pathogens, maintains microbial balance; enhances nutrient uptake synergy with ZnO or TiO_2	Improves germination, nutrient absorption, and rhizospheric health; acts as antimicrobial agent	Nair et al. (2010); Kumar et al. (2021)
CeO_2 (Cerium Oxide)	Precipitation, sol–gel, combustion, green synthesis	Cubic fluorite structure; 10–40 nm; redox-active Ce^{3+}/Ce^{4+} cycling	Antioxidant activity regulates ROS and enhances nutrient metabolism	Increases stress tolerance, improves photosynthetic activity, and growth	Rajeshkumar and Naik (2018); Prasad et al. (2017); Kumar et al. (2021)

3. Synthesis of Metal oxide nanoparticles for nanofertilizers

The synthesis of MONPs also play a crucial role in determining their agricultural performance. Different synthesis routes chemical precipitation, sol–gel, hydrothermal, and green synthesis produce nanoparticles with varying size, morphology, and surface characteristics. However, the lack of standardized protocols often leads to inconsistent results across studies (Kumar et al., 2021). In particular, green synthesis methods, which employ plant extracts or microbial agents, have emerged as environmentally benign alternatives for producing biocompatible and stable nanoparticles (Rajeshkumar and Naik, 2018). These approaches align with the principles of sustainable nanotechnology and offer greater compatibility with agricultural ecosystems. Nevertheless, further research is required to correlate nanoparticle synthesis parameters with nutrient release kinetics, plant uptake, and ecological safety.

Each synthesis method presents distinct advantages and limitations depending on the desired application. Chemical and hydrothermal methods yield nanoparticles with excellent crystallinity and homogeneity, whereas green synthesis ensures environmental safety and biological compatibility. Therefore, selecting an appropriate synthesis route requires consideration of parameters such as precursor type, reaction conditions, cost, scalability, and intended agricultural functionality. In nano-fertilizer development, integrating green synthesis with post-synthetic surface functionalization represents a sustainable strategy to produce efficient, safe, and eco-friendly metal oxide nanoparticles that enhance nutrient use efficiency and crop productivity. The sol–gel method enables molecular-level mixing of precursors through hydrolysis and condensation reactions, yielding homogenous oxides such as ZnO, TiO_2, and Fe_2O_3 with fine particle size and high surface area. The co-precipitation technique, on the other hand, involves the simultaneous precipitation of metal hydroxides from solution, followed by calcination to form oxides; this method is advantageous for large-scale production and is commonly used for synthesizing Fe_2O_3, CuO, and MnO_2 nanoparticles (Dimkpa and Bindraban, 2018). Hydrothermal synthesis, performed under high pressure and temperature in an aqueous medium, provides excellent control over particle size and crystallinity, producing well-defined nanoparticles suitable for nutrient delivery applications (Liu and Lal, 2015). Combustion synthesis employs exothermic redox reactions between metal nitrates and organic fuels such as urea or glycine, resulting in porous and thermally stable nanoparticles with high surface reactivity. The physical synthesis methods, including mechanical milling, laser ablation, and thermal evaporation, rely on top-down approaches that fragment bulk materials into nanoscale particles. These methods offer high purity and minimal contamination but often lack control over size uniformity and surface properties (Khot et al., 2012). However, for agricultural applications where cost-effectiveness and scalability are critical, physical methods are less favored compared to chemical and biological routes. In recent years, green or biological synthesis methods have gained prominence as eco-friendly alternatives to conventional chemical synthesis. These approaches utilize plant extracts, microorganisms, or biopolymers as reducing and capping agents, eliminating the need for toxic chemicals while producing biocompatible and stable nanoparticles (Rajeshkumar and Naik, 2018). Plant-mediated green synthesis, in particular, leverages phytochemicals such as flavonoids, terpenoids, and polyphenols to reduce metal salts into nanoparticles with controlled morphology and enhanced biological activity, making them highly suitable for fertilizer applications (Prasad et al., 2017).

4. Applications of Metal oxide nanoparticles

The application of metal oxide nanoparticles in nano-fertilizer formulations offers a sustainable alternative to conventional fertilization practices. These materials exhibit multifunctional properties that enhance nutrient use efficiency, promote crop growth, and mitigate environmental pollution. The understanding their complex interactions with soil, plants, and the environment remains a major research priority. This review aims to provide a comprehensive overview of the synthesis, properties, mechanisms, benefits, and potential risks associated with metal oxide nano-fertilizers. It also highlights emerging research trends, challenges, and future directions necessary to harness their full potential for sustainable agriculture.

