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From cultivation to Consumption: Evaluating the effects of nano fertilizers on food quality and safety

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ABSTRACT

Nanofertilizers represent a breakthrough in sustainable agriculture, offering innovative solutions to improve nutrient efficiency, crop productivity, and environmental resilience. Engineered at the nanoscale, these fertilizers possess unique physicochemical properties, such as increased surface area, targeted delivery, and controlled release, which enhance nutrient uptake while reducing losses associated with conventional fertilizers. This review examines the evolving role of nanofertilizers in sustainable agricultural systems, exploring technological innovations, benefits, limitations, and potential risks. It aims to provide a comprehensive overview of their significance in advancing food security and environmental sustainability, while highlighting critical areas for future research and policy development. In particular, nanofertilizers show strong potential in improving food quality and safety by enhancing crop nutritional content, reducing pesticide residues, and boosting plant resistance to environmental stressors. Their roles in biofortification of staple crops such as wheat, rice, and maize could play a crucial part in addressing widespread micronutrient deficiencies globally. Furthermore, integrating nanofertilizers with precision agriculture technologies, including GPS mapping, remote sensing, and smart sensors, could enable site-specific nutrient management, optimizing fertilizer use and reducing environmental impact. However, concerns remain regarding their long-term effects on soil health, water systems, human health, and non-target organisms. Limited regulatory frameworks and high production costs also pose significant barriers to widespread adoption. This review underscores the need for interdisciplinary collaboration, green synthesis approaches, and ecosystem-level studies to ensure the safe and effective use of nanofertilizers. Ultimately, nanofertilizers offer transformative potential to support sustainable food systems and meet the growing demands of the global population.

1. Introduction

Agricultural systems worldwide are undergoing a period of significant transformation, driven by the urgent need to meet increasing food demands while mitigating environmental degradation. With the global population expected to surpass 9 billion by the year 2050, agricultural output must grow substantially to meet future consumption requirements.[1] This demand surge places unprecedented pressure on natural resources, particularly land, water, and soil nutrients. The expansion of agricultural productivity, however, cannot rely on traditional farming practices alone, as these methods have historically led to a range of environmental issues such as land degradation, loss of biodiversity, greenhouse gas emissions, and contamination of water bodies due to excessive fertilizer and pesticide use.

Conventional agriculture is largely dependent on synthetic chemical inputs, especially inorganic fertilizers, which are often applied in excess to maximize crop yields. While effective in the short term, such inputs have long-term consequences, including nutrient leaching, eutrophication, reduced soil fertility, and disruption of microbial ecosystems. Moreover, these practices have also been linked to a reduction in the nutritional composition of crops, diminishing the quality of the food supply and potentially affecting public health. Therefore, developing

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innovative and sustainable agricultural practices that support high productivity without compromising environmental health is a major global priority.[2,3]

One of the most promising scientific advances addressing these challenges is nanotechnology, which has found growing application in agriculture. Nanotechnology involves the manipulation of materials at the nanoscale (1–100nm), where unique physical, chemical, and biological properties emerge. In the agricultural sector, nanotechnology has been explored for numerous applications, ranging from crop protection and pest management to water purification and nutrient delivery. Among these, nanofertilizers have garnered particular interest due to their potential to improve nutrient use efficiency, reduce environmental losses, and enhance plant growth and crop quality.

Nanofertilizers are innovative formulations in which essential nutrients are encapsulated within or coated onto nanomaterials. These fertilizers are designed to release nutrients slowly and in a controlled manner, thereby aligning nutrient availability with the specific demands of plants at different growth stages. Compared to conventional fertilizers, nanofertilizers offer multiple advantages, including improved solubility and bioavailability of nutrients, reduction in nutrient leaching, targeted delivery, and enhanced uptake by plant cells.[4] This controlled release mechanism is particularly effective in preventing the rapid loss of nutrients due to volatilization, runoff, or fixation in the soil, thereby ensuring that plants receive nutrients precisely when needed.

Nanoparticles act not only as nutrient carriers but also as sources of nutrients. Their extremely small size and large surface-area-to-volume ratio enable higher nutrient loading and facilitate interactions with plant roots and leaves. This leads to improved absorption, efficient translocation within plant tissues, and accelerated metabolic activity. In particular, nanofertilizers can be engineered to be absorbed via foliar or root pathways, offering flexibility in application methods. Moreover, nano-scale delivery systems can penetrate plant cellular structures more effectively than conventional fertilizers, enhancing nutrient assimilation and physiological responses.[5]

An important dimension of nanofertilizer use is their interaction with soil microorganisms. Soil microbial communities play an essential role in nutrient cycling, organic matter decomposition, and overall soil health. The influence of nanofertilizers on microbial activity is still being explored, but preliminary findings suggest that specific nano formulations may promote beneficial microbial populations or stimulate enzymatic activity that supports nutrient availability.[6] This dynamic interaction between nanoparticles and soil biota may contribute to more sustainable and resilient agricultural ecosystems.

Beyond their functional benefits, nanofertilizers address some of the key limitations associated with conventional fertilizers. For example, high-solubility fertilizers often leach into groundwater or are lost through surface runoff, particularly during irrigation or rainfall. This not only reduces the effectiveness of nutrient delivery but also contributes to environmental pollution. In contrast, nanofertilizers are typically less prone to leaching, as they can remain dispersed in solution due to their nanostructure and release nutrients at a slower, more controlled pace. In many cases, nutrients are either adsorbed onto the surface of porous nanoparticles or encapsulated within biodegradable polymeric shells. These structures can be tailored to release nutrients in response to specific environmental cues such as moisture, pH, or temperature fluctuations.[5]

The concept of "smart fertilizers," which is related but not identical to "nanofertilizers," is increasingly gaining traction. Smart fertilizers typically refer to nutrient delivery systems that respond to physiological or environmental stimuli, and nanomaterials can be one of the technologies used to achieve this responsiveness. For instance, nanoparticles can be developed to release antimicrobial agents in response to bacterial infections that alter the pH of the soil or plant tissues. Similarly, nutrient release can be timed to coincide with particular growth stages, ensuring plants receive tailored nutrition that supports optimal development. Such intelligent delivery systems represent a leap forward in precision agriculture, promising to increase yields while minimizing environmental inputs.[7]

The potential of nanofertilizers extends beyond yield enhancement. By increasing nutrient efficiency and reducing chemical inputs, they contribute to improved crop quality and food safety. This is particularly relevant in the context of food fortification, enhancing the nutritional value of crops by increasing their content of essential micronutrients such as iron, zinc, and selenium.[8] These improvements not only benefit consumer health but also support national food security and combat malnutrition. Additionally, by reducing the dependency on agrochemicals like herbicides and pesticides, nanofertilizers help lower the presence of toxic residues in agricultural produce.

However, the use of nanomaterials in food production also raises important questions about safety and long-term sustainability. While many studies highlight the positive effects of nanofertilizers on plant physiology and productivity, less is known about their fate in the environment, potential toxicity to non-target organisms, or accumulation in the food chain. These knowledge gaps highlight the need for systematic and long-term research to understand how nanoparticles behave under different climatic, soil, and crop conditions.[9] The ecological risks and bioaccumulation potential of these materials must be thoroughly evaluated to ensure their safe use in agriculture.

Soil health is another critical area where nanofertilizers can make a meaningful impact. By enhancing nutrient availability and stimulating microbial communities, they can restore degraded soils and improve their physical and chemical properties. Additionally, nanofertilizers have been reported to enhance soil water retention by influencing soil structure and organic matter content. This feature is particularly valuable in arid and semi-arid regions, where water scarcity is a major constraint on agricultural productivity.[10]

Despite their potential, several challenges must be addressed before nanofertilizers can be widely adopted in agriculture. These include the scalability and cost-effectiveness of production, uncertainties regarding environmental and human toxicity, and the lack of clear regulatory guidelines. Moreover, there is limited infrastructure in many countries to support the testing, approval, and monitoring of nano agricultural inputs. Regulatory frameworks must evolve to include robust safety assessments, risk management protocols, and standardized testing procedures to ensure responsible development and deployment.[11]

While previous reviews have covered various aspects of nanofertilizers such as synthesis methods or nutrient efficiency, this review provides a broader perspective by linking nanofertilizer use to food safety, reduction in chemical residues, and biofortification. It also integrates recent findings on long-term ecological impacts and toxicological risks, offering a more comprehensive view that includes environmental, agronomic, and public health dimensions. This comparative positioning underscores the relevance of the review not only as a technical summary but also as a strategic contribution to responsible innovation in agriculture.

