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The impact of metal oxide-based nanofertilisers on the physicochemical properties of agricultural plants

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Abstract. This study aimed to conduct a comprehensive analysis of existing research on the effects of metal oxide-based nanofertilisers, such as zinc oxide (ZnO), iron oxide (Fe_2O_3), and titanium dioxide (TiO_2), on plant development and growth. The research methodology was based on the analysis of scientific articles examining the influence of nanofertilisers composed of ZnO, Fe_2O_3, and TiO_2 on the physicochemical properties of crops such as wheat and soya beans. The study employed methods such as the analysis, generalisation, and comparison of various research findings. It explored multiple aspects of using these nanofertilisers, including their effects on improving the growth, development, and health of agricultural crops, particularly wheat and soya beans, the determination of optimal concentrations, and potential risks that may impact productivity and environmental safety. Given the challenges associated with enhancing agricultural efficiency, reducing environmental impact, and ensuring stable yields, the research aimed to identify optimal concentrations of nanofertilisers that could maximise positive effects on plants without the risk of adverse consequences. The literature review included an analysis of laboratory experiment results involving the use of various concentrations of nanofertilisers at different stages of plant development. Key parameters examined in these experiments, such as chlorophyll content in leaves, antioxidant enzyme activity, water balance, and root growth and development, were discussed. The review suggested that low to moderate concentrations of nanofertilisers have a positive effect on photosynthetic activity, root system development, and the overall condition of plants. However, it was emphasised that high concentrations of nanofertilisers can inhibit plant growth and lead to negative consequences. These findings highlighted the importance of precise dosing and careful monitoring when applying nanofertilisers to achieve optimal results. The research demonstrated the

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significant potential of metal oxide-based nanofertilisers in agriculture to enhance crop resilience to environmental stress factors and improve their productivity

Keywords: mineral modification; nutrient bioavailability; agricultural productivity; antioxidant activity; effects on the root system

INTRODUCTION

Sustainable agricultural development is a crucial issue in the context of population growth and increasing pressure on natural resources. Traditional methods of enhancing crop yields, such as the use of synthetic chemical fertilisers, have contributed to increased production but have had adverse environmental effects. Excessive use of such fertilisers has led to soil degradation, water pollution, and disruption of ecological balance. This has reduced soil fertility, its water retention capacity, and caused eutrophication of water bodies and a decline in biodiversity. Consequently, the need has arisen for environmentally safe and economically viable alternatives to improve the efficiency of agricultural systems. One such solution has been the use of metal oxide-based nanofertilisers, which enhance the nutritional status of plants and improve their resilience to stress. Nanotechnology offers the potential to increase nutrient availability to plants through the unique properties of nanoparticles, facilitating more efficient nutrient delivery and stimulating physiological processes.

Nanotechnology, including nanofertilisers, offers significant advantages over traditional plant nutrition methods and introduces new possibilities in agronomy. Metal oxide nanoparticles, such as ZnO, Fe_2O_3 and TiO_2, due to their unique properties, have demonstrated effectiveness in agronomy. These nanoparticles possess a larger specific surface area, which promotes better adsorption and nutrient uptake by the root system, reducing the need for large volumes of conventional fertilisers and minimising negative environmental impacts. Nanoparticles interact with plant cells at the molecular level, allowing for more efficient element transport. For instance, ZnO influences chlorophyll synthesis, increasing the number of photosynthetic pigments and improving photosynthetic activity (Gorobets *et al.*, 2023). Fe_2O_3 nanoparticles act as cofactors for enzymes critical to protein synthesis, respiration, and nitrogen fixation, which positively affect plant growth and resilience. TiO_2 nanoparticle fertilisers stimulate root growth and enhance the plant's ability to absorb water and nutrients, improving drought tolerance and resilience to other stressful conditions. However, the use of nanofertilisers requires careful monitoring to assess potential risks and their long-term impact on ecosystems.

Iron (Fe) is an essential micronutrient for plants and plays a key role in various biochemical processes, including electron transport in respiration and photosynthesis, nitrate synthesis, and nitrogen fixation, all of which are vital for amino acid and protein formation, as well as plant hormone synthesis (Prasad *et al.*, 2017). Iron oxide nanoparticles, such as Fe_3O_4 (magnetite) and γ-Fe_2O_3 (maghemite), possess unique properties, including superparamagnetism and a large specific surface area. Superparamagnetism enables them to retain magnetic properties only in the presence of an external magnetic field, while the large specific surface area enhances iron absorption by plants. The biocompatibility of these nanoparticles ensures their safety and effectiveness for long-term use. Fe_3O_4 and γ-Fe_2O_3 nanoparticles are utilised not only in agronomy but also in advanced technologies, such as magnetic resonance imaging, due to their ability to improve nutrient delivery to plants, increasing their bioavailability and absorption.

