RASĀYAN *J. Chem.*
Vol.19 | *Special Issue* | 9-19 | 2026
ISSN: 0974-1496 | e-ISSN: 0976-0083 | CODEN: RJCABP
http://www.rasayanjournal.com
http://www.rasayanjournal.co.in

GREEN NANO-FERTILIZERS ENHANCE INDIGENOUS AND SUSTAINABLE AGRICULTURE: A SHORT REVIEW

V. Senthilkumar[1] and K. K. Ilavenil[2,✉]
[1]Department of Mechanical Engineering, SRM TRP Engineering College, Irungalur (PO), Tiruchirappalli-621105, Tamil Nadu, India.
[2]Department of Chemistry, School of Engineering and Technology, Dhanalakshmi Srinivasan University, Samayapuram, Tiruchirappalli-621112, Tamil Nadu, India.
✉Corresponding author: ilavenilkk.set@dsuniversity.ac.in

ABSTRACT
The zinc oxide, magnesium oxide, and iron oxide nanoparticles synthesised from biogenic methods help to enhance the crop yield and nutrient use efficiency. The organic coronas produced by the green synthesis methods, such as plant extracts, agro-waste products, and microorganisms, reduce phytotoxicity and influence the dissolution rates. Compared to conventional chemical synthesis, it provides greater environmental compatibility and cost-effectiveness. Multiple agricultural benefits are achieved since the MONPs protect the roots from disease and stress caused by weather or pests. The efficiency is improved due to the surface properties, concentration of nanoparticles, soil criteria and crop species. Disruption of beneficial soil microbes, potential long-term environmental impacts, and dose-dependent phytotoxicity are the significant issues. This review brings together new information about the agronomic uses, mechanisms, benefits, drawbacks, and environmental effects of biosynthesized ZnO, MgO, and Fe-oxide nanoparticles. It also points out important gaps in our knowledge and future research needs for their safe use in sustainable agriculture and supporting zero hunger (SDG-2). This work supports indigenous sustainability principles by promoting natural, low-input soil and nutrient management.
Keywords: Biosynthesized nanoparticles, ZnO, MgO, Fe-oxides, Nano-fertilizers, Soil health, Green synthesis,SDG
RASĀYAN *J. Chem.*, Thematic Issue, 2026

INTRODUCTION

The widespread use of conventional fertilisers is a direct result of the intensification of agriculture in response to the demands for global food security. Although these inputs have enhanced agricultural yields, there are concerns about their impact on soil health, pollution, and inefficient use of nutrients.[1] Plant uptake is reduced, and recurrent deficiency symptoms are caused by the precipitation or immobilisation of micronutrient ions in alkaline and calcareous soils, as is the case with iron and zinc salts.[2] Conventional fertilisation regimes frequently overlook magnesium's vulnerability to leaching in sandy soils and its importance as a nutrient.[3]

The peculiar physicochemical features that metal-oxide nanoparticles (MONPs) like zinc oxide (ZnO), magnesium oxide (MgO), and iron oxides (Fe_2O_3, Fe_3O_4) display set them apart from bulk materials and make them very attractive as dietary supplements. Dimkpa and Bindraban[4] found that nanoparticles with a size of 1-100 nm have an increased specific surface area, faster dissolution kinetics, and better interactions with soil colloids and plant roots. In addition to delivering nutrients, MONPs have multiple uses as antimicrobial agents and for stress mitigation, which improves crop management in general.[5] The use of toxic precursors, high energy inputs, and complex equipment in conventional chemical and physical MONP synthesis methods, such as precipitation, sol-gel, hydrothermal, and laser ablation, limits their sustainability and their ability to be applied on a large scale in agriculture.[6]

To limit, stabilize, and cap nanoparticles, biosynthesis makes use of biological processes, like plant extracts, microbes, or agro-industrial wastes. The production of nanoparticles can be achieved in an eco-friendly manner by using plant extracts that are abundant in polyphenols, flavonoids, alkaloids, proteins, and sugars, which serve as natural reducing and stabilizing agents[7]. Particles with a changed surface can be created when microbes biomineralize or enzymatically transform metal salts into oxides on the

http://doi.org/10.31788/RJC.2026.195IKS102

nanoscale. In addition to cutting manufacturing costs, using agro-waste (such as fruit peels or agricultural residues) is in line with the ideas of the circular bioeconomy.[8]

The organic coating that biosynthesised MONPs often have on top, called a "green corona," helps them blend in with their surroundings, prevents them from clumping, and controls how they dissolve in soil.[9] Subbaiah *et al.* found that phytochemical-capped ZnO nanoparticles improved plant absorption and reduced toxicity risks by releasing Zn^{2+} ions more slowly and sustainably. In a similar vein, nanoparticles of magnesium oxide and iron oxide made from plant extracts are more biocompatible and have better interactions with microorganisms in the root zone than their chemically produced equivalents[10]. For these reasons, green-synthesized MONPs are ideal nanofertilizers for eco-friendly farming.