Given these considerations, it is essential to foster interdisciplinary collaboration among nanotechnologists, agronomists, environmental scientists, toxicologists, and policymakers. Such cooperation is necessary to address technical, ethical, and regulatory concerns, and to build public trust in these emerging technologies. Moreover, investment in education and extension services will be key to supporting farmers in adopting and benefiting from nanofertilizers, particularly in regions where traditional practices dominate.

In this context, the review explores the evolving role of nanofertilizers within sustainable agricultural systems by examining technological innovations, their benefits and limitations, as well as associated risks. It provides a thorough overview of their significance in advancing food security and environmental sustainability. Additionally, the review identifies critical areas for future research and policy development, emphasizing the importance of knowledge generation, stakeholder engagement, and regulatory clarity for the responsible integration of nanotechnology into global agricultural practices.

2. Innovative roles of nanofertilizers in enhancing agricultural efficiency

Nanotechnology, through the precise manipulation of matter at the nanoscale, has emerged as a transformative force in agriculture and food systems. By leveraging nanoparticles for targeted applications, this technology contributes to enhanced crop performance, improved food quality, and better public health outcomes. Among the most widely studied and utilized nanoparticles are carbon-based nanomaterials, titanium dioxide (TiO_2), zinc oxide (ZnO), gold (Au), and silver (Ag), primarily due to their antimicrobial properties and high functional versatility. These nanoparticles are produced in quantities significantly higher than many other nanomaterials and are commonly found in a variety of products such as air filters, medical bandages, paints, deodorants, and food packaging materials.[12]

In the context of agriculture, nanofertilizers represent a promising innovation aimed at overcoming the limitations associated with conventional fertilizers. Traditional fertilizer practices often suffer from poor nutrient use efficiency and significant environmental runoff. Nanofertilizers, by contrast, are engineered to enhance nutrient delivery, reduce environmental losses, and optimize resource utilization. This is particularly relevant in addressing global concerns around soil degradation, declining crop yields, and the sustainable intensification of food production (Table 1).

One of the key advantages of nanofertilizers lies in their ability to enhance nutrient uptake and improve nutrient use efficiency. Their nanoscale structure provides a larger surface area, enabling better adhesion to plant roots and facilitating more effective absorption of essential elements.[14] Nutrients are often bound to nano-adsorbents that allow for slow and controlled release, ensuring that plants receive a steady nutrient supply throughout critical growth stages.[15]

This section delves into the diverse agricultural applications of nanofertilizers, emphasizing their mechanisms of action and their positive impacts on crop performance and resource conservation (Fig. 1).[17] Through these attributes, nanofertilizers contribute to more resilient and sustainable agricultural practices worldwide.

Although the use of nanoparticles (NPs) as fertilizers to promote agricultural production and enhance nutrient availability is gaining momentum, several challenges and concerns must be addressed to enable their safe and effective large-scale application. Toxicity-related risks, gaps in legislation, insufficient monitoring, and inconsistent research outcomes remain key obstacles. These small particles can deeply penetrate biological systems and may pose risks to plant health, soil ecosystems, and human safety. The toxicity (Fig. 2), safety, and environmental effects of various nanomaterials are still not fully understood.[18]

Nanoparticles produced through chemical and physical methods are generally more hazardous than those synthesized biologically. Furthermore, organic NPs are found to be less toxic to soil microorganisms compared to metallic and metal oxide NPs.[19] Although NPs are increasingly used to deliver essential nutrients, nano-toxicity remains a central concern for both human health and the environment.[20,21] Hence, extensive research is required to better understand the potential impacts and mechanisms of toxicity, particularly in the case of biologically synthesized NPs.

At present, no comprehensive legislation or risk management framework exists to govern the use of nanofertilizers in sustainable crop production. Moreover, production levels remain insufficient to meet the quantities required for broad agricultural application.[22] The high production cost of nanofertilizers, significantly higher than that of conventional fertilizers, is another barrier, especially under diverse soil and climatic conditions. The lack of recognized standardization and formulation further contributes to variable and sometimes contradictory results, even when the same nanomaterials are applied to the same crops in different regions.[23,24]

A further concern is the marketing of many products labeled as “nano” fertilizers that do not meet the nano-size criterion (<100 nm), often consisting of larger micron-sized particles. This indicates a lack of proper regulation and monitoring in the current commercial landscape.[25,26]

Additionally, studies indicate that long-term persistence of nanoparticles in plant systems may lead to severe toxic effects. At high concentrations, nanoparticles can interfere with key physiological and morphological processes in plants. These include restricted root development, impaired nutrient and water uptake, reduced biomass production, delayed seed germination, and decreased leaf expansion. Toxic nanomaterials can also trigger oxidative stress, causing membrane disruption, altered gene expression, and disorganized chloroplast structures, all of which negatively affect photosynthesis and cellular integrity.[27]

Other practical limitations have been observed in the application of nanofertilizers. For example, foliar application requires large leaf surfaces and must be carefully dosed to avoid scorching. Efficacy is highly dependent on external conditions, such as weather and timing of application.[28] Moreover, there are challenges related to the uniformity of nanoparticle size, lack of standardized formulations, and incomplete knowledge regarding how these materials transform within the plant and move through the food chain. It remains uncertain whether all nanofertilizers are fully converted into ionic forms within plant systems, or if some remain intact and reach consumers via harvested food products. Most importantly, the majority of nanofertilizer studies to date have been conducted at laboratory or small experimental scales. More robust field research, detailed comparisons with conventional fertilizers, and improved characterization of nano-formulations are necessary to assess their real-world applicability and sustainability.[29]

Table 1
Advantages and disadvantages of various nanofertilizer formulation.[13].

CRNF Type	Advantages	Disadvantages
Carbon Based	These promote plant growth and help with water and nutrient retention. They also assist during drought stress.	The synthesis method is significantly more time-consuming.
Clay Based	These have a large surface area and exhibit nanolayer reactivity, which regulates the release of anions in a more controlled manner.	These affect leaf growth and transpiration, and sometimes inhibit them.
Nano-capsule Based	These have the ability to provide controlled release of encapsulated materials, making them highly efficient in nutrient delivery and reducing the risk of nutrient leaching.	These have a very complex synthesis process, and the materials required are not readily available.
Chitosan Based	These are biodegradable and adjustable in terms of size, can be easily modified, and have the ability to protect biomolecules from various environmental factors, making them highly suitable for hormone and enzyme applications.	These are water soluble (hydrophilic), have weak mechanical strength and properties, and also exhibit low encapsulation efficiency.
Nano-gel Based	These are highly soluble, which also makes them more biodegradable and non-toxic to the environment. They also aid in water retention.	These have limitations in optimizing biodistribution and degradation mechanisms.
Starch Based	These are renewable energy sources that produce little or no chemical waste.	These are more expensive and time-consuming to synthesize. They are also inherently unstable.
Zeolite Based	These have a better and improved nutrient delivery system, which reduces fertilizer costs more effectively.	These require specific formulations and synthesis processes for better and optimized performance. They are also not suitable for anionic nutrients.

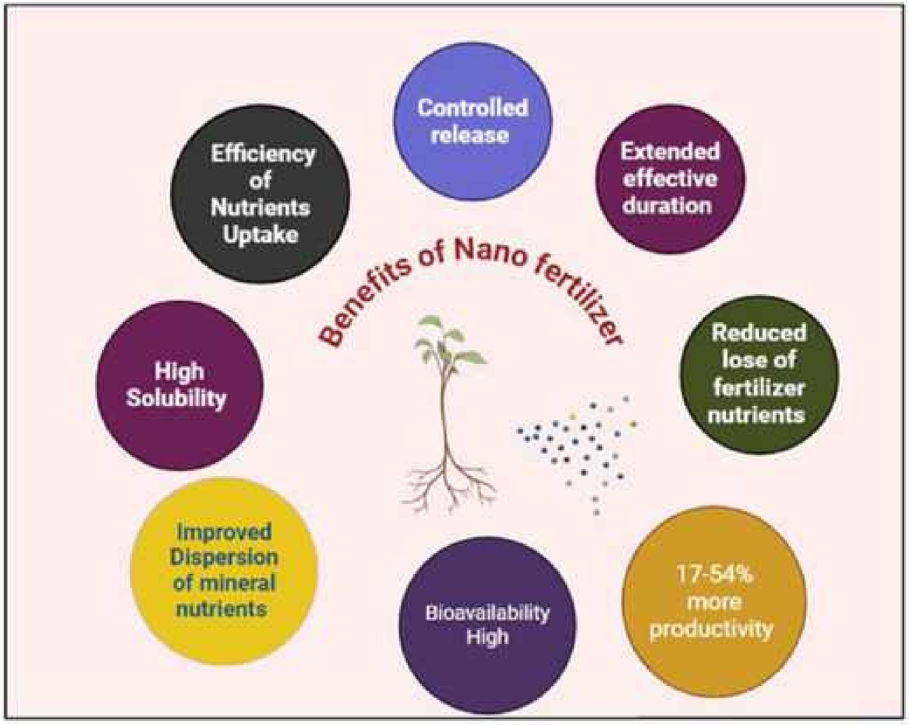

Fig. 1. Diagram shows the benefits of nanofertilizer[16].