The number of studies on the impact of metal oxide-based nanofertilisers on the growth and development of agricultural crops has significantly increased compared to previous decades when the focus was primarily on the use of traditional mineral fertilisers and chemicals to boost yields. This shift is due to growing interest in nanotechnology and its potential to address issues related to resource efficiency and environmental sustainability in the agricultural sector. Research on zinc, iron, and copper nanoparticles, in particular, has shown that their application can substantially increase crop yields, improve product quality, and reduce the need for conventional chemical fertilisers. For instance, zinc oxide nanoparticles can enhance the physicochemical properties of plants, increasing their photosynthetic activity and resilience to drought and soil salinity, owing to their ability to efficiently deliver nutrients. Moreover, nanofertilisers help reduce toxic emissions, contributing to environmental sustainability (Tombuloglu *et al.*, 2020). Despite their positive potential, the widespread use of nanofertilisers presents challenges, including potential risks to human health and the environment. High concentrations of nanoparticles may induce toxic effects on plants, delaying their growth and development due to accumulation in tissues and disruption of physiological processes (Yew *et al.*, 2020). There are also concerns about the accumulation of nanoparticles in soils and their possible entry into the food chain, which could have unpredictable consequences for ecosystems.

Therefore, it is crucial to conduct further research to understand the mechanisms of action, long-term effects, and potential risks of nanofertilisers to ensure their safe and effective use. This study aimed to perform a comprehensive analysis of research on the effects of metal oxide-based nanofertilisers, such as zinc oxide (ZnO), iron oxide (Fe_2O_3), and titanium dioxide (TiO_2), on plant growth and development, as well as their impact on plant physiological processes. The objectives included examining the influence of various sources on plant growth, analysing potential toxic effects, and assessing the long-term implications of their use.

MATERIALS AND METHODS

The literature search for this study was conducted using scientific databases such as Scopus and Web of Science, which provided access to a wide range of academic studies on the specified topic. The keywords used during the search included terms such as "magnetite nanoparticles", "wheat growth", "nanofertilisers", "plant physiology", and "plant nanoparticle uptake". Additional search queries were employed to refine the results, focusing on nanoparticle size and concentration, such as "8-10 nm magnetite nanoparticles" and "nanoparticle impact on wheat cultivation". Over 150 relevant scientific articles were identified. Based on a thorough analysis of the content and adherence to inclusion criteria, 35 articles were selected for detailed investigation. The inclusion criteria comprised publications released between 2010 and 2023, studies with a clear description of experimental conditions, the use of metal nanoparticles, particularly magnetite, and a detailed analysis of their effects on plants. Special attention was given to studies that included physiological measurements such as plant height, root length, chlorophyll content, and the plant's ability to absorb nanoparticles.

In contrast, studies lacking sufficient experimental data or providing an incomplete description of the methodology were excluded. Research involving other types of nanoparticles unrelated to metals, or those with insufficient replication or limited analytical methods, was also disregarded (Joshi *et al.*, 2022). For detailed examination and further analysis, 24 of the most relevant sources were selected, which are listed in the References section. These studies focused on key physicochemical properties of magnetite nanoparticles, such as their size and shape, which significantly influenced their effectiveness. In particular, the selected studies concentrated on the impact of magnetite nanoparticles on the growth and development of wheat, especially in terms of increasing plant height, root system length, enhancing chlorophyll content, and improving nutrient uptake. These studies formed the basis for subsequent conclusions regarding the effectiveness of using magnetite nanoparticles as fertilisers in this research. Based on the referenced scientific studies, various methods of introducing magnetite nanoparticles into hydroponic systems were thoroughly examined. By analysing the scientific literature, the impact of nanoparticles on the physiological and morphological characteristics of plants was assessed, enabling the identification of key patterns and the determination of the most effective nanoparticle concentration for enhancing plant growth.

RESULTS

A key focus of the research was to investigate the impact of nanoparticles on the uptake and translocation of elements within plant tissues. This is crucial because these processes directly influence the effectiveness of nanofertilisers as pesticides. Understanding how nanoparticles enter plant tissues is vital as it determines their efficacy as fertilisers. Nanoparticles can enter plant tissues through various pathways, including the root system and leaves. They may pass through root hairs and intercellular spaces, entering root tissues. Their size and surface properties play a significant role in this process (Telizhenko, 2020).