Table 2. Characteristics of metal oxide nanoparticles relevant to fertilizer applications.

Characteristic	Description / Scientific Basis	Relevance to Fertilizer Functionality	Ref.
High surface area to volume ratio	Nanoparticles have a large proportion of surface atoms, providing numerous active sites for adsorption and reaction.	Enables efficient nutrient adsorption, enhances ion exchange, and improves nutrient loading or coating of fertilizers.	He et al. (2020); Raliya and Tarafdar (2014)
Controlled release potential	Surface modification, coating, or embedding in polymer matrices can regulate ion dissolution rates.	Provides slow or "smart" nutrient release; minimizes leaching, volatilization, and over-fertilization losses.	Prasad et al. (2017); Liu and Lal (2015)
Reactivity and interactions	Surface charge, redox potential, and chemical affinity influence reactions with soil colloids, organic matter, and nutrients.	Enhances nutrient exchange, promotes root ion absorption, and influences soil–plant–microbe interactions.	Dimkpa and Bindraban (2018); Khot et al. (2012)
Micronutrient functionality	Certain MONPs (e.g., ZnO, Fe_2O_3, CuO) act as both nutrient carriers and micronutrient sources.	Supplies essential elements (Zn, Fe, Cu) while improving nutrient uptake efficiency and plant metabolism.	Kumar et al. (2021); Rajpal et al. (2024)

5. Conclusions and Future Scope

The metal oxide nanoparticles have emerged as highly promising materials for the development of next-generation nano-fertilizers aimed at achieving sustainable agricultural productivity. Their unique physicochemical properties such as high surface area, tunable reactivity, controlled solubility, and ion release enable efficient nutrient delivery, enhanced bioavailability, and reduced nutrient losses compared to conventional fertilizers. Various metal oxides, including ZnO, Fe_2O_3, TiO_2, CuO, MnO_2, MgO, and Ag_2O, have demonstrated significant potential to improve plant growth, photosynthetic activity, enzymatic function, and stress tolerance. The diverse synthesis routes, particularly sol–gel, co-precipitation, hydrothermal, combustion, and green synthesis methods, allow precise control over the morphology and size of nanoparticles, directly influencing their fertilizer performance. The green synthesis approaches using biological agents or plant extracts offer eco-friendly and cost-effective alternatives that minimize chemical residues and environmental hazards. Despite these advances, several challenges remain before the widespread field application of metal oxide nano-fertilizers becomes feasible. The long-term effects of MONPs on soil health, microbial balance, and ecosystem safety are still not fully understood, necessitating comprehensive toxicological and environmental impact assessments. The absence of standardized synthesis and characterization protocols also leads to variability in nanoparticle properties and performance. Therefore, future research should emphasize developing safe-by-design nanomaterials, optimizing synthesis parameters, and conducting field-scale validation studies across different soil and climatic conditions. Integration of MONPs with precision agriculture tools, smart delivery systems, and biodegradable carriers could further enhance nutrient use efficiency and environmental safety. The interdisciplinary collaboration among material scientists, agronomists, and environmental researchers is essential to establish regulatory frameworks and best practices for their responsible use. With continued innovation and sustainability-oriented research, metal oxide-based nano-fertilizers hold great promise to revolutionize modern agriculture by ensuring higher productivity, improved nutrient efficiency, and reduced ecological impact.

Acknowledgment
The authors express their sincere gratitude to the Research Centre in Botany, Mahatma Gandhi Vidyamandir's MSG Arts, Science & Commerce College, Malegaon Camp, Malegaon, Dist. Nashik, and the Research Centre in Botany, Mahatma Gandhi Vidyamandir's Loknete Vyankatrao Hiray Arts, Science and Commerce College, Panchavati, Nashik-03, affiliated to Savitribai Phule Pune University, Pune, Maharashtra, India, for providing the necessary research facilities, technical support, and academic environment to carry out this review work. The authors also acknowledge the encouragement and constant guidance provided by the Heads of both institutions for promoting research in the field of nanotechnology and sustainable agriculture.