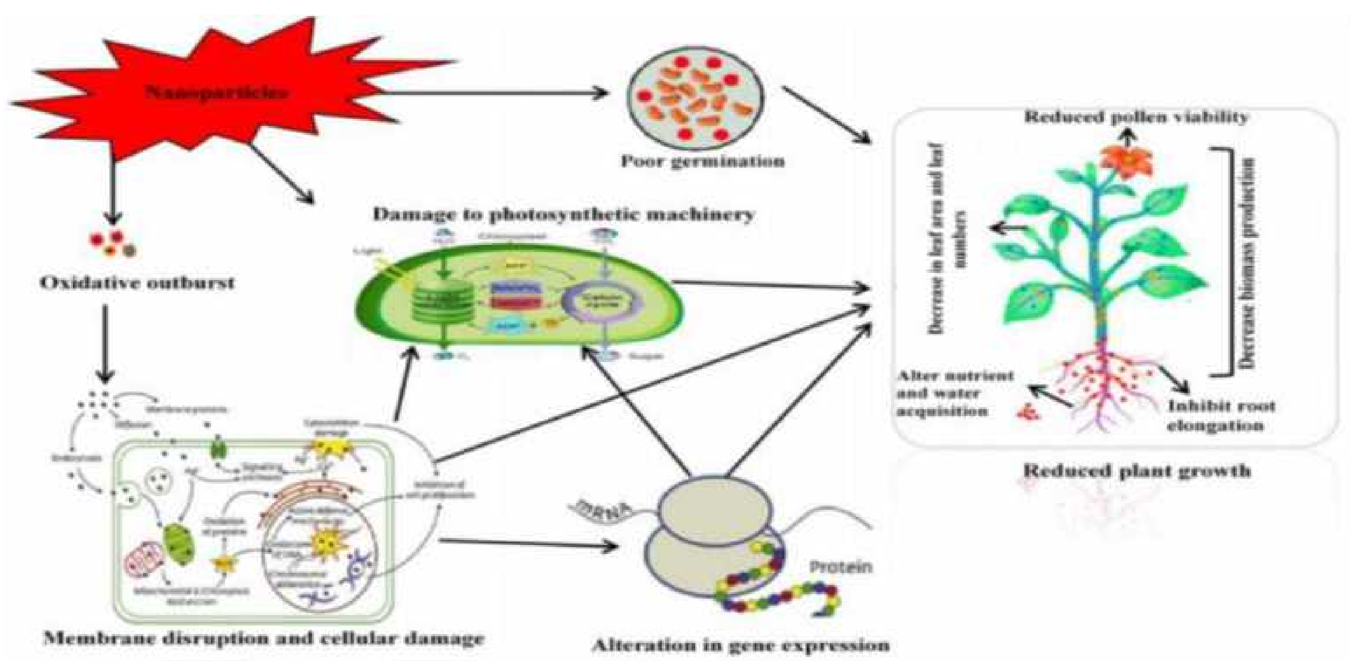

Fig. 2. Harmful impacts of nanoparticles on plant growth and development[80].

2.1. Improving nutrient solubility and plant uptake efficiency with nanofertilizers

One of the most compelling benefits of nanofertilizers is their capacity to improve nutrient solubility and bioavailability, particularly when compared to traditional fertilizer formulations. Conventional fertilizers often encounter limitations such as nutrient fixation in the soil or leaching, which reduces the proportion of nutrients accessible to plants. In contrast, nanofertilizers harness the distinct physicochemical properties of nanoparticles, such as their expansive surface area and nanoscale size, to facilitate superior nutrient delivery and assimilation. This enhanced efficiency stems from the ability of nanoparticles to move more freely within soil matrices and plant tissues, penetrating root and leaf structures to deliver essential elements with higher precision. For example, nanoscale formulations of nitrogen, phosphorus, and potassium demonstrate markedly better uptake by roots, resulting in more effective fertilization and reduced environmental losses.[30]

In modern agriculture, especially in systems experiencing soil exhaustion from intensive cropping, nutrient availability remains a critical limiting factor. Fertilization strategies must not only remedy nutrient deficiencies but also ensure appropriate elemental interactions to sustain productivity over time. Fertile soils demand maintenance to uphold their health, whereas nutrient-poor soils require strategic interventions to restore balance. Among the leading constraints in horticulture are inadequate nutrient levels, water scarcity, and unsuitable soil pH. Thus, a comprehensive approach, incorporating laboratory diagnostics and agrochemical analysis, is essential for crafting tailored soil fertility programs.[31]

Empirical studies further validate the promise of nanofertilizers. For instance, Ref. 8 reported that wheat treated with nano-coated urea experienced a 30 % improvement in growth compared to those receiving conventional urea. Additionally, nano-silica has been shown to boost the absorption of vital trace elements like iron and zinc, thereby enriching the micronutrient profile of crops.

Recent work by[32] underscores the broader implications of nanofertilizers on crop quality. These formulations not only enhance nutrient availability but also support vital biochemical processes, leading to superior produce in terms of nutritional content, physiological integrity, and post-harvest longevity.

2.2. Environmental impacts and minimizing environmental footprint

Conventional fertilizer use often leads to serious ecological problems, including nutrient leaching, water pollution, and soil degradation. Nanofertilizers offer a promising alternative by significantly reducing nutrient loss and environmental harm. Their controlled-release capabilities allow gradual nutrient delivery, preventing excess runoff into groundwater and nearby ecosystems.[4,32] This sustained release enhances nutrient retention in soil and uptake by crops, reducing the quantity of fertilizer needed and lowering greenhouse gas emissions associated with fertilizer production and use.[4,33]

However, the presence of nanoparticles (NPs) in the environment may have complex effects on plants and ecosystems. NPs can be absorbed directly through plant surfaces or indirectly via the environment, potentially accumulating in seeds and transferring to subsequent generations, which may cause toxicity if concentrations surpass bioconcentration thresholds. Yet, NPs also can protect plants against abiotic stressors, enhance photosynthesis, and mimic antioxidant enzymes.[34] The impact of NPs varies with plant species and concentration, influencing germination, growth, biomass, and nutrient uptake.

Despite environmental benefits like reduced nutrient leaching and decreased emissions of nitrous oxide,[33] concerns remain regarding the accumulation of nanoparticles in soil and water, potentially affecting beneficial soil microbes, aquatic life, and non-target organisms.[4,35] The interactions between nanofertilizers and indigenous soil microbiota, crucial for soil health and ecosystem functioning, require further investigation.[34] Comprehensive, long-term ecological and toxicological studies are essential to ensure the sustainable and safe use of nanofertilizers in agriculture.

2.3. Advancing crop quality and minimizing pesticide residues

Nanofertilizers improve nutrient uptake efficiency by delivering nutrients in a targeted, controlled manner tailored to soil and crop needs, thus supporting optimal growth and increasing yields.[36,37] Beyond yield enhancement, they contribute to the nutritional fortification of crops by increasing the levels of essential minerals, vitamins, and antioxidants. For example, nanofertilizers containing trace elements such as iron and zinc have been shown to significantly enhance the micronutrient content of staple crops like wheat and rice, addressing widespread micronutrient deficiencies.[8]

Furthermore, nanofertilizers can reduce the agricultural sector's reliance on chemical pesticides. Nanomaterials with antimicrobial properties, such as nano-silver, effectively suppress plant pathogens, decreasing the need for synthetic pesticides and reducing pesticide residues in food products and the environment.[9,38,39] This dual function of enhancing nutritional quality while minimizing harmful agrochemical residues supports a more holistic approach to food safety and sustainable agriculture. As shown in Fig. 3, the integration of nanofertilizers into crop production supports a more holistic approach to food safety – enhancing both the nutritional value of crops and reducing exposure to potentially harmful agrochemicals.