For instance, nanoparticles with a large specific surface area can easily adhere to root tissues, facilitating uptake. Once absorbed by root cells, nanoparticles are then transported throughout the plant to the stem and leaves via the xylem and phloem. In the xylem, which transports water and dissolved substances from the roots to other parts of the plant, nanoparticles can move along with water and solutes. In the phloem, which is responsible for transporting organic compounds from the leaves to other parts of the plant, nanoparticles are transported with essential nutrients. The efficacy of nanofertilisers depends on their ability to be absorbed and translocated. Nanoparticles that are successfully taken up and transported have a positive impact on the physical and chemical properties of the plant – they can increase the content of micronutrients and other nutrients and improve overall plant productivity (Kornarzyński *et al*., 2020). For example, iron nanoparticles can enhance root growth and improve the uptake of water and nutrients. Copper nanoparticles positively influence photosynthesis, increasing chlorophyll levels and biomass. However, the effectiveness of nanofertilisers can be hindered by various factors, including agronomic conditions, nanoparticle concentration, size, and shape. J. Li *et al*. (2016) investigated the effects of copper nanoparticles and showed that excessive concentrations can cause toxic effects such as oxidative stress, DNA damage, mitochondrial dysfunction, and apoptosis. High doses of nanoparticles were also found to affect the structure of cell membranes, altering their permeability and disrupting cellular homeostasis. This highlights the importance of determining optimal conditions for using nanofertilisers to maximise their benefits and minimise negative side effects.

Results of the study demonstrated that the root system development of plants treated with metal oxide-based nanofertilisers was significantly improved. Specifically, the use of iron oxide (Fe_2O_3) nanoparticles at concentrations of 10 mg/L and 20 mg/L resulted in a significant increase in root length and biomass. This was confirmed by experimental data showing an increase in root length and a significant increase in total root mass compared to the control group. Additionally, concentrations of zinc oxide (ZnO) and magnesium oxide (MgO) nanoparticles in the range of 5-15 mg/L were investigated. Treatment with these nanoparticles was found to promote root elongation and increased biomass. Experimental data showed that plants treated with ZnO and MgO nanoparticles had significantly longer roots and higher root biomass compared to control samples, indicating the effectiveness of these nanofertilisers in stimulating root development. The positive impact of metal oxide nanoparticles on root development can be attributed to their ability to enhance the uptake of minerals and water, which are essential for plant growth. Figure 1 illustrates the processes of nanoparticle uptake by plants, their transport through the root system, and their impact on different parts of the plant. The figure demonstrates how nanoparticles penetrate roots, are transported through the vascular system, and influence the growth and development of the above-ground plant parts. The mechanisms of nanoparticle interactions with plant tissues highlighted in the figure underscore the crucial role of the root system in their uptake and distribution.

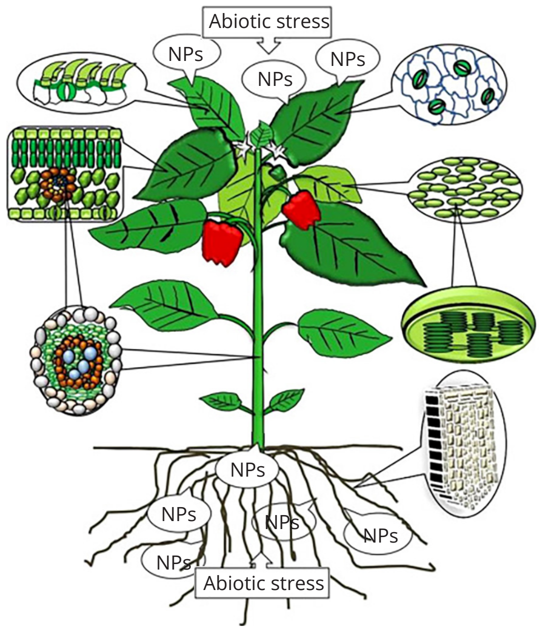

Figure 1. Schematic representation of nanoparticle uptake by a plant
Note: arrows indicate the direction of nanoparticle movement through plant tissues
Source: D.K. Tripathi *et al*. (2020)

A study conducted by N. Joshi *et al*. (2022) revealed a significant impact of biocompatible Fe_3O_4 and MnO_2 nanoparticles on tuber formation in potatoes (*Solanum tuberosum L*.). The experiment utilised nanoparticles at various concentrations (0.5; 1; 2 g/L), and the results demonstrated a substantial increase in tuber number by 25% and tuber size by 30%. This was achieved through the enhancement of physiological processes in plants, such as increased cell growth activity and improved nutrient uptake. The impact of nanoparticles also included the stimulation of new shoot formation and increased photosynthetic efficiency, collectively leading to higher potato yields. This confirms the importance of biocompatibility in nanomaterials for agriculture, as biocompatible nanoparticles can interact with biological systems without causing toxic effects, promoting plant growth and development.