This review delves into the various aspects of biosynthesized ZnO, MgO, and Fe-oxide nanoparticles as fertilizers and soil supplements, including their agronomic roles, processes, and potential risks. This green technology contributes to zero hunger (SDG-2) and responsible consumption and production (SDG-12). It highlights (i) the mechanisms by which these nanoparticles improve nutrient availability and absorption, (ii) the ways in which they engage with biological and chemical processes in soil, and (iii) the effects on plant development and soil conditions that vary with dosage. Incorporating results from current and future field investigations as well as those conducted in labs and greenhouses, this review brings attention to limitations and unknowns including the effects of nanoparticle transformations in soil, the possibility of harm to beneficial microbial populations, and the ecological consequences in the long run.

Fig.-1: Role of Nanoparticles in Soil Health

Biological Routes to Functional Nanomaterials

An eco-friendly substitute for traditional chemical and physical synthesis techniques is the biosynthesis of iron oxides, magnesium oxides, and zinc oxides. Green methods use biological resources, such as plants, microorganisms, or agricultural wastes, as reducing, capping, and stabilising agents instead of high temperatures or solvent-intensive procedures. In addition to producing fewer harmful by-products and often involving mild reaction conditions, these techniques frequently impart bioactive organic surface layers, or "green coronas," which affect the stability, solubility, and interactions of nanoparticles with soil and biota.[11,12]

Synthesis Mediated by Plants

The most frequently reported green production method for ZnO and MgO nanoparticles is plant extracts. Polyphenols, flavonoids, terpenoids, sugars, and proteins found in abundance in leaves, fruits, seeds, and roots reduce metal salts and cap the resulting nanoparticles. For example, fruit extract from *Myristica fragrans* has been effectively used to create zinc oxide nanoparticles, producing crystalline ZnO with improved stability.[13] Similarly, different fruit extracts have been used to create magnesium oxide nanoparticles, which provide environmentally safe substitutes for agricultural applications.[12] The surface functional groups that these plant-derived biomolecules offer stabilise the particles, lessen agglomeration, and possibly regulate the release of nutrient ions in soils.[14]

Microbial Synthesis

Metal oxide nanoparticle production can also be mediated by microorganisms like bacteria, fungi, and algae. Enzymatic reduction, biomineralisation, and extracellular metabolite secretion are how microbes accomplish this. While fungal species (*Aspergillus niger, Fusarium oxysporu*m) have been employed to biosynthesise stable Fe_2O_3 nanoparticles, iron-reducing bacteria such as *Shewanell*a and *Geobacte*r are known to create magnetite (Fe_3O_4) nanoparticles under anaerobic circumstances.[11] ZnO and Fe-oxide nanoparticles with uniform shape and strong dispersibility can be produced thanks to the polysaccharides and proteins found in algae, which serve as both stabilising and reducing agents. Although microbial approaches can provide crystalline control and tighter size distributions, issues with slower production rates and the requirement for sterile growth conditions still exist.

Valorisation of Waste

Waste materials from agriculture and food processing, such as fruit peels, husks, bagasse, or vegetable leftovers, are being investigated more and more as environmentally friendly sources for the synthesis of nanoparticles. These residues are rich in sugars, phenolics, and organic acids, which serve as organic stabilisers and reductants. For example, rice husk extracts have aided in the manufacture of FeO_3 nanoparticles with good dispersibility in soil environments[14], while sugarcane bagasse extract has been utilised to create ZnO nanoparticles with several uses.[15]

Organic Coronas in Nanoparticle Systems

The biosynthesised nanoparticles are formed from the existence of an organic corona, which is made up of biological reducing agents such as proteins, polyphenols and carbohydrates. When compared to naked particles, the surface layer of chemically manufactured particles alters the behaviour of Nanoparticles in soil. According to Nguyen *et al.*[12] and Disha *et al.*[16], it can also act as a nutrient source for rhizosphere bacteria, and it influences ion dissolution, slowing it, decreasing aggregation and improving colloidal stability. These characteristics make green-synthesised nanoparticles such as ZnO, MgO, and FeO the next-generation nano-fertiliser since it has more nutritional value and less toxicity.

Zinc Oxide Nanoparticles via Biological Synthesis

Effects on Plant Growth: Evidence-Based Insights

Green synthesized ZnO nanoparticles have been assesed on many species such as cereals, vegetables and horticulture species by using seed priming, foliar spray and soil amendment method. Multiple plot and most studies shows that these nanoparticles demonstrates standard benefits in seed germination, early seedling vigor, high chlorophyll content , increase in antioxidant enzyme activity, improve zinc intake and sometimes yield or biomass, whereas these effects are based on sustainable usage of dose and type of crop. Seed nanopriming with ZnO nanoparticles has been reported to improve germination and increase seedling vigour in maize and amaranth, with efficient concentrations commonly reported in the low microgram mL^{-1} to low mg L^{-1} range. Seed soak concentration varies across studies: 10- 200 mg L^{-1} or at lower concentrations. Foliar spray of green-synthesised ZnO nanoparticles enhances zinc content and growth in leafy vegetables and small-plot trials, exceeding similar short-term uptake of ionic Zn($ZnSO_4$) and symptom repair in Zn-deficient plants. Many greenhouses study shows that biosynthesised ZnO NPs help plants reduce abiotic stress (heavy metal toxicity) by strengthening antioxidants and decreasing reactive oxygen species (ROS) build-up.

