Review Article

Metallic Nano-oxides and their Attributes in Agricultural Traits and Sustainability for Future Food industries.

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Abstract
The continuous degradation of soil over time has led to reduced crop productivity and lower nutritional value, largely due to the excessive use of traditional fertilizers, which are not only expensive but also environmentally harmful and unsustainable. In recent years, nanoparticles have emerged as promising tools in agriculture, offering a sustainable approach to soil restoration. These nanoscale materials have shown potential as fertilizers because they are more easily absorbed and utilized by plants compared to their conventional, bulk forms. Despite this promise, there is still limited research detailing the role of nanoparticles in crop nutrition and protection. This review aims to shed light on the use of nanosized nutrients such as, iron, and titanium nano-oxide, as fertilizers and growth promoters. It also highlights the importance of adopting nanomaterials to reduce reliance on toxic agrochemicals, while discussing the wide-ranging advantages of nanoparticles, including enhanced plant growth and increased resistance to diseases.

Keywords: Nanoparticles, Environment, Agriculture, Food Industry

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Introduction

1. Nanoparticles and environment.

Nanotechnology is rapidly emerging across various fields, and the unique size-dependent properties of nanomaterials have opened the door to innovative applications. These nanoscale materials often behave very differently from their larger counterparts in the environment, leading to distinct environmental pathways and interactions. With their increasing use in consumer products, nanomaterials offer promising solutions to long-standing challenges. However, their widespread application also raises concerns about potential unforeseen environmental and health risks, especially in the area of nanotoxicity. (1) The situation is further complicated by the absence of comprehensive regulations governing the use of nanomaterials. Key environmental concerns include accidental releases, atmospheric deposition, deliberate environmental applications (such as in pesticides and soil remediation), the use of nanomaterial-containing soil additives (like manure and sludge), and contaminated irrigation water. (2)

Recent research has highlighted the potential advantages of using nanoparticles (NPs) in agriculture. Nanotechnology holds the promise to transform the agricultural sector by introducing advanced tools to improve crop productivity. This evolving field, known as agri-nanotechnology, focuses on optimizing the use of essential agricultural resources like water, nutrients, and agrochemicals through highly efficient nanoparticle-based products such as nanopesticides. Additionally, nanosensors have been developed not only to detect pests but also to monitor and regulate soil nutrient levels and water stress. This contributes to more efficient fertilizer use and helps reduce environmental pollution. (3)

Among the various types of engineered nanomaterials, metal oxide nanoparticles (MONPs) are some of the most widely produced and utilized. Due to their distinctive chemical, electronic, and optical characteristics, they are commonly used across multiple sectors. However, their solubility and tendency to release metal ions can potentially increase their environmental impact. (4, 5)

2. The characteristics of nano-oxide particles involved in fate of plants

The beneficial or harmful effects of metal oxide nanoparticles (MO NPs) on seed germination, plant growth, and morphology are largely influenced by how these nanoparticles behave and persist in the plant growth environment. These outcomes are determined by internal factors such as the NPs' chemical composition, size, shape, surface properties, reactivity, and applied dose. They are also shaped by external or environmental factors, including the type of growth medium, method of application, nanoparticle aging, plant species, and the specific localization of MO NPs within plant tissues. (6)

Particle size plays a critical role in enabling nanoparticles to penetrate plant cells. Transport across the plasma membrane is facilitated by ion channels and transporter proteins. Once inside the cell, nanoparticles can interact directly with organelles involved in oxidation, like mitochondria and chloroplasts, or with nutrient transport pathways, including biomolecules and pores. Generally, plants allow nanoparticles ranging from 20 to 50 nm in size to move into and accumulate within their cells. (7)