K. Kornarzyński *et al*. (2020) investigated the effects of combining Fe_3O_4 nanoparticles with a constant magnetic field in the 100-200 mT range on seed germination and the levels of key nutrients, such as iron, phosphorus, and potassium, in plants. The results confirmed that this combination improved seed germination, leading to increased crop quality and yield. The constant magnetic field, together with Fe_3O_4 nanoparticles, facilitated increased concentrations of iron and phosphorus, which are critical for plant growth and development. Iron and phosphorus play key roles in plant metabolic processes, such as photosynthesis and respiration, as well as in the formation of new cells. These findings underscore the importance of integrating magnetic fields and nanoparticles to achieve better agronomic outcomes and improve agricultural practices. J.A. Teixeira da Silva & J. Dobránszki (2016) investigated the effects of 150 mT magnetic fields on plant physiological processes and overall growth and development. The results indicated that magnetic fields can stimulate plant growth by enhancing various physiological processes such as photosynthesis and respiration. Specifically, magnetic fields improve the transport of water and nutrients within plant tissues, leading to increased overall productivity. The application of magnetic fields opens up new avenues for modern agriculture, providing new opportunities to increase crop yield and quality. These findings suggest that magnetic fields can be used as an additional agronomic tool to improve crop cultivation efficiency. H. Zhu *et al*. (2008) studied the uptake, transport, and accumulation of iron oxide nanoparticles in pumpkin (*Cucurbita pepo*) plants. They demonstrated that iron oxide nanoparticles are effectively absorbed through the root system, transported via the xylem, and accumulate in leaves, stems, and fruits of plants. This confirms their potential to improve plant agronomic characteristics, such as increasing overall stress tolerance and enhancing nutrient uptake. Iron oxide nanoparticles, due to their efficient transport and accumulation properties, can enhance plant growth and development. H. Wang *et al*. (2011) studied the uptake and accumulation of magnetite (Fe_3O_4) nanoparticles in perennial ryegrass (*Lolium perenne* L.) and pumpkin (*Cucurbita mixta*) plants. The results showed that magnetite nanoparticles can improve plant growth, enhance photosynthetic activity, and strengthen antioxidant defence mechanisms. These effects contribute to an overall increase in plant tolerance to stress factors such as drought or diseases.

R. Rahmatzadeh *et al*. (2020) focused on the impact of Fe_3O_4 magnetic nanoparticles on tomatoes (*Solanum lycopersicum*) under cadmium stress conditions. The results indicate that magnetic nanoparticles can mitigate the negative effects of cadmium contamination, which is crucial for maintaining plant health and productivity in heavy metal-polluted environments. The application of Fe_3O_4 nanoparticles improved tomato growth, enhancing their tolerance to stressors such as cadmium contamination. This may be due to the ability of nanoparticles to neutralise the toxic effects of cadmium or to increase the antioxidant activity of plants, thus reducing oxidative damage and improving overall plant health. These findings support the potential of magnetic nanoparticles as an effective tool for enhancing plant tolerance to heavy metals and improving their overall productivity.

Figure 2 visually illustrates the key stages of magnetic nanoparticle uptake by plants and their impact on physiological processes. Initially, magnetite nanoparticles, due to their size and morphological characteristics, penetrate the plant root system through apoplastic or symplastic transport. This process occurs via root hairs, allowing the nanoparticles to effectively integrate

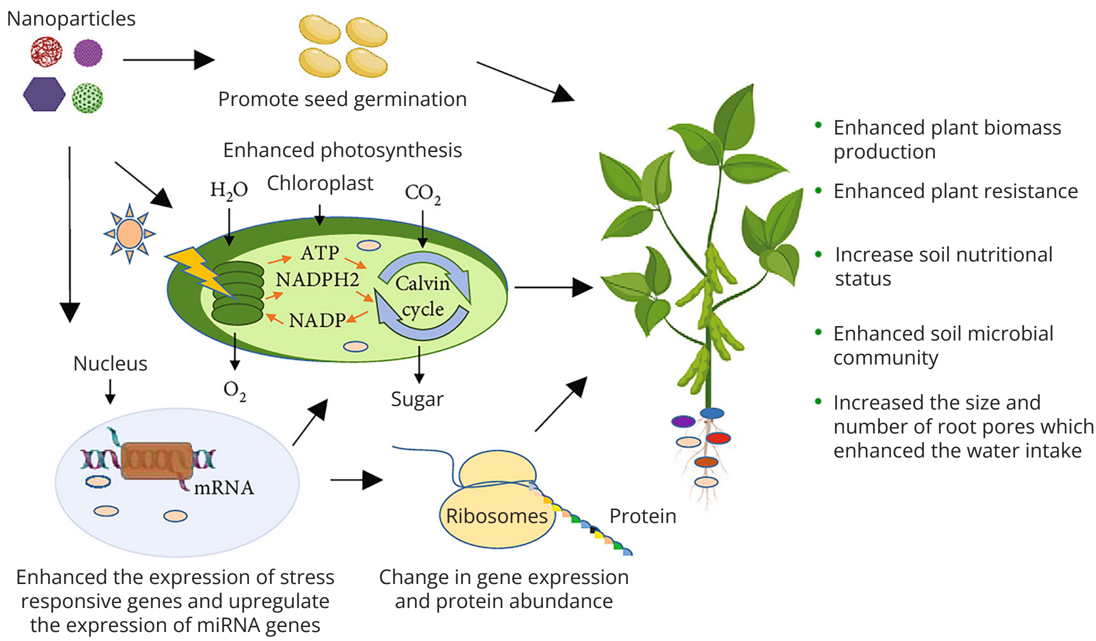

Figure 2. Positive impact of nanoparticles on plant growth and development
Source: S. Shahid *et al*. (2021)

into the plant tissues.