2.4. Nanofertilizers and their role in soil health and microbial dynamics

Soil microorganisms form the backbone of essential biogeochemical processes, playing a critical role in the cycling of nutrients, decomposition of organic matter, and synthesis of proteins and nucleic acids. They are especially important in the transformation of phosphorus and other essential elements required for plant development. Alongside particle size, various soil characteristics, including pH, organic matter content, and ionic strength, significantly influence the behavior of nanoparticles and their interactions with soil microorganisms and plant roots.[40]

The development of nano-bio fertilizers, which integrate beneficial soil microbes with nanotechnology, represents a major innovation in sustainable agriculture. These hybrid fertilizers aim to enhance nutrient availability, stimulate plant growth, and improve soil structure and biological activity. However, their influence on soil biological activity is not universally positive or guaranteed; it depends on several prerequisites and influencing factors such as soil type, microbial community composition, environmental conditions, and application methods. Understanding these factors is crucial to optimize their effectiveness and minimize potential adverse effects.[41]

By combining nanoparticles with microbial inoculants, nano-bio fertilizers support both the chemical and biological fertility of soil ecosystems. However, despite their many potential advantages, careful assessment of the risks and long-term effects of nanofertilizers remains crucial. The unregulated release of nanoparticles into the environment raises concerns related to human health, food safety, and ecological balance.[14]

Soil characteristics such as pH and phosphate levels greatly influence nanoparticle chemistry. Under low pH, certain nanoparticles may dissolve more readily, releasing reactive oxygen species that can be detrimental to soil organisms. Conversely, interactions with organic matter may stabilize nanoparticles, modifying their surface properties and, consequently, their behavior in soil systems. These changes can alter how nanoparticles affect plant roots and soil microorganisms. Additionally, microbial communities themselves can impact the fate and transport of nanoparticles through their metabolic processes and secretions.[36]

Nanofertilizers can have both beneficial and adverse effects on soil microbial communities. On the positive side, specific nanoparticles may stimulate the proliferation of beneficial microbes involved in nitrogen fixation, phosphorus solubilization, and organic matter decomposition. For example, nano-enabled fertilizers may enhance soil aggregation and porosity, leading to improved water retention and aeration, conditions favorable for microbial life and root development.[42] As shown in Fig. 4, these improvements in microbial interactions directly contribute to healthier soil and enhanced crop productivity.

Furthermore, nanofertilizers can promote microbial diversity, a key indicator of soil ecosystem resilience. Enhanced microbial diversity supports a wide array of soil functions and can buffer ecosystems against environmental stresses, contributing to long-term agricultural sustainability. Over time, reliance on conventional mineral fertilizers has been shown to degrade soil organic matter and disrupt microbial communities, weakening soil structure and increasing greenhouse gas emissions. This reinforces the need for more environmentally sound fertilization strategies such as nano formulations.[43,44] (Table 2).

The impact of nanofertilizers on soil microbial activity is not uniform

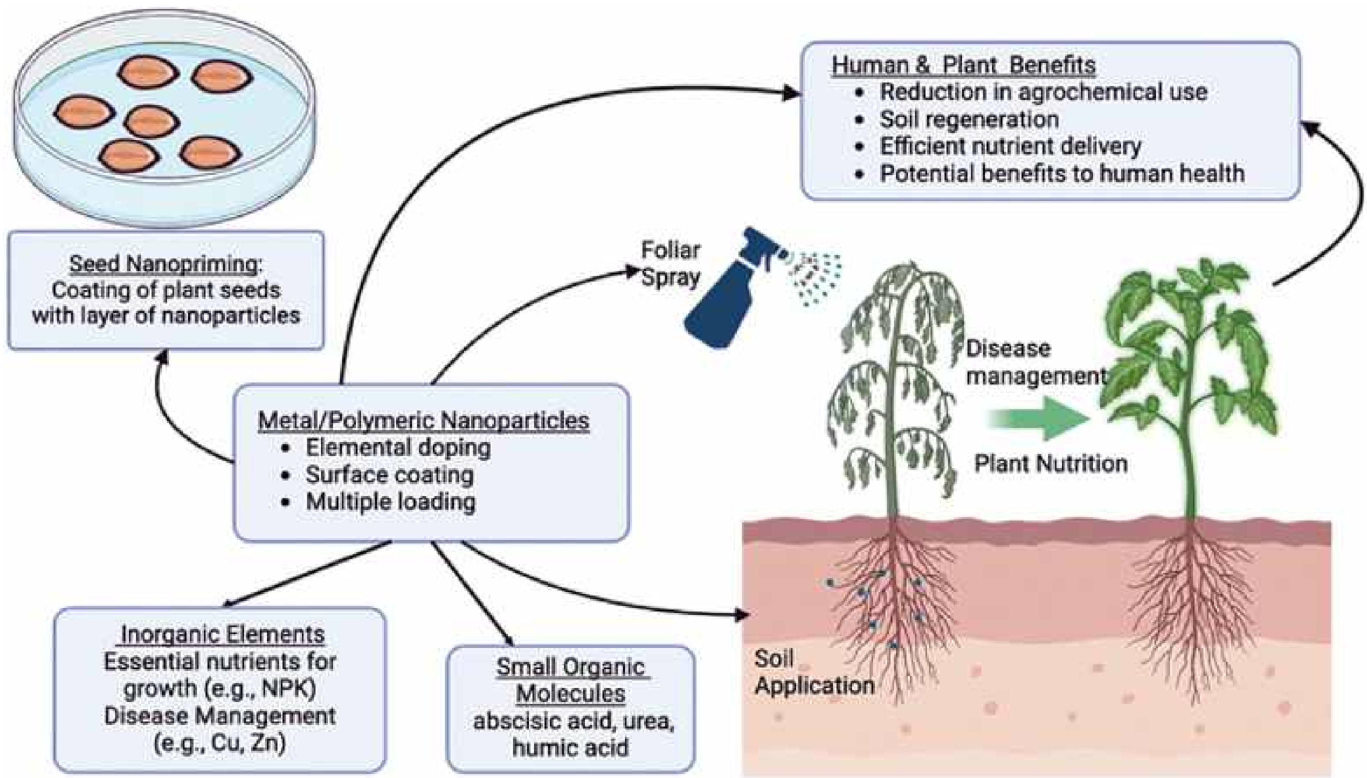

Fig. 3. Advantages of delivering nanofertilizers and nanostimulants for promoting plant growth and supporting environmental sustainability[5].

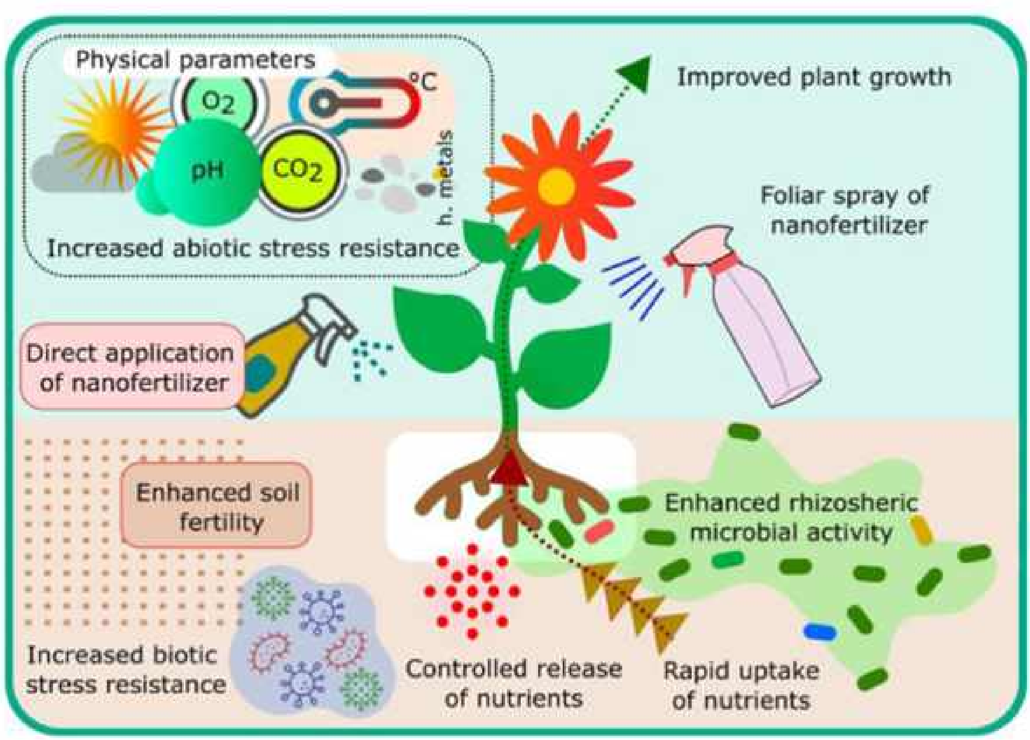

Fig. 4. The use of nanofertilizers offers multiple benefits to plants, such as enhanced nutrient absorption, stimulated microbial activity, greater resistance to biotic stresses, improved tolerance to abiotic conditions, and overall enhancement of soil fertility, all contributing to better plant growth and development[36].

and varies according to soil type and its physicochemical properties. pH, in particular, plays a decisive role. For instance, zinc oxide (ZnO) nanoparticles are more likely to convert into their ionic forms under acidic conditions, potentially increasing toxicity to soil biota. At higher pH levels, nanoparticles tend to form aggregates, which may limit their bioavailability. Most nanomaterials have demonstrated moderate to