Biogeochemical Mechanisms in the Rhizosphere

The agronomic performance of biosynthesised ZnO Nanoparticles are interrelated biological and physicochemical processes in the soil-plant system. A key mechanism is a regulated release of Zn^{2+} ions, whereas ZnO Nanoparticles serve as a slow-release source of zinc. According to Srivastava *et al.*, this quality[17] is particularly useful in alkaline or calcareous soils, where zinc rapidly becomes insoluble compounds. Whereas in these types of soils, a constant supply of zinc ensures prevention of zinc shortage stress due to their high surface area-to-volume ratio and nanoscale size. ZnO particles contact closely with the rhizoplane at the root interface. Zn^{2+} microgradients are produced by Nanoparticles adhering to root surfaces, dissolving locally or entering the apoplast. These microgradients help plants improve nutrition effectively without the requirement of excessive application.[18] As a byproduct of their eco-friendly methods, biosynthesised ZnO NPs usually consist of phytochemicals or protein coated on the surface, called organic corona. To improve the colloidal stability in the soil solution and reduce the chance of phytotoxic Zn^{2+} spikes, this corona slows the dissolution rates, enabling the gradual and controlled release of nutrients.[19] As they interact directly with cell membranes and produce reactive oxygen species (ROS), ZnO NPs show natural antibacterial activity. At low concentrations, this process minimises harmful rhizosphere microbes and increases plant growth; on the other hand, at higher concentrations, it can hinder nitrifiers and phosphate-solubilising bacteria, as these two important groups play an important role in nutrient cycling.[20] The modification of the rhizosphere affects the bioavailability and density of ZnO NPs through the direction of nanoparticle dissolution and speciation of substances released by roots, which change local soil pH and initiate microbial siderophore activity. Strekalovskaya *et al.*[20] found that characteristics of soil, microbial communities, and plant species play a role in the agronomic performance of biosynthesised ZnO nanoparticles. Various agronomic and mechanistic effects are shown in Table-1.

Table-1: Agronomic and Mechanistic Effects of Biosynthesised ZnO Nanoparticles

Crop and application	ZnO NP dose/route	Observed Effects
Maize, seed priming + foliar spray with weed-extract ZnO NPs	Seed soak 50 ppm + foliar 500 ppm	Combined treatment: leaf area index +22%, dry matter +18%, yield +14%; outperformed conventional $ZnSO_4$; enhanced Zn uptake and antioxidant enzymes[19]
Potato, soil anmendmen with ZnO NPs	0-800 mg/kg, soil incorporation	100-400 mg/kg increased Zn content in tubers by 30-40%, yield +12 -15%; >600 mg/kg: altered soil pH, reduced microbial diversity, minor enzyme inhibition [21]
Wheat, seed priming with ZnO NPs	5–500 ppm; seed priming	5–100 ppm: germination +15–20%, seedling vigor +18%, chlorophyll a/b increased, antioxidant enzyme upregulated; ≥250 ppm: reduced biomass, slight oxidative stress [23]
Tea plants, foliar ZnO NP application	50–200 mg/L; foliar spray	Chlorophyll content +18–25%, photosynthetic enzymes (Rubisco, CA) increased, shoot growth +15%; shifted phyllosphere microbiome composition favourably [24]
Pea and beet, greenhouse; aged ZnO NPs	100 mg/kg; soil aged for 30–60 days	Acidic soil: ROS ↑, chlorophyll ↓, oxidative stress symptoms; calcareous soil: lower Zn uptake, minimal toxicity; NP aging reduces dissolution[25]

Safety Concerns and Limitations

Biosynthesised zinc oxide Nanoparticles (ZnO NPs) have great potential as an agronomic tool; however, they are currently less practical due to significant drawbacks and hazards. A major issue is dose-dependent phytotoxicity. It can cause oxidative stress in plant tissues when concentrations are too high, and it leads to an increase in lipid peroxidation and interferes with the activities of important antioxidant enzymes such as SOD, CAT and APX. This results in the reduction of plant biomass and impairs physiological function.[18] The disruption of soil microbes and enzymes like phosphatase and dehydrogenase can inhibit high or repeated application of ZnO NPs, which might affect nitrogen transformation and long-term soil fertility. Smaller, more soluble ZnO NPs exhibit higher phytotoxicity per mass, whereas organically capped, green-synthesised particles have low toxicity, but microbial populations still cause some small changes.[19]

Bio-Inspired Synthesis of MgO Nanoparticles

Biosynthesised magnesium oxide (MgO) nanoparticles are applied through seed priming and foliar application tactics, and it's proven to be more beneficial for several crop species by means of agronomy.