Studies investigating the effects of nanoparticles and magnetic fields on plants demonstrate significant potential for their use in agriculture to enhance plant growth and development, although caution is warranted due to potential negative effects. Numerous studies have revealed common trends confirming the positive impact of nanoparticles and magnetic fields on plants. Specifically, the study by N. Joshi *et al*. (2022) demonstrated that biocompatible Fe_3O_4 and MnO_2 nanoparticles significantly optimised tuber formation in potatoes, increasing tuber number by 25% and size by 30%. This highlights their great potential for improving root crop productivity. K. Kornarzyński *et al*. (2020) confirmed that the combination of Fe_3O_4 nanoparticles and an induced magnetic field not only improved seed germination but also increased the concentration of essential macronutrients such as iron and phosphorus, contributing to optimised plant growth and nutritional quality. This demonstrated the versatility of the positive impact of nanoparticles on plant physiological processes. Studies by H. Zhu *et al*. (2008) and H. Wang *et al*. (2011) indicated the effective uptake of magnetite and iron oxide nanoparticles by plants through the root system, their transport via the xylem, and their accumulation in various plant parts. H. Zhu *et al*. (2008). showed that iron oxide nanoparticles were absorbed by pumpkins and transported to leaves, stems, and fruits, confirming their ability to improve agronomic characteristics.

H. Wang *et al*. (2011) added that magnetite nanoparticles also enhanced plant growth, photosynthetic activity, and antioxidant defence, indicating their efficiency in transport and accumulation in plants. These combined results emphasised the importance of improved nanoparticle uptake and transport for achieving optimal agronomic results. J.A. Teixeira da Silva & J. Dobránszki (2016) demonstrated the positive impact of magnetic fields on plant growth and productivity. Scientists indicated that magnetic fields stimulated plant growth and development, contributing to improved physiological processes and overall productivity. Overall trends emerging from the studies confirmed that the use of nanoparticles and magnetic fields could positively influence plant growth, development, and productivity. The uptake and transport of nanoparticles, coupled with the stimulatory effect of magnetic fields, provided improvements in plant physiological and agronomic characteristics.

However, as shown in Table 1, various researchers concluded that to achieve optimal results, it is necessary to consider the concentration of nanoparticles and the strength of magnetic fields to avoid potential negative effects.

Specifically, M.H. Ghafariyan *et al*. (2013) noted that excessive concentrations of magnetite nanoparticles reduced chlorophyll content, negatively affecting plant photosynthetic activity. Other studies, such as that of M.F. Iannone *et al*. (2016), confirmed that optimal concentrations of magnetite nanoparticles improved antioxidant activity and contributed to increased tolerance to heavy metal-induced stress. As shown in Table 1, various authors have also investigated the effects of other metal nanoparticles. For example, M. Delfani *et al*. (2014) studied the effects of zinc and magnesium nanoparticles on plant root systems, and the results indicated improved root growth and biomass at optimal concentrations. Thus, these common trends highlighted the importance of further research and optimisation of technologies to maximise the positive impact of nanoparticles and magnetic fields on plant agronomic characteristics. Table 1 presents key studies, authors, and their findings regarding the impact of nanoparticles on the physiological processes of plants, allowing for a comparison of various approaches and concentrations to achieve the maximum positive effect.

Table 1. Research on the impact of nanoparticles on plant physiological processes

Research	The material under consideration	Plant species	Main findings	Conclusion
J. Li *et al.* (2016)	Copper nanoparticles	-	Excessive concentrations may cause toxic effects or impact cell membranes	It is important to determine optimal conditions for the use of nanofertilisers
N. Joshi *et al.* (2022)	Fe_3O_4 and MnO_2 nanoparticles	Potato (*Solanum tuberosum L.)*	Increase in the number and size of tubers, improvement of physiological processes	Biocompatible nanoparticles enhance tuber formation and yield
V.S. Telizhenko (2020)	Magnetite nanoparticles	Tomatoes (*Solanum lycopersicum*)	Increase in plant height and stem diameter	Magnetite nanoparticles improve the growth and morphological parameters of tomatoes
H. Wang *et al.* (2011)	Magnetite nanoparticles	Perennial ryegrass (*Lolium perenne*) and pumpkins Zucchini (*Cucurbita mixta*)	Improvement in growth, photosynthetic activity, and antioxidant defence	Magnetite nanoparticles enhance plant resistance to stress factors
H. Zhu *et al.* (2008)	Iron oxide nanoparticles	Pumpkins (*Cucurbita pepo*)	Absorption through the root system, transport to leaves and fruits	Iron oxide nanoparticles improve the agronomic characteristics of plants
R. Rahmatzadeh *et al.* (2020)	Magnetic Fe_3O_4 nanoparticles	Tomatoes (*Solanum lycopersicum*)	Reduction of the negative impact of cadmium stress, improvement in growth and stress resistance	Magnetic nanoparticles enhance plant resistance to heavy metal pollution