Table 2
Impact of different nanofertilizers and nanoparticles on soil microbial communities and enzyme activity.[36]

Nanofertilizers/ nanoparticles	Dose and mode of application	Effect on microorganism	Effect on microbial functions	References
Metallic silver (Ag)	0.01–1 mg/kg, direct application to soil 50 mg/kg, direct application to soil 15–500 μ g/g, direct application to soil	Increased abundance of Proteobacteria, Acidobacteria; Enhanced abundance of Proteobacteria; reduced abundance of Acidobacteria Increased diversity of Proteobacteria	Improved microbial metabolic activity; Degradation potential of soil pollutant like xenobiotic compounds increased Increased organic decomposition of soil pollutants like xenobiotic compounds.	45
Metallic copper (Cu)	80–280 mg/kg, direct application to soil; 3 mg/kg, direct application to soil	Significant increase in Bacteroidetes and Saccharibacteria; Improved activity of Ammonia Oxidizing Bacteria	No harmful effects on P solubilization and nitrogen fixation; Enhancement in nitrification.	46
Copper oxide (CuO)	10–1000 mg kg, direct application to soil; 1–100 mg kg, direct application to soil	Significant increase in population of Caulobacterales, Burkholderiales, Xanthomonadales and Clostridiales were; Improved relative abundance of members belonging to Proteobacteria and Bradyrhizobiaceae family and decline in diversity of Firmicutes.	Proper regulation of nitrogen cycles; Enhanced nitrogen fixation and reduction in soil pollutant	47
Iron oxide (Fe_3O_4)	NA	Relative abundance of Bacillales is significantly enhanced.	Improved degradation potential of synthetic compounds in soil is reported in members of the family like Bacillales.	46
Zinc oxide (ZnO)	0.5–2 mg/g, direct application to soil; 0–500 mg/kg, direct application to soil	Improved relative abundance of Bacilli, and γ-Proteobacteria α-Proteobacteria; No profound effect on fungal diversity but bacterial community was sensitive	NA NA	48,49

severe toxicity to soil microorganisms at pH values between 4.5 and 7.2.[50]

Research by[50] investigated the effects of four types of nanomaterials – ZnO, titanium dioxide, cerium dioxide, and magnetite, on bacterial populations in different soils. Results showed that ZnO nanoparticles improved microbial diversity more in saline-alkaline soils than in weakly acidic soils. Additionally, soil enzyme activity was more negatively affected in acidic soils than in calcareous soils when exposed to ZnO nanoparticles. Paradoxically, despite higher metal sorption in calcareous soil, microbial catabolism suffered greater inhibition, underscoring the complex interactions between soil type, nanoparticle chemistry, and microbial function.

Nanofertilizers offer significant potential to enhance soil fertility through improved nutrient delivery and stimulation of beneficial microbial activity. However, their effects on soil ecosystems are nuanced and context-dependent. Understanding the interaction between soil properties and nanoparticle characteristics is essential to harnessing the benefits of nanofertilizers while minimizing ecological risks. Ongoing research is needed to fully explore these relationships and develop guidelines for their safe and effective use in sustainable agriculture.

3. Challenges and considerations in the application of nanofertilizers in agriculture

Nanotechnology holds considerable promise as a transformative approach in the agricultural sector, offering novel tools to investigate plant biochemical processes and improve traditional farming methods. It facilitates the evaluation of environmental impacts while enhancing agricultural productivity through technological innovations. When compared with other green technologies and agricultural biotechnology, nanotechnology emerges as a more rapid and effective means of influencing the agricultural value chain, with implications for environmental, legal, ethical, and public welfare considerations.[51]

The integration of nanoscale agrochemicals, such as nanofertilizers, nanoformulations, nanopesticides, and nanosensors, has the potential to revolutionize conventional agricultural practices. These materials contribute to making agriculture more efficient and environmentally friendly by improving nutrient delivery and reducing input losses. However, despite these promising advancements, the widespread use of nanofertilizers in real-world agricultural settings is still constrained by several challenges. These include technical hurdles, environmental safety concerns, regulatory ambiguity, and economic feasibility. Addressing these limitations requires ongoing research and innovation.

In recent years, significant strides have been made in both agricultural practices and nanomaterial engineering. These advancements have introduced precision-targeted technologies with enhanced functional properties. Nanotechnology, in particular, is increasingly recognized for its capacity to address multiple agricultural issues by improving nutrient bioavailability and enhancing plant metabolic functions. The conventional overuse of agrochemicals such as herbicides, pesticides, and synthetic fertilizers has led to adverse ecological and social effects. Nanofertilizers (NF), as a more recent development, offer a promising alternative by participating in essential physiological and biochemical processes through their high surface-area-to-volume ratio and improved nutrient interaction.[16]

Nanotechnology provides smart tools, such as nanoscale nutrient carriers and responsive delivery systems, which optimize plant uptake and support resistance against pathogens. This innovation has the potential to reshape the agricultural and food industries. Nevertheless, the indiscriminate or excessive use of conventional fertilizers has historically degraded soil chemistry and structure, reducing the arable land available for cultivation. In contrast, the careful application of nanofertilizers can enhance crop yields, boost soil health, minimize nutrient runoff, and support the development of beneficial soil microflora.[52] As such, the formulation and responsible use of nanofertilizers are gaining increased attention from soil scientists and environmental researchers focused on achieving sustainable agricultural practices.

3.1. *Scalability and cost-effectiveness*

A major obstacle to the widespread adoption of nanofertilizers lies in the challenges associated with scaling up their production and ensuring economic viability. Although numerous laboratory experiments have confirmed the effectiveness of nanofertilizers in improving plant nutrition and growth, replicating these outcomes on a commercial scale remains complex. This difficulty stems primarily from the intricate and expensive nature of nanoparticle synthesis, which often requires advanced technological infrastructure and high-cost raw materials that are not yet suitable for mass production.[53]

To facilitate broader use in agriculture, especially in resource-limited regions, production methods must evolve to become more cost-effective and scalable. Ensuring that nanofertilizers are competitively priced is essential for encouraging adoption among farmers, particularly in developing countries where traditional fertilizers continue to be more accessible and affordable. The economic feasibility of nanofertilizer production must be considered alongside its technical benefits to ensure integration into mainstream agricultural practices (Table 3).[60]

3.2. Regulatory challenges and safety considerations

The rapid progress of nanotechnology in agriculture has highlighted a significant gap in regulatory frameworks designed to ensure the safety and effectiveness of nanofertilizers. The absence of standardized testing protocols and clear safety guidelines for nanomaterials presents a major challenge to the widespread adoption of these innovations. Key regulatory bodies, such as the U.S. Environmental Protection Agency (EPA) and the European Food Safety Authority (EFSA), have yet to establish specific regulations for the approval of nanofertilizers. This regulatory uncertainty could slow down the commercialization of nanofertilizers, as both producers and farmers may be reluctant to adopt technologies that lack clearly defined approval procedures.[61]

Moreover, the wide variety of nanomaterials, each with distinct properties and compositions, complicates the creation of universal safety standards. The unique characteristics of each nanoparticle, including size, shape, surface charge, and chemical composition, may result in different behaviors and risks. This diversity makes it difficult to formulate broad regulatory frameworks that can address the safety of all forms of nanofertilizers. As a result, comprehensive research into the specific risks and long-term impacts of individual nanoparticles used in fertilizers is essential to ensure they do not present significant health threats to humans, animals, or ecosystems.[62]

3.3. Knowledge gaps and the need for long-term data

Although initial studies on nanofertilizers have shown promising results, significant knowledge gaps remain regarding their behavior and efficacy in real-world agricultural environments. Most of the existing research has been conducted under controlled laboratory conditions or in small-scale field trials. While these studies provide valuable insights, their findings may not always be directly applicable to large-scale agricultural operations.[8] Factors such as soil composition, local climate, and the specific crop species involved can all influence the performance of nanofertilizers. Therefore, additional research is required to assess their effectiveness in a variety of agricultural settings.

Furthermore, the long-term effects of nanofertilizers on crop productivity, food safety, and environmental health are still largely unknown. While short-term studies have indicated potential benefits, such as improved nutrient uptake and higher yields, the sustainability of these benefits over multiple growing seasons has not been thoroughly examined. Long-term research is crucial to assess the potential accumulation of nanoparticles in the soil, as well as their long-term impacts on plant growth, soil health, and the broader agricultural ecosystem.[63] Such studies will help to better understand the environmental and health risks associated with the prolonged use of nanofertilizers, ensuring their safe and sustainable integration into agricultural practices.