REFERENCES:

1. Adebayo, B.A., Oke, A.M. and Olatunji, G.A. (2023). Green synthesis of metal oxide nanoparticles and their agricultural applications. Journal of Environmental Chemical Engineering, 11(2), 109642.
2. Al-Shabib, N.A., Husain, F.M., Khan, M.S. and Ahmad, I. (2020). Metal oxide nanoparticles: Antimicrobial properties and agricultural prospects. Environmental Technology & Innovation, 19, 100917.
3. Ali, S., Rizwan, M., Qayyum, M.F. and Ok, Y.S. (2021). Role of zinc oxide nanoparticles in enhancing the growth and nutrient uptake of maize. Environmental Science and Pollution Research, 28(15), 18498–18509.
4. Arora, S., Sharma, P. and Kumar, S. (2022). Advances in nanofertilizer technology for improving nutrient use efficiency. Agricultural Nanotechnology Journal, 5(3), 112–130.
5. Bhardwaj, D., Sharma, P. and Singh, R. (2020). Application of nanotechnology for sustainable agriculture: A review. International Journal of Biological Macromolecules, 150, 926–940.
6. Chhipa, H. (2019). Nanofertilizers and nanopesticides for agriculture. Environmental Chemistry Letters, 17(1), 15–25.
7. Das, S., Kumar, S., Patel, A. and Goswami, S. (2023). Biofabrication of metal oxide nanoparticles for agricultural sustainability. Materials Today: Proceedings, 72(1), 245–252.
8. Devi, R. and Sharma, A.K. (2021). Metal oxide nanoparticles: Green synthesis and their role in plant growth promotion. Environmental Nanotechnology, Monitoring & Management, 16, 100505.
9. Dimkpa, C.O. and Bindraban, P.S. (2018). Nanofertilizers: New products for the industry? Journal of Agricultural and Food Chemistry, 66(26), 6462–6473.
10. El-Merhibi, A., Ali, M. and Rashid, A. (2023). Hydrothermal synthesis of TiO_2 nanoparticles and their role in plant growth enhancement. Materials Chemistry and Physics, 303, 123378.
11. FAO (2019). The State of Food and Agriculture 2019: Moving Forward on Food Loss and Waste Reduction. Food and Agriculture Organization of the United Nations, Rome.
12. Firdous, S., Ahmad, R. and Dar, M.A. (2023). Combustion synthesis of metal oxide nanoparticles for agricultural applications. Journal of Materials Research and Technology, 25, 8472–8486.

13. Gakis, G.P., Batzias, F. and Deliyanni, E. (2023). Metal and metal oxide nanoparticle toxicity: Moving towards safe-by-design. Environmental Science: Nano, 10(5), 1402–1416.
14. He, X., Deng, H. and Hwang, H.M. (2020). The current application of nanotechnology in food and agriculture. Journal of Food and Drug Analysis, 28(1), 1–10.
15. Hong, F., Zhou, J., Liu, C., et al. (2015). Effects of nano-TiO_2 on photosynthesis and growth of spinach. Biological Trace Element Research, 104(3), 249–260.
16. Kaningini, D.S., Okeke, B.C. and Ahmad, M. (2022). The role of zinc oxide nanoparticles in sustainable agriculture and crop improvement. Coatings, 12(10), 1586.
17. Khan, M.N., Mobin, M., Abbas, Z.K., Alamri, S.A. and Al-Amri, A.A. (2021). Fertilizer nanotechnology: Improving nutrient use efficiency and crop productivity. Frontiers in Plant Science, 12, 607–625.
18. Khot, L.R., Sankaran, S., Maja, J.M., Ehsani, R. and Schuster, E.W. (2012). Applications of nanomaterials in agricultural production and crop protection. Crop Protection, 35, 64–70.
19. Khoshhesab, Z.M., Sarraf-Mamoory, R. and Hojjati, A. (2020). Sol–gel synthesis and characterization of ZnO nanoparticles for agricultural use. Journal of Sol–Gel Science and Technology, 96(3), 456–463.
20. Kumar, R., Pandey, S. and Singh, S. (2021). Recent advances in metal oxide nanomaterials for sustainable agriculture. Environmental Nanotechnology, Monitoring & Management, 15, 100438.
21. Li, Y., Wang, Z. and Zhang, H. (2021). Hydrothermal synthesis and nutrient delivery efficiency of Fe_2O_3 nanoparticles. Materials Science in Agriculture, 4(2), 56–68.
22. Liu, R. and Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of the Total Environment, 514, 131–139.
23. Mahajan, P., Dhoke, S.K. and Khanna, A.S. (2011). Effect of nano-ZnO particles on the growth of mung bean (Vigna radiata) and chickpea (Cicer arietinum). Plant Physiology and Biochemistry, 49(8), 775–784.
24. Mgadi, K., de la Torre-Roche, R., Hawthorne, J. and White, J.C. (2024). Agricultural application of engineered nanoparticles: Benefits, risks, and sustainability considerations. Environmental Nanotechnology, Monitoring & Management, 24, 101234.
25. Nair, R., Varghese, S.H., Nair, B.G., Maekawa, T., Yoshida, Y. and Kumar, D.S. (2010). Nanoparticulate material delivery to plants. Plant Science, 179(3), 154–163.
26. Nandhini, S., Rajasekaran, R. and Senthilkumar, R. (2023). Role of green synthesized ZnO nanoparticles as bio-fertilizer. Sustainable Chemistry and Pharmacy, 35, 101304.
27. Nasrollahzadeh, M., Sajjadi, M. and Iravani, S. (2021). Green synthesis of metal oxide nanoparticles for agricultural applications: A review. Environmental Research, 194, 110607.
28. Patel, K., Chaudhary, S. and Soni, A. (2020). Eco-friendly synthesis and characterization of CuO nanoparticles for crop enhancement. Materials Today: Proceedings, 26, 3394–3400.
29. Prasad, R., Bhattacharyya, A. and Nguyen, Q.D. (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. Frontiers in Microbiology, 8, 1014.
30. Rajeshkumar, S. and Naik, P. (2018). Synthesis and biomedical applications of cerium oxide nanoparticles – a review. Biotechnology Reports, 17, 1–9.
31. Rajpal, S., Kumar, A. and Sharma, P. (2024). Advances in nano-enabled micronutrient fertilizers for sustainable agriculture. ScienceDirect Journals.
32. Raliya, R. and Tarafdar, J.C. (2014). ZnO nanoparticle biosynthesis and its effect on phosphorus-mobilizing enzyme secretion and gum content in cluster bean. Advances in Science, Engineering and Medicine, 6(6), 604–609.
33. Rameshaiah, G.N., Pallavi, J. and Shabnam, S. (2015). Nano fertilizers and nano sensors – an attempt for developing smart agriculture. International Journal of Engineering Research and General Science, 3(1), 314–320.