Source: compiled by the authors

Research into the effects of nanoparticles on plants has revealed a significant potential for their application in agriculture but has also highlighted the need to consider potential negative consequences. The use of nanotechnology, particularly magnetic and metallic nanoparticles, has had a marked impact on plant growth and development, enhancing stress tolerance and optimising physiological processes. However, research has shown that the concentration of these nanoparticles can have detrimental effects on plants if not properly controlled, underscoring the importance of precise dosing and monitoring during application.

Researchers have found that excessive concentrations of nanoparticles can negatively impact plants, causing disruptions to physiological processes and growth retardation. For instance, a study by M.H. Ghafariyan *et al*. (2013) demonstrated that high concentrations of magnetite (Fe_3O_4) significantly reduced the photosynthetic activity of soya beans (*Glycine max*). The primary cause of this was a decrease in chlorophyll levels in plant leaves, which directly affected photosynthetic efficiency. The experiment revealed that high concentrations of magnetite delayed seed germination and significantly reduced plant growth during the early stages of development. This negatively impacted final physiological parameters, such as plant biomass and nutrient uptake capacity. Specifically, plants treated with excessive nanoparticle concentrations exhibited impaired nitrogen and phosphorus uptake, indicating reduced efficiency at excessive application rates.

The research highlights the importance of precisely determining the optimal concentration of nanoparticles to avoid negative consequences and maximise positive effects; R. Rahmatzadeh *et al*. (2020) reported on the impact of magnetite (Fe_3O_4) magnetic nanoparticles and investigated the effect of magnetite on tomatoes (*Solanum lycopersicum*) subjected to cadmium stress. Results showed that at moderate concentrations, magnetite-treated plants were more resistant to cadmium toxicity, maintained higher chlorophyll concentrations, and had lower biomass losses. However, it was also emphasised that prolonged use of nanoparticles can lead to potential toxic effects, such as metal accumulation in plant tissues and metabolic changes. This indicates that for the effective use of nanoparticles in agriculture, their concentration must be carefully controlled following the principle of moderation. These observations highlight the need for further research into the mechanisms of nanoparticle action on plants to develop safer and more efficient technologies.

Research on metal nanoparticles has also shown that their effects depend not only on concentration but also on particle size and morphology. For instance, smaller magnetite nanoparticles (8-10 nm in size) penetrate plant tissues more effectively and interact more actively with cellular structures. However, to ensure the most effective and safe use of nanoparticles, several factors must be considered, including concentration, particle size, and duration of application. These factors can influence final agronomic performance and, if ignored, can lead to adverse outcomes. Notably, the findings of H. Zhu *et al*. (2008) confirmed that at appropriately selected concentrations, magnetic nanoparticles can mitigate the negative effects of toxic metals, such as cadmium, on plants. Excessive doses, on the other hand, led to accumulation in tissues, reduced product quality, and impacted environmental safety. These aspects should be given special attention when planning agricultural practices involving nanoparticles. It is also important to consider the impact of external environmental conditions, such as temperature, humidity, and soil type, on the efficacy of nanofertilisers. Further research can provide a better understanding of the mechanisms of interaction between nanoparticles and plant tissues and their long-term effects on crop productivity.

DISCUSSION

Research into the effects of metal oxide-based nanofertilisers on the physicochemical properties of agricultural plants is opening up new avenues for enhancing agronomic practices and ensuring sustainable agriculture. In the last 5 years, nanofertilisers have attracted significant attention due to their ability to improve plant growth and development, increase yield, and ensure more efficient use of soil resources. Studies conducted by F. Nudelman & N.A. Sommerdijk (2012) have demonstrated a significant impact of metal oxide nanoparticles, particularly iron oxide and copper oxide, on the growth, development, and physiological and biochemical characteristics of agricultural plants. One of the key advantages of using nanofertilisers is their ability to penetrate plant tissues due to their small size, which significantly enhances their efficacy compared to traditional fertilisers. In particular, nanofertilisers not only stimulate plant growth, increasing root length and overall biomass but also activate plant defence mechanisms, notably increasing antioxidant protection. This can significantly enhance crop tolerance to various stress conditions such as drought, high temperatures, soil salinity, and other environmental factors. Experiments investigating iron oxide nanoparticles have shown a significant impact on root development, which may be attributed to improved access to water and nutrients in the soil. This effect can be critically important in areas with limited water supply or under drought conditions, as demonstrated in studies. These studies indicate that the treatment of plants with iron oxide nanoparticles leads to a significant increase in root length, plant height, and biomass.