For MO NPs that are relatively soluble, both size and shape significantly influence their dissolution rate due to differences in surface area-to-mass ratios. Smaller nanoparticles possess a higher specific surface area, greater saturation solubility, and a thinner diffusion layer compared to larger ones—factors that accelerate their dissolution. Once dissolved, the resulting metal ions can affect cellular functions by binding to cell components and altering their activities. These metal ions can also drive biochemical reactions that may lead to phytotoxic effects and negatively influence plant physiology. (8)

Even without entering plant cells, the toxicity of MO NPs can still be substantial. Their solubility can modify the ionic balance in the immediate surroundings of the cell–nanoparticle interface, which may also result in toxic effects. (9)

3. Impact of different metallic nano-oxides on the growth and development of Crops.

3.1 Iron Oxide nanoparticle

Iron oxide nanoparticles (Fe_2O_3 NPs) are extensively used across multiple sectors such as catalysis, bioengineering, and medicine. Over time, they find their way into agricultural ecosystems primarily through wastewater discharge and atmospheric emissions. As with many nanoparticles, some level of phytotoxicity toward plants is expected. However, numerous studies suggest that Fe_2O_3 NPs can actually have beneficial effects on plants—particularly in rice cultivation. (10) Research indicates that these nanoparticles can enhance rice seed germination, alleviate oxidative stress caused by environmental stressors, and support overall plant growth. In adverse soil conditions, such as those with iron deficiency or drought, Fe_2O_3 NPs have been successfully employed as nano-fertilizers to improve the development of rice seedlings. (11) In a 2013 study, Alidoust et al. reported that iron oxide nanoparticles coated with citric acid (measuring 6 nm) could accelerate rice root elongation and exhibited lower toxicity compared to micron-sized iron oxide under reducing soil conditions. Since then, interest in the use of Fe_2O_3 NPs for improving rice seed germination has grown significantly. (12) One notable example involves iron oxide nanoparticles synthesized from *Cassia occidentalis* L. flower extract. These nanoparticles were found to penetrate the rice seed coat, suppress seed dormancy, enhance starch metabolism, and significantly boost germination—especially in sensitive, early-flowering mutant rice strains exposed to environmental stress. (13)

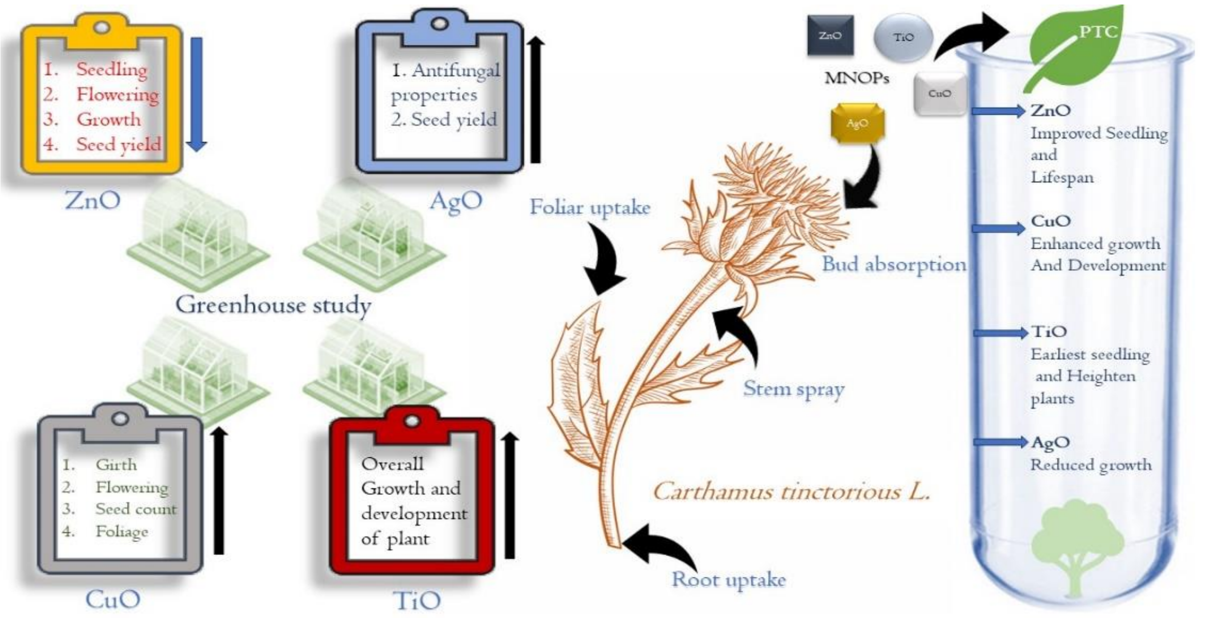
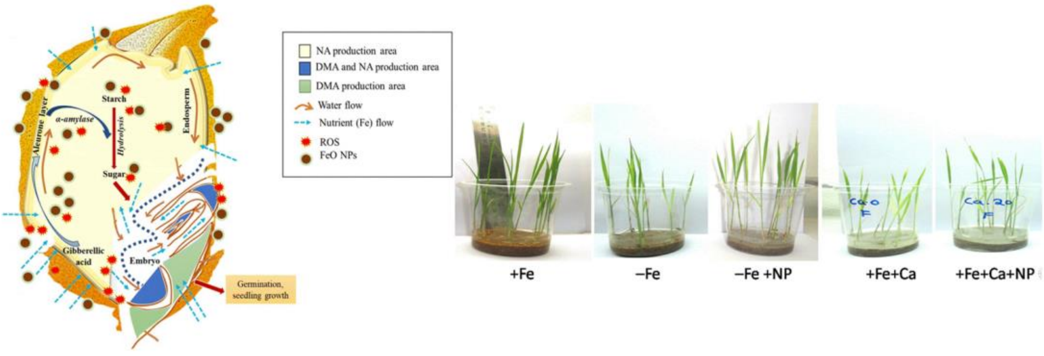