Table 3
Newly developed nanofertilizers and their practical applications.[14]

Nanofertilizers	Application	Reference
Nanoscale iron oxide	Have been used to coat urea in nanofertilizers. This coating helps control water nutrient loss in soil.	30
Slow-release phosphorus nanofertilizers	Nano-rock phosphate and nano-hydroxyapatite, have shown promising results in supplying phosphorus to plants throughout their life cycle, improving phosphorus utilization, and enhancing plant growth and yield.	54
Calcium nanoparticles	Enhance calcium availability to plants. This can improve plant growth and development enhancing plants' resistance to disease and pests.	55
Magnesium nanoparticles	To provide plants with readily available magnesium. This micronutrient is essential for various physiological processes in plants.	56
Copper nanoparticles	Enhance copper availability to plants. Copper is a micronutrient required for various plant metabolic processes.	57
Zinc nanoparticles	Can improve zinc uptake by plants. Zinc is an important micronutrient for plant growth and development.	48
Potassium nanoparticles	Improve potassium availability to plants. Potassium is a macronutrient required for various plant metabolic processes, higher absorption rates and are more resistant to leaching.	58
Boron nanoparticles	To enhance boron availability to plants. Boron is a micronutrient required for various plant physiological processes.	59

3.4. Farmer education and adoption challenges

The successful integration of nanofertilizers into agricultural practices heavily relies on the willingness of farmers to adopt this innovative technology. In many regions, particularly in developing countries, farmers tend to stick with traditional fertilization methods due to factors such as cost, familiarity, and a lack of awareness regarding the potential benefits of nanofertilizers. To overcome this barrier, it is crucial to implement extensive education and outreach programs that can inform farmers about the advantages of nanofertilizers, including improvements in crop yield, nutrient efficiency, and environmental sustainability.[64]

Furthermore, the high initial cost of nanofertilizers, along with the uncertainty surrounding the safety and effectiveness of this new technology, could deter many farmers from making the transition. Given that nanofertilizers represent a significant upfront investment, financial support mechanisms such as subsidies or incentives from governments, agricultural organizations, or other stakeholders may be necessary to alleviate financial concerns and encourage the widespread adoption of nanofertilizers.[65]

4. IMPACT of nanofertilizers on food quality, safety, and nutritional enhancement

Nanotechnology is increasingly being applied across various sectors, including agriculture and food processing, offering exciting opportunities for enhancing food quality, safety, and nutritional content. Nanotechnology can improve food processing and packaging, enhance flavor and nutrition, and produce functional foods with added medicines and supplements. It also contributes to more cost-effective food production and increased overall food output.[66]

By modifying the size and aggregation of particles, as well as manipulating the surface charge of food nanomaterials, nanotechnology improves food stability, texture, taste, and bioavailability (Fig. 5).[67] In food packaging, for example, bionanocomposites, hybrid nanostructured materials, are used to enhance mechanical, thermal, and gas barrier properties, resulting in extended shelf life and providing more environmentally friendly solutions by reducing reliance on plastic packaging materials.[66]

Weiss et al.[68] have highlighted key advancements that nanotechnology is expected to bring to the food industry, including.

1. Enhanced security in food manufacturing, processing, and shipping, through sensors capable of detecting pathogens and contaminants.
2. Devices to maintain historical environmental records and track shipments, ensuring better transparency and quality control.

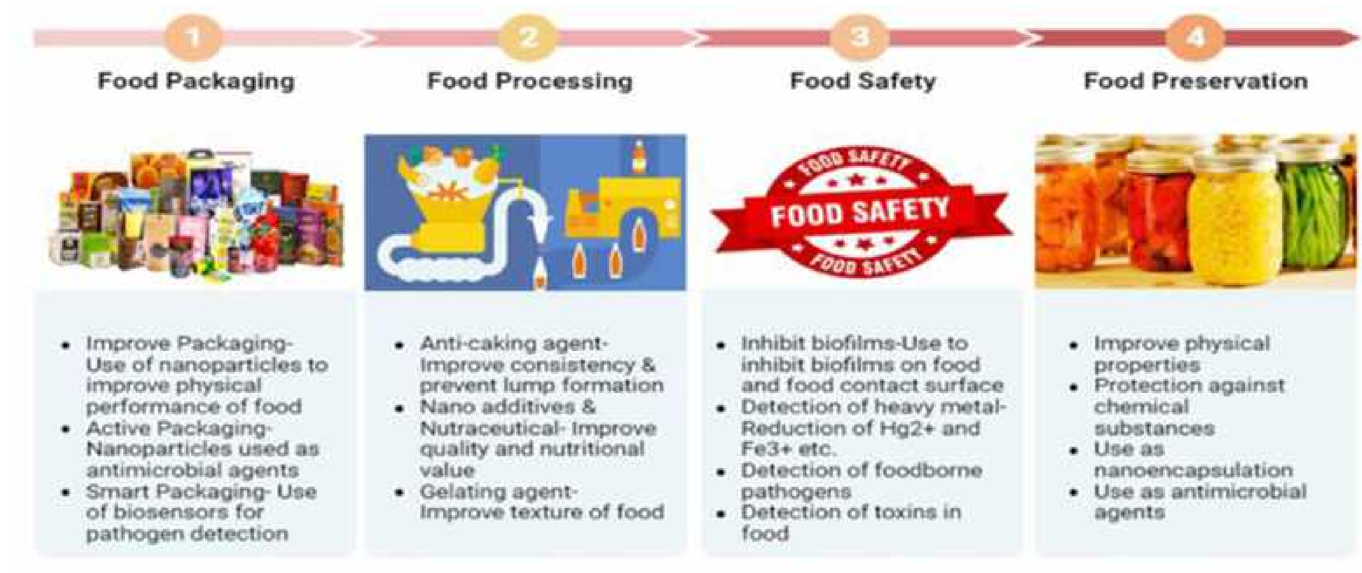

Fig. 5. Nanotechnology applications in the food industry[67].

3. The development of integrated systems that combine sensing, localization, reporting, and remote control, boosting food processing and transportation efficiency.
4. Advanced encapsulation and delivery systems designed to protect and deliver functional food ingredients to specific target areas within the body.

However, it is important to clarify that this review specifically focuses on nanofertilizers and their direct impact on food quality, safety, and nutritional enhancement in agricultural production. Therefore, while general nanotechnology applications in food processing and packaging are significant, this section emphasizes the role of nanofertilizers in improving crop nutrient content, reducing harmful chemical residues, and enhancing food safety through sustainable agricultural practices.[69]

The application of nanofertilizers in agriculture is not only aimed at improving crop yields and sustainability but also plays a crucial role in enhancing food quality and safety. By delivering nutrients more efficiently, nanofertilizers can improve the nutritional content of crops, address micronutrient deficiencies, and reduce the reliance on harmful chemicals, all of which contribute to safer, more nutritious food. This section delves into the various ways in which nanofertilizers contribute to food quality, safety, and nutritional enhancement[63] (Table 4).

Food safety is a major public concern, with foodborne illnesses causing significant health risks. Nanotechnology has the potential to play a crucial role in food safety management by providing innovative solutions to reduce foodborne diseases and ensuring the overall quality of food products.[75] Nanomaterials, such as polymeric nanoparticles, nano-loaded emulsions, and nano-vesicles, are already being studied and used to improve food quality by extending shelf life, detecting freshness, and identifying contaminants like chemicals, heavy metals, and allergens (Table 5).

Furthermore, nanotechnology offers promising applications in the development of functional foods with enhanced nutritional content and flavor. Techniques like nanoencapsulation allow for gradual release of flavors and preservation of nutrients, improving bioavailability and ensuring that delicate functional compounds are protected and delivered effectively.[76,77]

The role of nanotechnology in food safety extends across the entire food supply chain. Traditional food analysis, which is often done in centralized labs and involves testing only a limited number of samples, can be improved with portable, quick, and affordable testing systems. These systems, powered by nanomaterials, can enable real-time monitoring of food quality and safety during transportation, storage, and usage. By utilizing chemical transduction or biosensing technologies, these platforms offer improved selectivity and can measure volatile substances or detect specific biomolecules, enhancing the overall safety and quality of food products.[67]

Table 4
Nano-formulations of various forms and their uses in the food sector.[67]

Method	Ingredients	Functions	Product	Reference
Emulsification with ultrasound	Ultrasound rays with a high concentration	To modify the attributes of the targeted items	Nanoemulsions of water and oil	70
Encapsulation	Liposomes	Incorporate food anti-microbial to safeguard food items	Phospholipids	71
Nanoencapsulation	Liposomes	Carriers for antioxidants based on lipids	Nanoliposomes	72
Encapsulation	NPs made of biopolymers that degrade	Deliver medications, vaccinations, but also proteins in capsule form	Polylactic-acid	73
Nanoemulsions	Droplets containing food ingredients	Foods with flavours, mineral, vitamin and antioxidant-fortified milk	Droplets with colloidal-dispersion	74
Nanospray drying	Nano-capsules of superior functionalities	Drying and encapsulation of different food ingredients	Vitamins and minerals, phenolic compounds, carotenoids and essential oils and fatty acids	67
Optical method	A monoclonal antibody-based gold nanoparticle immune-chromatographic assay	Detection of mycotoxins	Corn	67