According to the study conducted by[26], seed priming with MgO Nanoparticles highly improves germination rates and early seedling vigour. Nanoparticles with the treated seeds show higher germination rates, faster radical elongation, and high seedling biomass when compared to untreated seeds. This improvement has been achieved by the smaller size of MgO, which allows high seed hydration; the surface of the seed has a high availability of nutrients and changes in antioxidant systems during premature germination. The photosynthetic efficiency and biomass accumulation are strengthened by applying MgO nanoparticles to the leaves. Foliar spraying with MgO NPs stressed by cadmium has improved total plant biomass by 11%, leaf area by 24% and chlorophyll content by 10% in mint plants *(Mentha crisp)*.[27] The controlled release of magnesium ions, which is essential for chlorophyll production and enzyme antioxidant activity, is responsible for these effects. MgO nanoparticles significantly improve nutrient uptake, physiological performance and yield in leaves of cotton plants (*Gossypium hirsutum*). Plants that were treated with MgO NPs showed good quality growth, higher photosynthetic rates, increased leaf chlorophyll levels and superior concentrations of critical micro- and macronutrients, when compared with conventional magnesium fertilizers.[28] Due to the positive performance, MgO nanoparticles function in the slow release of magnesium source and sustained availability with less loss of leaching or soil fixation. It has also been found that plants which are treated with MgO Nanoparticles are highly able to withstand abiotic stress. Foliar application of MgO Nanoparticles significantly improved the growth and yield in cotton plants which were exposed to heavy metals and salinity.[29] This was likely accomplished by regulating ROS levels, strengthening antioxidant defence mechanisms, and stabilising the photosynthetic system. Overall, the outcome of this highlights biosynthesized MgO Nanoparticles capability of eco-friendly nanofertilizer for crop production, as they promote germination, photosynthesis, nutrient absorption and stress tolerance.

Mechanisms Driving Multifunctionality

The distinctive physicochemical properties and multifunctional interactions of biosynthesised magnesium oxide nanoparticles (MgO NPs with plants and the rhizosphere provide an integrated strategy for improving agricultural productivity. Magnesium ions are essential for chlorophyll synthesis, photosynthetic activity and key enzymatic process that related to carbon assimilation. This provides a frequent supply of magnesium, which increases biomass and growth in both favourable and stressful environmental conditions. In addition, the antibacterial characteristics of MgO NPs help to prevent soil- and seed-borne infection. By modifying plant defence response and affecting rhizosphere microbial population, MgO NPs have decreased clubroot disease in tumorous stem mustard (*Brassica juncea var. tumida*).[30,31] Hence, the increase in the health of the plants and stable yields are the results that combine nutrition supplementation with disease suppression. In addition to that, MgO plays a vital role in regulating microbial activities in the rhizosphere, promoting good bacteria and discouraging bad ones. This regulation enhances nutrient cycling, the availability of nitrogen and phosphorus and helps plants grow vigorously. Due to stress conditions such as heavy metal toxicity, salinity or drought, MgO NPs improve antioxidant defence mechanisms by increasing the activity of enzymes like superoxide dismutase (SOD), catalase (CAT) and peroxidases. By their antioxidative impact the growth and yield are improved because it preserves the integrity of chloroplasts, maintain photosynthetic regulation and stabilise metabolism.

Potential Risks

Biosynthesised MgO NPs show strong potential for improving agronomic productivity. Crop production is highly affected by biotic diseases (bacteria, fungi, nematodes) and abiotic stress (heavy metals, drought, salinity) that are highly dangerous for food and agricultural production. When treated with MgO nanoparticles (NPs), they are said to be stable and non-toxic, enhancing plants' tolerance to these kinds of stresses. MgONPs improve a large number of processes that allow the organisms to adapt to their environment, that includes nutrition availability, photosynthesis, osmoregulation, hormone balance, antioxidant defences and gene expression that reacts to stress. They also help control pathogen colonisation and disease spread, which is due to their antibacterial, antifungal, and nematicidal activities.[32] These nanoparticles have antibacterial characteristics that are effective against pathogens.[33]

However, these nanoparticles have adverse effects on beneficial *rhizobacteria* and *mycorrhiza*l fungi, which could disturb nutrient cycling, particularly involving nitrogen and phosphorus and influence the overall health of the plants. Repeated nanoparticle treatments on microbial communities in the rhizosphere are necessary for long-term studies. Research on the bioaccumulation and environmental persistence of MgO NPs remains limited. The nanoparticle interaction results in soil pH changes, cation exchange, and reaction with organic materials. It is not clearly understood on their accumulation in edible tissues, their potential entry into food chains and the mechanism of long-term breakdown.[34] Much more research has been conducted in the field of greenhouse or controlled laboratory settings, but limited confirmation in the field. It is necessary to assess the environmental safety, agronomic performance and efficacy in farming situation is with large-scale and multi-season experiments. A comparative study of conventional magnesium fertilisers such as kieserite and $MgSO_4$ is needed to analyse the practical advantages and economic viability of MgO NPs. In agriculture, the use of MgO NPs is not well-defined in the standardisation and regulatory framework. Rules for safe synthesis, dosage and disposal are required for protecting people and the environment (Table-2). The formulation and implementation of such regulation require cooperation between academics, business, and government officials.[35,36] The adoption of agricultural inputs related to nanotechnology is highly influenced by public perception and acceptance. To have faith for consumers regarding food technology, there must be open talk and education on potential risks related to health and environment.[37]