Figure: 1 Greenhouse study and Impact of different metallic nano-oxides on the growth and yield of safflower. Permission from the Ref. (24)



(a) (b)

Figure 2. (a) Representation of iron-oxide-nanoparticle-treated germination in rice. permission from Ref. [12]. 2021, Springer-Verlag; (b) rice growth response. Reprinted with permission from Ref. [14]. 2017, American Chemical Society.

Table: 1. Impact of Iron Metal Nano-oxides on the growth of Rice crop. (Ref. 28)

Particle Size	Concentration of MNO	Exposure time	Observed Effects	Reference
8 nm	500, 1000, 2000 mg/L	10 weeks	Stimulated the development of rice root systems.	[10]
18 nm	20, 40 mg/L	22 hours	Enhanced α-amylase activity and starch breakdown, leading to improved seed germination and seedling strength.	[12]
<12 nm	20 mg/L	21 days	Under calcium stress, improved productivity, electron transport in photosynthesis, antioxidant activity, and iron uptake.	[14]
20–25 nm	50, 250, 500 mg/L	3 weeks	Reduced oxidative stress in iron-deficient rice; enhanced growth and regulated iron-related plant hormones.	[11]
14.1 nm	2000 mg/L	5 days	Promoted seedling growth and increased chlorophyll and antioxidant levels; reduced toxicity from 3-nitrophenol.	[15]
10–50 nm	0.0025 mg/kg	40 days	Boosted chlorophyll and potassium content, reducing stress caused by cadmium (Cd) and sodium (Na).	[17]
70–100 nm	10, 20, 30 mg/L	4 weeks	Improved biomass and iron levels in rice; helped lower cadmium accumulation.	[16]
18–94 nm	25, 50, 100 mg/kg	30 days	Enhanced biomass, antioxidant enzyme production, and photosynthetic function; reduced ROS levels and tolerance to cadmium and drought.	[18]
Not Available	40, 320 mg/L	6 days	Increased dry weight of rice and facilitated cadmium transport and accumulation in plant tissues.	[23]
5–10 nm	125 mg/kg	25 days	Lowered lead concentrations in rice roots and shoots.	[19]
21.3 nm	200 mg/L	7 days	Prevented arsenic transfer to above-ground plant parts, aiding in detoxification.	[20]
60–80 nm	5, 10, 15 ppm	7 days	Suppressed arsenic uptake while promoting overall plant growth.	[21]
20–30 nm	25, 50 mg/L	21 days	Enhanced iron absorption and improved resistance to oxidative stress; lowered arsenic accumulation in rice.	[22]