Table 5
Examples of foods, agricultural products, and packaging materials that incorporate nanomaterials.[66]

Type of product	Product name and manufacturer	Nano content	Purpose
Beverage	Oat Chocolate and Oat Vanilla Nutritional Drink Mixes; Toddler Health	300 nm particles of iron (SunActive Fe)	Nano-sized iron particles have increased reactivity and bioavailability.
Food additive	Aquasol preservative; AquaNova	Nanoscale micelle (capsule) of lipophilic or water insoluble Substances	Nano-encapsulation increases absorption of nutritional additives, increases effectiveness of preservatives and food processing aids. Used in wide range of foods and beverages.
Food additive	Bioral™ Omega-3 nanocochleates; BioDelivery Sciences International	Nano-cochleates as small as 50 nm	Effective means for the addition of highly bioavailable Omega-3 fatty acids to cakes, muffins, pasta, soups, cookies, cereals, chips and confectionery.
Food additive	Synthetic lycopene; BASF	LycoVit 10 % (<200 nm synthetic lycopene)	Bright red colour and potent antioxidant. Sold for use in health supplements, soft drinks, juices, margarine, breakfast cereals, instant soups, salad dressings, yoghurt, crackers etc.
Food contact material	Antibacterial kitchenware; Nano Care Technology/ NCT	Nanoparticles of silver	Ladles, egg flips, serving spoons etc. have increased antibacterial properties.
Food packaging	Nano ZnO Plastic Wrap; SongSing Nanotechnology	Nanoparticles of zinc oxide	Antibacterial, UV-protected food wrap.
Plant growth treatment	PrimoMaxx, Syngenta	100 nm particle size emulsion	Very small particle size means mixes completely with water and does not settle out in a spray tank.

4.1. Innovations in natural polymer nanomaterials for enhancing food safety

Recent advancements in the application of natural polymer nanoparticles (NPs) have opened up exciting opportunities for improving food safety and quality. One notable development is the use of nanocellulose, a nanomaterial derived from cellulose, which is gaining traction in food packaging applications. Nanocellulose-based films and coatings exhibit exceptional barrier properties, preventing gases and moisture from penetrating the packaging, thus preserving the freshness and quality of food products. Additionally, nanocellulose-based sensors are being developed to detect signs of food decomposition, enabling real-time monitoring of product freshness and safety.[78]

Another significant innovation in food safety involves the use of chitosan nanoparticles (NPs), which are derived from chitin, a natural polymer found in the exoskeletons of shellfish. Chitosan NPs have demonstrated strong antibacterial properties, making them effective in combating pathogenic bacteria in food products. These nanoparticles can be incorporated into edible coatings, films, and packaging materials, creating protective barriers that reduce the risk of contamination.[79]

Furthermore, chitosan NPs can encapsulate bioactive substances, such as vitamins and antioxidants, gradually releasing them to enhance the nutritional value and safety of the food.[75]

The use of natural polymer NPs in food safety not only addresses challenges related to food preservation and quality but also aligns with growing consumer demand for sustainable and environmentally friendly packaging solutions. By utilizing biodegradable materials like nanocellulose and chitosan, the food industry can reduce its reliance on synthetic polymers, which have adverse environmental impacts. These advancements reflect a promising direction toward both enhancing food safety and meeting the increasing need for sustainable practices in the food industry.

Additionally, in the context of nanofertilizers, recent innovations have focused on integrating natural polymer-based nanomaterials to improve nutrient delivery while simultaneously enhancing crop protection. For example, chitosan-based nanofertilizers not only promote efficient nutrient uptake but also exhibit antimicrobial properties that reduce the need for chemical pesticides, thereby lowering pesticide residues on food products and contributing directly to improved food safety. These multifunctional nanofertilizer formulations represent a promising area of development for sustainable and safer food production.[75]

Indeed, nano-fertilizers provide a multifaceted approach to improving plant nutrition and resilience. They can be applied via foliar spray or soil amendment to deliver essential nutrients more efficiently and with reduced losses compared to conventional fertilizers. For example, Thavaseelan and Priyadarshana (2021)[80] demonstrated that nano-fertilizers significantly increase chlorophyll content in leaves, directly enhancing photosynthetic capacity and thus promoting plant growth.

Moreover, nano-fertilizers are cost-effective and highly efficient, as supported by Zahra et al. (2022),[81] who reported improved nutrient uptake efficiency and reduced environmental pollution. Guru et al. (2015)[82] highlighted the environmental benefits, showing that these fertilizers contribute to pollution prevention by minimizing nutrient runoff. Additionally, nano-fertilizers improve plant tolerance to abiotic stresses such as salinity and drought, a critical factor in climate change adaptation.[83]

Common nano-fertilizer components include zinc (Zn), calcium (Ca), manganese (Mn), silica (Si), and iron (Fe) oxides,[30,84] each playing distinct physiological roles (Fig. 6).

Specifically, zinc oxide nanoparticles (ZnO-NPs) have been extensively studied. Ahmad et al. (2023)[85] found that foliar application of ZnO-NPs on maize (Zea mays) increased growth by 11 %, enhancing phosphorus uptake and chlorophyll content, which directly correlates to improved biomass accumulation. Palacio-Márquez et al. (2021)[86] further demonstrated that zinc nitrate complexed with chitosan not only promotes photosynthetic activity but also accelerates plant maturation, as seen in green beans (*Phaseolus vulgaris*), offering practical advantages for crop management and harvest timing.

Magnesium-based nanoparticles, such as MgO and $MgCO_3$, have shown promise in mitigating drought stress. Silva et al. (2023)[87] reported increased accumulation of chlorophyll *a, b*, and carotenoids in lettuce (*Lactuca sativa*) after treatment, indicating enhanced stress resilience.

Additionally, salicylic acid (SA) nanoparticles can improve plant tolerance to abiotic stress like anoxia caused by excessive precipitation. Errázuriz-Montanares et al. (2023)[88] observed that foliar SA application in cherries (*Fragaria ananassa*) under root submersion stress improved stomatal conductance and transpiration, thereby enhancing gas exchange and overall physiological performance both pre- and post-harvest.

Collectively, these studies underscore the practical benefits of nanofertilizers, which not only boost plant growth and yield but also enhance stress tolerance and environmental sustainability.

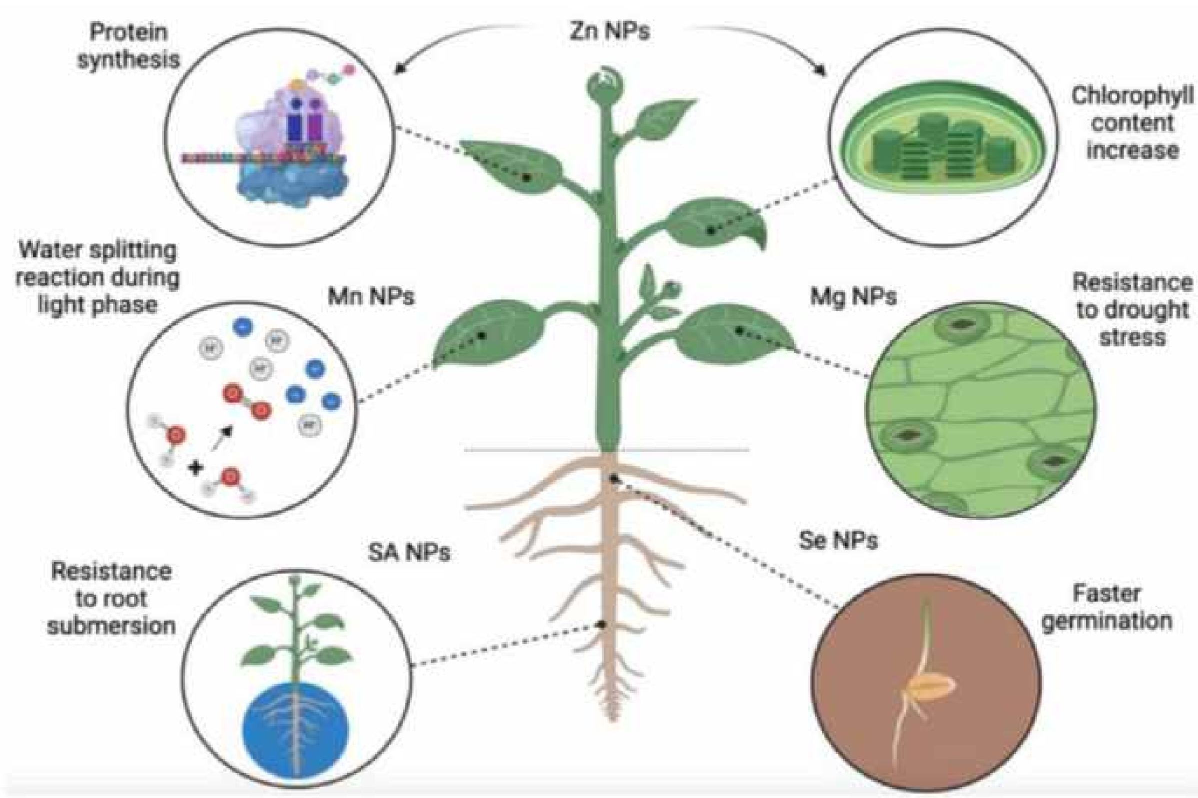

Fig. 6. Diagram illustrating the various advantages of using nanoparticles made from different chemical elements.[113]