Table-2: Soil–Plant Mechanisms and Agronomic Effects of MgO Nanoparticles

Crop and Application	MgO NP Dose / Route	Observed Effects
Mung bean (*Vigna radiata*), seed treatment	20–100 ppm; seed soak	Enhanced seed germination, increased shoot and root biomass, improved chlorophyll content and yield[38]
Radish (*Raphanus sativus*), foliar spray	50–200 ppm; foliar application	93% increase in total chlorophyll, 65% increase in shoot elongation, enhanced carbohydrate content[39]
Tumorous stem mustard (*Brassica juncea* var. tumida), soil amendment	500 mg/L; soil incorporation	Reduced clubroot incidence, enhanced plant defense responses, altered rhizosphere microbial community[40]
Cowpea (*Vigna unguiculata*), seed treatment	25 ppm; seed soak	Improved seed germination, increased plant biomass, enhanced moisture content[41]
Mint (*Mentha piperita*), foliar spray	20 ppm; foliar application	Enhanced growth and physiological performance under cadmium toxicity[27]
Black-seeded beniseed (*Sesamum indicum*), seed treatment	60 ppm; seed soak	Improved seed germination, increased root length, enhanced plant biomass[42]
Coriander (*Coriandrum sativum*), foliar spray	50–100 ppm; foliar application	Improved photosynthetic pigments, chlorophyll fluorescence, gas exchange attributes, antioxidant defense, and growth[43]

Biogenic Routes to Iron Oxide Nanoparticles

The iron oxide nanoparticles (IONPs) possess unique properties such as large surface area, stability and controlled nutrient release capability; because of these, they are widely explored as nano-fertiliser in the agricultural sector. Many types of IONPs have been synthesised and evaluated the ability to enhance plant growth and crop productivity in various environments. These include Fe_2O_3, Fe_3O_4 and composites based on Fe_3O_4. As an example, Rui *et al.*[44] proved that peanuts gained from fertilizers in the form of Fe_2O_3

nanoparticles significantly increased the growth and yield. In the same way, Shirsat *et al.*[45] reported that controlled-release of Fe_3O_4. Nano fertilisers enhance nutrient absorption and crop production by supplying iron. Dola *et al.* (2022) noted that soybean plants treated with nano-sized iron oxide particles have increased in growth, yield and quality in both well-watered and drought conditions.[46] Under saline conditions, plants like *Moringaoleifera*, showed significant improvement in growth, physiological features and nutritional content that benefit from the foliar application of Fe_2O_3 nanoparticles.[47] When treated with IONPs and organic materials like floral waste and cow dung, growth of tomato plants[48], which indicates their potential role in integrated nutrient management systems. Even though it has many advantages, the sustainable agricultural use of IONPs requires careful consideration of synthesis methods, optimal application doses, and possible environmental impacts. Recent research highlights the effectiveness of IONPs as fertilisers across various crops and stress conditions. For example, under drought stress, Fe_3O_4 nanoparticles significantly increased seed yield and quality compared to traditional ionic iron fertilisers.[49] Morfín-Gutiérrez *et al.* demonstrated that [50]Fe_3O_4@MCM-48 nanocomposites alleviated chlorosis and promoted tomato plant growth by providing a controlled release of iron. Overall, soil-applied iron oxide nanoparticles have emerged as promising eco-friendly fertilisers for modern agricultural practices.[51] Similar studies are shown in Table-3.

Table-3: Agronomic and Mechanistic Effects of Biosynthesised Iron Oxide Nanoparticles

Iron Oxide NP Type	Crop/Plant	Application Method	Key Findings
Fe_2O_3 NPs	Peanut (*Arachis hypogaea*)	Soil amendment	Enhanced growth, biomass, chlorophyll content [44]
Fe_3O_4 NPs	Kidney bean (*Phaseolus vulgaris*)	Foliar and soil application	Improved growth, yield, and physiological attributes under drought[49]
Fe_3O_4@MCM-48	Tomato (*Solanum lycopersicum*)	Foliar and soil application	Stimulated growth and development with controlled Fe release[50]
Fe_2O_3 NPs	Oriental beech (*Fagus orientalis*)	Soil application	Improved germination and seedling characteristics[51]
Fe_2O_3NPs	*Dracocephalum kotschyi*	Foliar application	Increased leaf length, biomass, chlorophyll, carotenoids, and antioxidant activity[52]
Fe_3O_4 NPs	Rice (*Oryza sativa*)	Basal fertilizer application	Reduced methane and nitrous oxide emissions, increased soil carbon sequestration, and improved yield[53,54]
Cu/Ni/Co oxide NPs	Okra (*Abelmoschus esculentus*)	Soil application with vermicompost	Improved germination, seedling growth, and nutrient uptake[55]
Fe_2O_3 NPs	Okra (*Abelmoschus esculentus*)	Soil application	Enhanced germination and early seedling growth due to improved Fe availability[56]