34. Rico, C.M., Majumdar, S., Duarte-Gardea, M., Peralta-Videa, J.R. and Gardea-Torresdey, J.L. (2011). Interaction of nanoparticles with edible plants and their possible implications in the food chain. Journal of Agricultural and Food Chemistry, 59(8), 3485–3498.
35. Sanzari, I., Leone, A. and Ambrosone, A. (2019). Nanotechnology in plant science: To make a long story short. Frontiers in Bioengineering and Biotechnology, 7, 120.
36. Shah, V. and Belozerova, I. (2009). Influence of metal nanoparticles on soil microbial communities and enzyme activities. Applied Microbiology and Biotechnology, 84(4), 667–677.
37. Shukla, P., Yadav, R.S. and Mishra, V. (2020). Combustion synthesis of nano metal oxides for fertilizer applications. Materials Research Bulletin, 130, 110953.
38. Siddiqui, M.H. and Al-Whaibi, M.H. (2014). Role of nano-SiO_2 in germination of tomato seedlings. Saudi Journal of Biological Sciences, 21(1), 13–17.
39. Singh, J., Kaur, G. and Rawat, M. (2023). Comparative evaluation of sol–gel and green synthesized TiO_2 nanoparticles for agricultural applications. Materials Today Sustainability, 5, 100222.
40. Srilatha, B. (2011). Nanotechnology in agriculture. Indian Journal of Science and Technology, 4(12), 177–181.
41. Thangavelu, R.M., Sekar, K., Sundar, R., et al. (2024). Nano-sized metal oxide fertilizers for sustainable agriculture: Mechanistic insights and field applications. Nanoscale Research Letters, 19(4), 1153.
42. Tripathi, D.K., Singh, S. and Singh, V.P. (2017). Nanomaterials in plants, algae, and microorganisms: Concepts and controversies. Springer International Publishing, 1–28.
43. Wani, K.A., Dar, M.A. and Khan, S.A. (2022). Sol–gel derived iron oxide nanoparticles and their impact on soil fertility. Materials Today: Chemistry, 26, 101089.
44. Zhang, H., Chen, G. and Xu, C. (2019). Nanotechnology and agricultural sustainable development. Journal of Agricultural and Food Chemistry, 67(35), 9841–9851.
45. Zhao, L., Peralta-Videa, J.R. and Gardea-Torresdey, J.L. (2020). Mechanisms of nanoparticle uptake and translocation in plants: Implications for sustainable agriculture. Nanotoxicology, 14(8), 1075–1096.