This effect can be attributed to improved water and nutrient exchange in plant tissues, facilitated by the ability of nanoparticles to penetrate plant tissues and stimulate root development. Increased root mass and length are critical factors influencing a plant's ability to absorb water and nutrients, especially under conditions of limited water supply or in soils with low nutrient content. Research findings by I. Afzal *et al*. (2021), who investigated the impact of a magnetic field and iron nanoparticles on the physiological and biochemical processes in sunflower plants, support these observations. Their results demonstrated that the combined effect of a magnetic field and iron nanoparticles significantly enhances plant growth and development, increasing yield. This is achieved through the activation of metabolic processes, improved protein synthesis, increased levels of antioxidant enzymes such as superoxide dismutase and catalase, and enhanced water retention in plant cells. Similar results were obtained in a study by M.F. Iannone *et al*. (2016), who investigated the effects of magnetite nanoparticles on wheat development. Their experiments showed that treating wheat with magnetite nanoparticles increased biomass and improved overall plant health. However, the authors also highlighted the risk of oxidative stress caused by increased levels of lipid peroxidation in cells. Oxidative stress can lead to damage to cell membranes, proteins, and DNA, negatively impacting plant growth and development. Therefore, despite the positive effects of nanoparticles on wheat growth, the possibility of negative side effects, such as increased levels of oxidative stress, must be considered. This may require additional measures to mitigate this stress, such as the combined use of antioxidant compounds.

Copper oxide has demonstrated a high efficacy in increasing plant biomass, which is likely due to enhanced photosynthetic processes within plant tissues. Copper oxide nanoparticles can influence several key aspects of photosynthesis, including increasing chlorophyll content, which is critical for efficient light absorption and, consequently, organic matter synthesis. Increased chlorophyll content can improve overall photosynthetic efficiency, which in turn promotes biomass growth. M. Delfani *et al*. (2014) provide further evidence for this, showing that iron and magnesium-based nanofertilisers can significantly impact plant physiological responses, particularly chlorophyll levels. Their experiments demonstrated that plants treated with iron and magnesium nanoparticles had significantly higher chlorophyll levels in their leaves, directly affecting their photosynthetic potential. This, in turn, led to increased biomass, indicating the ability of nanoparticles to optimise photosynthetic processes and improve overall plant productivity (Konate *et al*., 2017). The results also align with the study, investigated the impact of copper nanoparticles on plant physiological characteristics. In research employed non-toxic methods for synthesising copper nanoparticles, using ascorbic acid and polyvinylpyrrolidone, which enabled the creation of stable and highly dispersed nanoparticles. They demonstrated that these nanoparticles can significantly increase chlorophyll levels in plants, aligning with the findings regarding the positive impact of copper oxide on photosynthetic processes. An important aspect of the study is the approach to nanoparticle synthesis that ensures stability and effectiveness in agricultural applications, while simultaneously minimising potential toxic effects (Li *et al*., 2016).

An analysis of research into metal oxide-based nanofertilisers, particularly iron and copper oxides, reveals significant potential for enhancing the physicochemical properties of agricultural plants (Binhi, 2020). These findings open new avenues for further research and the practical application of nanoparticles in agriculture but also highlight the need for a cautious approach to their use (Anand *et al*., 2020). One of the primary advantages of nanofertilisers is their ability to significantly improve plant growth and development: studies by N. Joshi *et al*. (2022) and K. Kornarzyński *et al*. (2020) have demonstrated that combining magnetite nanoparticles with a magnetic field positively impacts crop yield and physiological parameters. These results indicate the potential of nanoparticles in developing new agronomic technologies that can significantly enhance agricultural productivity (Sear, 2021). Improving physiological parameters such as root growth and overall biomass is crucial for enhancing crop productivity and ensuring tolerance to environmental stresses. Research by H. Zhu *et al*. (2008) and H. Wang *et al*. (2011) has shown that magnetite and iron oxide nanoparticles are not only effectively absorbed by plants but also transported to various plant parts. This confirms their potential for improving agronomic properties, such as increased water and nutrient uptake.