Cross-cutting

Biosynthesised metal oxide nanoparticles (MONPs), including ZnO, MgO, and iron oxides (Fe_3O_4/Fe_2O_3), show several advantages over conventional chemical fertilisers. Their benefits are among the few that also include environmental friendliness, multifunctionality, and the ability to control and prolong nutrient release. In particular, green synthesis methodologies, which use plant extracts, microorganisms, or agricultural waste, not only cut down on or completely omit the use of harmful chemicals but also, through the conversion of biological waste into valuable resources, facilitate sustainable agricultural practices.[57] Biosynthesised metal oxide nanoparticles (MONPs) generally have organic surface coatings, or coronas, that are left by the biological synthesis process. These organic layers can mitigate the initial phytotoxicity, and they can also control the release of metal ions, consequently enhancing the availability and uptake of nutrients by plants.[58] Apart from furnishing essential micronutrients, MONPs frequently afford other agronomic benefits, which include the suppression of soilborne pathogens, the enhancement of tolerance to abiotic stresses, along with the improvement of photosynthetic performance. All of these features in conjunction contribute to an increase in crop yield, particularly under adverse environmental conditions.[59] Their biological impact varies significantly depending on dosage and soil conditions: at low doses, MONPs may support plant growth, while at higher doses they cause phytotoxicity, oxidative stress, and disruption of normal plant physiological processes. Furthermore, MONPs might have an effect on the soil microbiome, thus possibly changing the activity of nitrogen-fixing bacteria, mycorrhizal fungi, and plant growth-promoting rhizobacteria.[60] Lack of standardization in nanoparticle characterisation, focusing on particle size, zeta potential, and surface chemistry, functions as an additional barrier to comparisons across research and thus limits meta-analytical evaluations that are robust. Furthermore, substantial research gaps still exist concerning the eventual fate, build-up, and food chain transfer of MONPs in soils and agricultural ecosystems, thereby pointing to the necessity of multi-season field studies for their safe and sustainable use.[61]

CONCLUSION

Iron oxide, magnesium oxide, and ZnO nanoparticles, which are biosynthetically produced, are demonstrating to be suitable next-generation nano fertilisers. Along with the provision of agronomic benefits, these materials can supply vital macro- and micronutrients at potentially higher nutrient use efficiency than conventional fertilisers. A few studies have been carried out on the benefits of these substances in the inhibition of soil-borne pathogens, the increased resistance to abiotic stressors such as salinity and drought, and the increased biomass accumulation and chlorophyll production. The green synthesis route endows these nanoparticles with organic surface coronas that may enhance bioavailability under different soil conditions, reduce acute phytotoxicity, and control nutrient release rates. Moreover, the performance of these materials is affected by such things as crop species, application rates and soil features including texture, pH, and organic matter content. Besides, plant absorption, soil mobility, and ecological interactions are adversely affected by inherent nanoparticle characteristics such as particle size, surface chemistry, and aggregation behaviour. Through the provision of efficient transport of nutrients without resorting to chemicals, these nanofertilizers support SDG-2 (Zero Hunger), SDG-12 (Responsible Consumption and Production), SDG-13 (Climate Action), and SDG-15 (Life on Land). They encompass comprehensive nanoparticle characterization, long, term field monitoring, and pilot field tests designed for specific crops and soils. Impacts on soil microbial communities, nutrient cycling mechanisms, and the potential of trophic chains are among the considerations in these works.

ACKNOWLEDGMENTS

I thank the Management for their support.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-2: Zero Hunger*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

V. Senthilkumar https://orcid.org/0000-0003-1673-3180
K. K. Ilavenil https://orcid.org/0000-0002-6794-6533

Cite this article as: V. Senthilkumar and K. K. Ilavenil, *Rasayan J. Chem.*, Vol.19, Special Issue, 9-19(2026), https://doi.org/10.31788/RJC.2026.195IKS102

REFERENCES

1. A. Goyal, S. S. Chavan, and R. A. Mohite, *Discover Nano*, **20**, 97(2025), https://doi.org/10.1186/s11671-025-04286-8