3.2 *Titanium nano-oxides*

Most studies to date have focused on treating seeds, particularly during the early stages of plant development. Some of these growth experiments have been conducted using Hoagland's nutrient solution (hydroponics) or in agar-based media. However, these studies often overlook the potential interactions between nanoparticles (NPs) and soil components. In contrast, research on foliar application of nanoparticles is limited and still not well understood. Recently, seed priming has emerged as a promising method to enhance seed vigor, improve germination uniformity, and support seedling growth under stressful environmental conditions. As a result, the influence of titanium dioxide (TiO_2) nanoparticles on seed germination has been extensively studied. Most of this research involves applying TiO_2 nanoparticle suspensions to seeds placed on moistened filter paper in Petri dishes, assessing their effects on germination and root development. (25)

Depending on the concentration used, TiO_2 nanoparticles can have either a stimulating or inhibiting effect. For example, when naturally aged spinach seeds were exposed to rutile-form TiO_2 NPs at concentrations between 250 and 4000 mg/L, a significant increase was observed in germination rate, germination index, seedling dry weight, and vigor index. However, higher concentrations (6000 and 8000 mg/L) led to a decline in these parameters. Similarly, canola seeds treated with various TiO_2 NP concentrations (10–2000 mg/L) showed enhanced germination and seedling vigor only at the 2000 mg/L concentration, while lower concentrations had no noticeable effect (26). TiO_2 nanoparticles appear to exhibit relatively low toxicity; however, the experimental methods used across studies have been inconsistent, leading to conflicting results. It is challenging to compare findings from different sources due to variations in how the nanoparticle suspensions were prepared, differences in particle size, and the specific allotropic form of TiO_2 used—factors that vary significantly between studies. (27)

4. Nano-oxides influence over seed germination.

To ensure a sustainable future for agriculture, it is crucial to adopt environmentally responsible seed treatment practices. Sustainable seed treatments aim to balance profitability, environmental protection, and social equity—benefiting both current and future generations. One key aspect of this approach is regulating the use of agrochemicals, as their uncontrolled application can lead to soil and water contamination, harm to non-target organisms (including plants, animals, birds, and aquatic life), and disruption of ecosystems. (30)

When used for seed treatment, agrochemicals can leach into surrounding soil and water bodies, eventually entering the food chain and accumulating in living organisms. Excessive use not only leaves harmful residues on crops but also contributes to nutrient imbalances and diminished quality of agricultural products. Moreover, overuse poses serious environmental risks—accelerating climate change, reducing biodiversity, polluting groundwater and soil, depleting natural resources, and causing air, noise, and waste-related pollution. To address these challenges, sustainable agricultural practices must be developed and promoted. A promising solution is the use of smart agrochemicals for seed treatment. These advanced formulations are designed to deliver nutrients efficiently, enhance crop yields, and reduce environmental harm, thereby supporting the goals of sustainable agriculture. (31,32)

5. Future outlook

A thorough understanding of the impact of metal oxide nanoparticles (MO NPs) on plants is crucial, particularly given their increasing production and widespread application in agriculture. Toxicological studies have shown noticeable phytotoxic effects of MO NPs, but these typically occur at concentrations much higher than those likely to be found in natural environments or required for agricultural use. The behavior and biological activity of MO NPs are largely influenced by soil properties, such as pH, organic matter content, and clay composition. However, many phytotoxicity studies are conducted using hydroponic systems or soil-less media, which may not accurately reflect real-world conditions. The most meaningful and reliable results come from tests conducted in natural soil under environmental conditions. Therefore, more long-term studies evaluating the effects of low concentrations of MO NPs in soil-based systems are needed.