Consequently, nanoparticles can more efficiently utilise soil resources and improve plant growth conditions, as demonstrated by J.A. Teixeira da Silva & J. Dobránszki (2016), where the positive impact of magnetic fields on plant growth and productivity opens up new horizons in agricultural technologies. The integration of magnetic fields with nanoparticles represents an innovative approach to the development of agricultural technologies (Osman *et al*., 2023). This combination has the potential to become a significant tool for enhancing plant resilience to various stress conditions. Research findings demonstrate the significant potential of using metal oxide nanoparticles, such as magnetite and iron oxide, to enhance agricultural crop productivity. The combination of these nanoparticles and magnetic fields has proven effective in stimulating plant growth, development, and improving physiological properties, leading to increased yields and enhanced stress tolerance. This approach opens up new possibilities for developing agricultural technologies aimed at more efficient resource utilisation and increased agricultural productivity.

CONCLUSIONS

Research into metal oxide-based nanofertilisers, such as iron and copper oxides, has revealed significant potential for improving the physicochemical properties of agricultural plants. The findings underscore the importance of optimising the use of nanoparticles in agriculture to maximise benefits while minimising the risks of adverse side effects. Firstly, the authors' research confirmed that nanoparticles can positively impact plant growth and development. This is possible due to their small size, allowing nanofertilisers to penetrate plant tissues and significantly enhance their efficacy. A crucial aspect was that iron oxide nanoparticles stimulated root development in plants. This is particularly important under conditions of limited water supply or in soils with low nutrient content.

Research has shown that the application of a magnetic field combined with iron oxide nanoparticles significantly enhanced plant growth and development. Results demonstrated a 15-30% increase in yield, indicating the effectiveness of nanoparticles in providing plants with nutrients, even under stress conditions. Iron oxide nanoparticles penetrate the root system, improving water and nutrient uptake, which is particularly beneficial for crops grown on depleted or unstable soils. This made plants more resilient to stress and increased their productivity, highlighting the potential of iron oxide-based nanofertilisers to improve agronomic practices and sustainable development in challenging growing conditions.

Studies have shown that copper oxide can increase photosynthetic activity in plants by 20-40%, promoting higher chlorophyll concentrations and improved light absorption. This leads to a 15-25% increase in plant biomass. However, high concentrations of copper oxide can induce oxidative stress, inhibiting plant growth and development. Therefore, optimising the concentration of nanoparticles is key to maximising positive effects and minimising negative consequences. Future research prospects include developing optimal nanoparticle concentrations and integrating them with technologies such as drip irrigation systems and bioengineering, which could enhance plant efficiency and resilience to stress conditions. Although nanofertilisers have significant potential, further research is needed to better understand their long-term impacts and ensure their effective use in the agricultural sector.

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CONFLICT OF INTEREST

None.

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Вплив нанодобрив на основі оксидів металів на фізико-хімічні властивості сільськогосподарських рослин

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Анотація. Метою роботи був всебічний аналіз наявних досліджень впливу нанодобрив на основі оксидів металів, таких як оксид цинку (ZnO), оксид заліза (Fe_2O_3) та діоксид титану (TiO_2), на розвиток та вплив рослин. Методологія дослідження базувалась на аналізі наукових статей, що досліджують вплив нанодобрив на основі оксидів металів (ZnO, Fe_2O_3 і TiO_2) на фізико-хімічні властивості таких культур, як пшениця та соя, із використанням таких методів, як аналіз різних досліджень, їх узагальнення та порівняння. В дослідженні розглядалися різні аспекти використання цих нанодобрив, їх вплив на покращення росту, розвитку та здоров'я сільськогосподарських культур, зокрема пшениці та сої, визначення оптимальних концентрацій, а також потенційні ризики, які можуть вплинути на продуктивність та екологічну безпеку. Враховуючи виклики, пов'язані з підвищенням ефективності сільського господарства, зменшенням впливу на навколишнє середовище та забезпеченням стабільної врожайності, дослідження було спрямоване на визначення оптимальних концентрацій нанодобрив, які могли б максимізувати позитивний вплив на рослини без ризику негативних наслідків. Огляд літератури включав аналіз результатів лабораторних експериментів з використанням різних концентрацій нанодобрив на різних стадіях розвитку рослин. Обговорювалися ключові параметри, що вивчалися в цих експериментах, такі як вміст хлорофілу в листках, активність антиоксидантних ферментів, водний баланс, ріст і розвиток коренів. Огляд літератури свідчив, що використання низьких і середніх концентрацій нанодобрив позитивно впливає на фотосинтетичну активність, розвиток кореневої системи та загальний стан рослин. Було підкреслено, що високі концентрації нанодобрив можуть пригнічувати ріст рослин і мати негативні наслідки. Дані висновки важливі для точного дозування та ретельного моніторингу при застосуванні нанодобрив для досягнення оптимальних результатів. Дослідження продемонструвало значний потенціал використання нанодобрив на основі оксидів металів у сільському господарстві для підвищення стійкості культур до стресових факторів навколишнього середовища та покращення їх продуктивності

Ключові слова: модифікація мінералів; біодоступність поживних речовин; аграрна продуктивність; антиоксидантна активність; дія на кореневу систему