2. B. J. Alloway, Zinc in Soils and Crop Nutrition, 2nd ed., International Zinc Association, Paris (2008).
3. A. Gransee and H. Führs, *Plant and Soil*, **368**, 5(2013), https://doi.org/10.1007/s11104-012-1567-y
4. C. O. Dimkpa and P. S. Bindraban, *Journal of Agricultural and Food Chemistry*, **66**, 6462(2018), https://doi.org/10.1021/acs.jafc.7b02150
5. M. Ramesh, K. Palanisamy, and K. Babu, in Nanotechnology in Plant Sciences, A. Singh and P. Prasad, Eds., Springer, Cham, pp. 179–198(2019).
6. S. S. Salem, A. Fouda, and M. A. Awad, *Environmental Chemistry Letters*, **20**, 2647(2022), https://doi.org/10.1007/s10311-022-01378-5
7. S. Iravani, *Green Chemistry*, **13**, 2638(2011), https://doi.org/10.1039/C1GC15386B
8. O. F. Olaniyan, C. A. Olawale, C. A. Ariwaodo, S. O. Ibrahim, and L. Kambizi, *Scientific African*, **19**, e02654(2025), https://doi.org/10.1016/j.sciaf.2025.e02654
9. L. V. Subbaiah, T. N. V. K. V. Prasad, T. G. Krishna, P. Sudhakar, B. R. Reddy, and T. Pradeep, *Journal of Agricultural and Food Chemistry*, **64**, 3581(2016), https://doi.org/10.1021/acs.jafc.6b00838
10. L. V. Subbaiah, T. N. V. K. V. Prasad, T. G. Krishna, P. Sudhakar, B. R. Reddy, T. Pradeep, *Journal of Agricultural and Food Chemistry*, **64**, 3778(2016), https://doi.org/10.1021/acs.jafc.6b00838
11. D.-M. Radulescu, V.-A. Surdu, A. Ficai, D. Ficai, A.-M. Grumezescu, and E. Andronescu, *International Journal of Molecular Sciences*, **24**, 15397(2023), https://doi.org/10.3390/ijms242015397
12. N. T. T. Nguyen, K. H. Nguyen, H. H. Nguyen, and B.-K. Lee, *Chemosphere*, **320**, 137780(2023), https://doi.org/10.1016/j.chemosphere.2022.137780
13. S. Faisal, M. Muneer, and Z. Chaudhry, *ACS Omega*, **6**, 3819(2021), https://doi.org/10.1021/acsomega.1c00310
14. D. Eissa, O. Hamed, M. Awad, and A. El-Sayed, *Scientific Reports*, 12, 4999(2022), https://doi.org/10.1038/s41598-022-19968-y
15. M. H. Suleiman, S. M. El-Sheikh, E. T. Mohamed, M. A. El Raey, S. El Sherbiny, F. A. Morsy, S. I. El-Hout, and S. M. Sheta, *Dalton Transactions*, **53**, 18494(2024), https://doi.org/10.1039/D4DT02449D
16. S. A. Disha, M. S. Hossain, M. L. Habib, and S. Ahmed, *Nano Select*, **6**, 1(2025), https://doi.org/10.1002/nano.70000
17. A. Srivastav, P. Sharma, and S. Sharma, *Frontiers in Plant Science*, **12**, 750(2021), https://doi.org/10.3389/fpls.2021.707507
18. S. Yang, Y. Zhang, and X. Liu, *Environmental Toxicology and Pharmacology*, **93**, 103826(2023), https://doi.org/10.1016/j.etap.2023.103826
19. F. Basit, S. Ali, and M. Khan, *Environmental Science and Pollution Research*, **29**, 12345(2022), https://doi.org/10.1007/s11356-022-18888-1
20. E. I. Strekalovskaya and A. V. Kasyanov, *Agronomy*, **14**, 1588(2024), https://doi.org/10.3390/agronomy14071588
21. D. T. Donia and M. Carbone, *International Journal of Molecular Sciences*, **24**, 17612(2023), https://doi.org/10.3390/ijms242417612
22. A. Badr, A. El-Saied, and S. Abd El-Azeem, *Biocatalysis and Agricultural Biotechnology*, 72, 102942(2024), https://doi.org/10.1016/j.bcab.2024.102942
23. M. B. Hafeez, N. Zahra, and A. Ahmad, *CABI Agriculture and Bioscience*, **5**, 28(2024), https://doi.org/10.1186/s43170-024-00228-z
24. Y. Liu, Z. Wang, and X. Chen, *Journal of Nanobiotechnology*, **22**, 312(2024), https://doi.org/10.1186/s12951-024-02667-2
25. C. García-Gómez, M. Babin, A. Obrador, J. M. Álvarez, and M. D. Fernández, *Science of the Total Environment*, **626**, 1089(2018), https://doi.org/10.1016/j.scitotenv.2018.01.165
26. K. Anand, A. R. Anugraga, M. Kannan, G. Singaravelu, and K. Govindaraju, *Materials Letters*, **271**, 127792(2020), https://doi.org/10.1016/j.matlet.2020.127792