Comparing findings across different studies remains difficult due to variations in experimental design. To address this, a more standardized and systematic approach is necessary—one that clearly defines all relevant parameters. This is important because both the inherent characteristics of nanoparticles and environmental factors can significantly influence outcomes. More significantly, metal oxide nanoparticles (MONPs) have considerable potential in the growing nano-fertilizer market. However, their application must be carefully managed—strict regulations should govern both the timing and frequency of use, and their composition should be regularly monitored through testing. It is essential to minimize any unintended damage to crops that could result from incorrect application or excessive dosages.

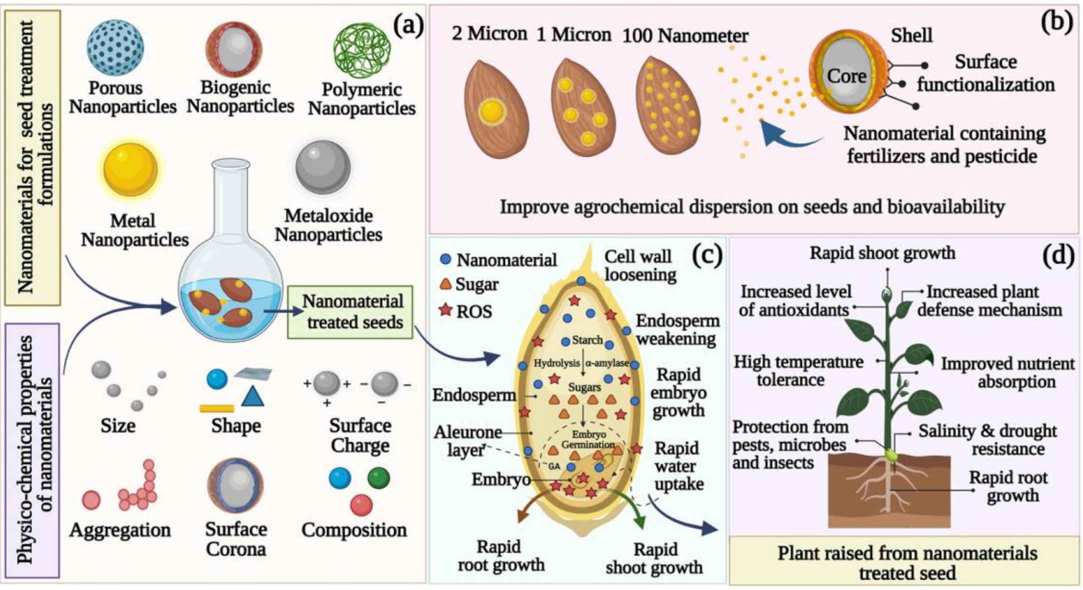


Figure 3. Type and impact of nanoparticles on seed germination, growth and metabolism. Fig taken from Ref. (29) for better understanding of metallic nano-oxide type and influence mechanism on seed growth.

Furthermore, when translating laboratory research into practical agricultural use, it is crucial to consider real-world environmental factors. These include the actual release levels of MONPs into the environment, their long-term stability, and the cumulative effects of natural elements such as wind, temperature fluctuations, rainfall, and drought.

Source of Support: Nil
Conflict of interest: Nil
Acknowledgement: None

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How to cite this article: Rana A, Kumar A**,** Kumar A**,** Dayal S. Metallic Nano-oxides and their Attributes in Agricultural Traits and Sustainability for Future Food industries.
Subharti J of Interdisciplinary Research, Aug. 2025; Vol. 7: Issue 2, 27 - 32