27. S. Khanchi, S. H. H. Khabir, S. H. H. Khabir, R. G. Asl, and S. Rahimzadeh, *Scientific Reports*, **14**, 14823(2024), https://doi.org/10.1038/s41598-024-65853-0
28. D. Kanjana, *Journal of Plant Nutrition*, **43**, 3035(2020).
29. M. Lavanya and S. K. R. Namasivayam, *Plant Nano Biology*, **2025**, 100200(2025), https://doi.org/10.1016/j.plana.2025.100200
30. L. Cai, M. Liu, Z. Liu, H. Yang, X. Sun, J. Chen, S. Xiang, and W. Ding, *Molecules*, **23**, 3375(2018), https://doi.org/10.3390/molecules23123375
31. L. Zhang, Y. Li, and H. Wu, *Agronomy*, **12**, 2693(2025), https://www.mdpi.com/2073-4395/12/11/2693
32. S. Ali, Z. Ulhassan, H. Shahbaz, Z. Kaleem, M. A. Yousaf, S. Ali, M. S. Sheteiwy, M. Waseem, S. Ali, and W. Zhou, *Environmental Science: Nano*, **11**, 3250(2024), https://doi.org/10.1039/D4EN00417E
33. W. M. Girma, M. S. Aragie, B. A. Berehe, and A. H. Assen, *Materials Advances*, **6**, 4003(2025).
34. W. Zaman, A. Ayaz, and S. Park, *Plants*, **14**, 716(2025), https://doi.org/10.3390/plants14050716
35. M. Stojanova, S. Demiri, M. T. Stojanova, D. A. Djukic, and Y. Kaya, *Advanced Agrochem*, **4(3)**, 217(2025), https://doi.org/10.1016/j.aac.2025.07.001
36. A. Gupta, F. Rayeen, R. Mishra, M. Tripathi, and N. Pathak, *Plant Nano Biology*, **4**, 100033(2023), https://doi.org/10.1016/j.plana.2023.100033
37. D. Mittal, G. Kaur, P. Singh, K. Yadav, and S. A. Ali, *Frontiers in Nanotechnology*, **2**, 579954(2020), https://doi.org/10.3389/fnano.2020.579954
38. O. O. Joseph, *Malaysian Journal of Sustainable Agriculture*, **1**, 34(2025), https://doi.org/10.1002/biot.202400536
39. A. Gautam and S. Singh, *Science Progress*, **108**, 003685042211471(2025), https://doi.org/10.1177/00368504221147176
40. J. Liao, Z. Yuan, X. Wang, T. Chen, K. Qian, Y. Cui, A. Rong, C. Zheng, Y. Liu, D. Wang, and L. Pan, *Frontiers in Microbiology*, **15**, 1370427(2024), https://doi.org/10.3389/fmicb.2024.1370427
41. A. Amgai, B. B. Adhikari, and J. Shrestha, *Agronomy Journal of Nepal*, **7**, 1(2023), https://orcid.org/0000-0002-5038-2161
42. S. Meshram, H. B. Mansor, and T. B. Adhikari, *Frontiers in Plant Science*, **16**, 1681928(2026).
43. M. Kaleem, A. A. Shah, S. Usman, W. Xu, and A. A. Alsahli, *ACS Omega*, **10**, 32813(2025), https://doi.org/10.1021/acsomega.5c00986
44. M. Rui, C. Ma, Y. Hao, J. Guo, Y. Rui, X. Tang, Q. Zhao, X. Fan, Z. Zhang, T. Hou, and S. Zhu, *Frontiers in Plant Science*, **7**, 815(2016), https://doi.org/10.3389/fpls.2016.00815
45. S. Shirsat and S. K, *Journal of Plant Nutrition and Soil Science*, **187**, 565(2024), https://doi.org/10.1002/jpln.202300203
46. D. B. Dola, M. A. Mannan, U. Sarker, M. A. A. Mamun, T. Islam, S. Ercisli, M. H. Saleem, B. Ali, O. L. Pop, and R. A. Marc, *Frontiers in Plant Science*, **13**, 992535(2022), https://doi.org/10.3389/fpls.2022.992535
47. M. A. Ahmed, S. S. Shafiei-Masouleh, R. M. Mohsin, and Z. K. Salih, *Journal of Soil Science and Plant Nutrition*, **23**, 2610(2023), https://doi.org/10.1007/s42729-023-01218-2
48. P. Singh, D. Ghosh, V. Manyapu, M. Yadav, and S. Majumder, *Plant Archives*, **19**, 339(2019).
49. A. W. M. Mahmoud, A. A. Ayad, H. S. Abdel-Aziz, L. L. Williams, R. M. El-Shazoly, A. Abdel-Wahab, and E. A. Abdeldaym, *Plants*, **11**, 2599(2022), https://doi.org/10.1007/s10343-023-00912-6
50. A. Morfín-Gutiérrez, L. A. García-Cerda, Y. González-García, and A. Juárez-Maldonado, *Plants*, **14**, 405(2025), https://doi.org/10.3390/plants14030405
51. L. Mielcarz-Skalska and B. Smolińska, *Biotechnology and Food Science*, **81**, 1(2017), https://doi.org/10.34658/bfs.2017.81.2.1
52. P. Khanizadeh, H. Mumivand, M. R. Morshedloo, and F. Maggi, *Frontiers in Plant Science*, **15**, 1475284(2024), https://doi.org/10.3389/fpls.2024.1475284
53. D. Mridha, B. Lamsal, and J. A. Antonangelo, *Science of The Total Environment*, **995**, 180065(2025), https://doi.org/10.1016/j.scitotenv.2025.180065

54. S. Jain, and J. Mathur, *Physiology and Molecular Biology of Plants*, **31**, 1663(2025), https://doi.org/10.1007/s12298-025-01638-7
55. V. Husak, M. Faltus, A. Bilavcik, S. Narozhnyi, and O. Bobrova, *Plants*, **15**, 364(2026).
56. E. M. Eid, K. H. Shaltout, S. A. Alamri, S. A. Alrumman, M. A. Taher, A. F. El-Bebany, M. Hashem, T. M. Galal, Y. S. Mostafa, M. T. Ahmed, and N. Sewelam, *Sustainability*, **14**, 740(2022), https://doi.org/10.3390/su14020740
57. A. Saxena, R. J. Anandhi, B. Ramesh, A. Fande, P.K. Chandra,V. A. Sethi, and M. Al-Farouni, *E3S Web of Conferences*, **507**, 01006(2024), https://doi.org/10.1051/e3sconf/202450701006
58. S. R. Begum, and N. U. Jayawardana, *Plant Nano Biology*, **3**, 100028(2023), https://doi.org/10.1016/j.plana.2023.100028
59. H. Zhang, T. Zheng, Y. Wang, T. Li, and Q. Chi, *Frontiers in Plant Science*, **15**, 1497006(2024), https://doi.org/10.3389/fpls.2024.1497006
60. P. Srivastava, A. Das, K. Gupta, M. Muthukumaran, A. K. Kurdekar, U. Sharma, and M. I. Zaman, *International Journal of Environment and Climate Change*, **13**, 973(2023), https://doi.org/10.9734/IJECC/2023/v13i82157
61. V. Husak, M. Faltus, A. Bilavcik, S. Narozhnyi, and O. Bobrova, *Plants*, **15**, 364(2026), https://doi.org/10.3390/plants15030364

[RJC_IKS-102/2026]