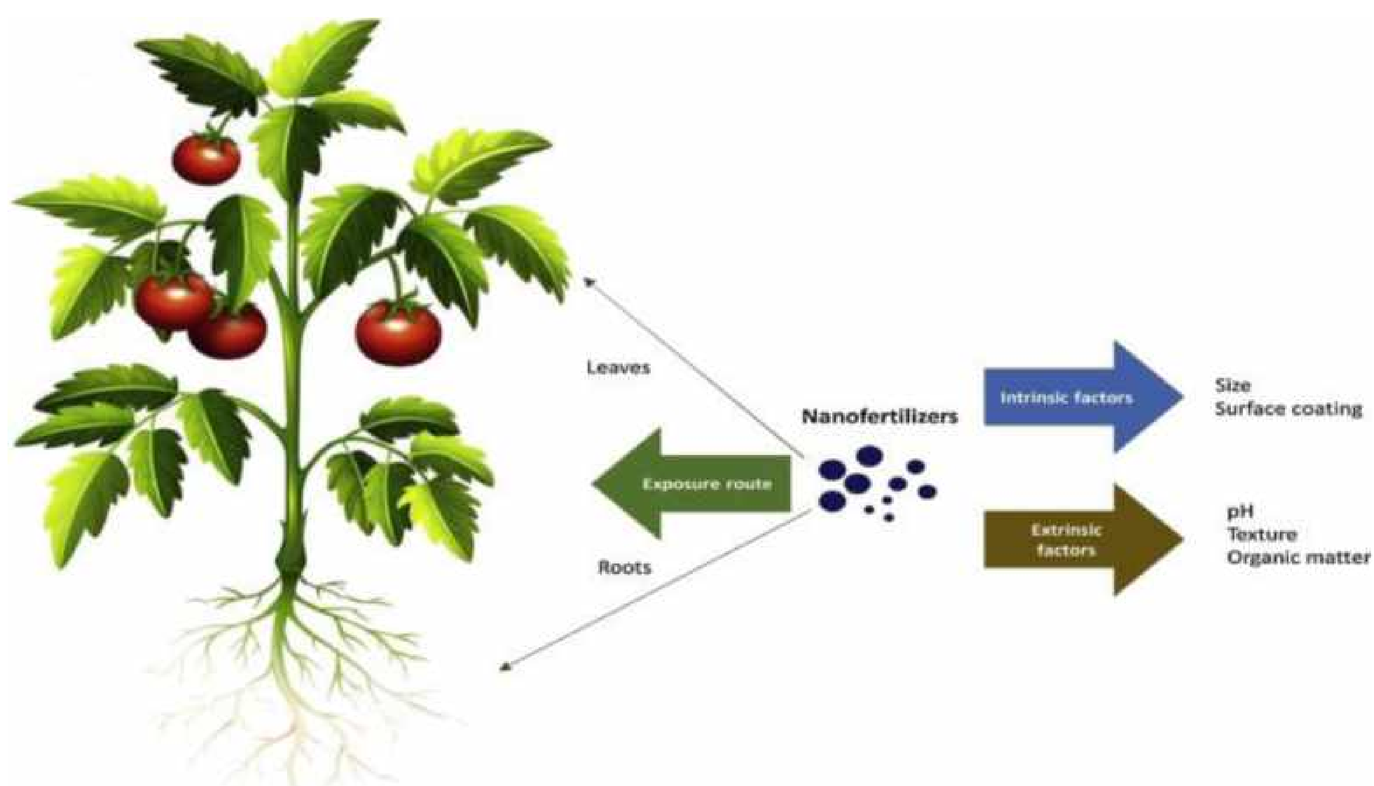

Fig. 7. Impact of nanofertilizers on crop quality[90].

4.2. Enhancing nutritional value and biofortification through nanofertilizers

One of the most promising applications of nanofertilizers is their role in improving the nutritional quality of crops while addressing global micronutrient deficiencies. Essential micronutrients, such as iron, zinc, calcium, and selenium, are often deficient in staple crops like rice, wheat, and maize, contributing to widespread health issues including iron-deficiency anemia and "hidden hunger". Nanofertilizers can help overcome these limitations by delivering nutrients in bioavailable forms, allowing plants to absorb them more efficiently.[16,89]

Nano-chelated forms of micronutrients, such as zinc and iron, have demonstrated a significant increase in micronutrient content in crops like beans, rice, and wheat.[16,89] These fertilizers are engineered to enable targeted and slow nutrient release, minimizing losses and reducing nutrient imbalances. Controlled-release nanofertilizers optimize nutrient uptake, leading to healthier crops enriched with vitamins, minerals, and antioxidants.[4] Fig. 7 illustrates the mechanism of controlled nutrient release and uptake efficiency in plants treated with nanofertilizers, highlighting their advantages over conventional fertilization methods. Furthermore, their nanoscale properties enhance nutrient penetration and retention in plant tissues, directly increasing the nutritional density of edible crop parts.[13]

In addition to micronutrient enhancement, nanofertilizers contribute to broader biofortification goals. When integrated with strategies like genetic improvement or traditional breeding, they offer a scalable and environmentally sustainable approach to nutritional security. Initiatives such as Harvest Plus have promoted nutrient-dense crops, e.g., vitamin A-enriched sweet potatoes and iron-rich beans, in low-income regions, with nanofertilizers playing a complementary role in increasing crop nutrient density.[12,91]

Recent research also highlights the potential of nanofertilizers to elevate levels of health-promoting phytochemicals like antioxidants and polyphenols, potentially leading to nutritionally superior foods (Fig. 8).[91] By supporting biofortification at the agronomic level, nanofertilizers can address malnutrition, particularly in regions where dietary diversity is limited. This makes them a vital component of integrated food security strategies aimed at improving global public health outcomes.[92]

It is important to note that while nanofertilizers contribute to improved nutritional value by enhancing nutrient uptake and reducing nutrient losses, food quality and safety are multifactorial outcomes. Their impact must be considered alongside other agricultural inputs, food handling practices, and environmental conditions. Thus, nanofertilizers should be viewed as an enabling technology within an integrated strategy for producing safe and nutritious food.

4.3. Enhancing crop resilience and post-harvest quality through nanofertilizers

Nanofertilizers also play a significant role in enhancing crop resilience to environmental stressors, including drought, salinity, and disease, which ultimately improves the post-harvest quality of food. By boosting plant defenses and optimizing nutrient absorption, nanofertilizers help crops endure harsh growing conditions, resulting in higher-quality produce with fewer defects and reduced spoilage. For example, the use of nano-silica has demonstrated its ability to improve drought tolerance and extend the shelf life of fruits and vegetables, reducing post-harvest losses and ensuring better quality food for consumers.[93]

Additionally, nanofertilizers can stimulate the production of secondary metabolites, such as antioxidants, flavonoids, and phenolic compounds, which are essential for enhancing the nutritional value and health benefits of crops (Table 6). These compounds not only improve the nutritional quality of food but also offer potential therapeutic benefits for consumers.[8]

Furthermore, nanotechnology can be applied to minimize post-harvest losses by developing functional packaging materials with bioactive constituents. These materials improve gas and mechanical properties while preserving the sensory qualities of fruits and vegetables. Edible coatings, for instance, are applied to food products to protect them from deterioration. These coatings, which can be made from carbohydrates, lipids, proteins, or their mixtures, prevent dehydration, slow respiration, preserve aroma compounds, and inhibit microbial growth. Nano-coatings on food items serve as a barrier against gas and moisture exchange while delivering essential nutrients, antioxidants, and preservatives, thus extending the shelf life of food products and improving overall food preservation.[51]

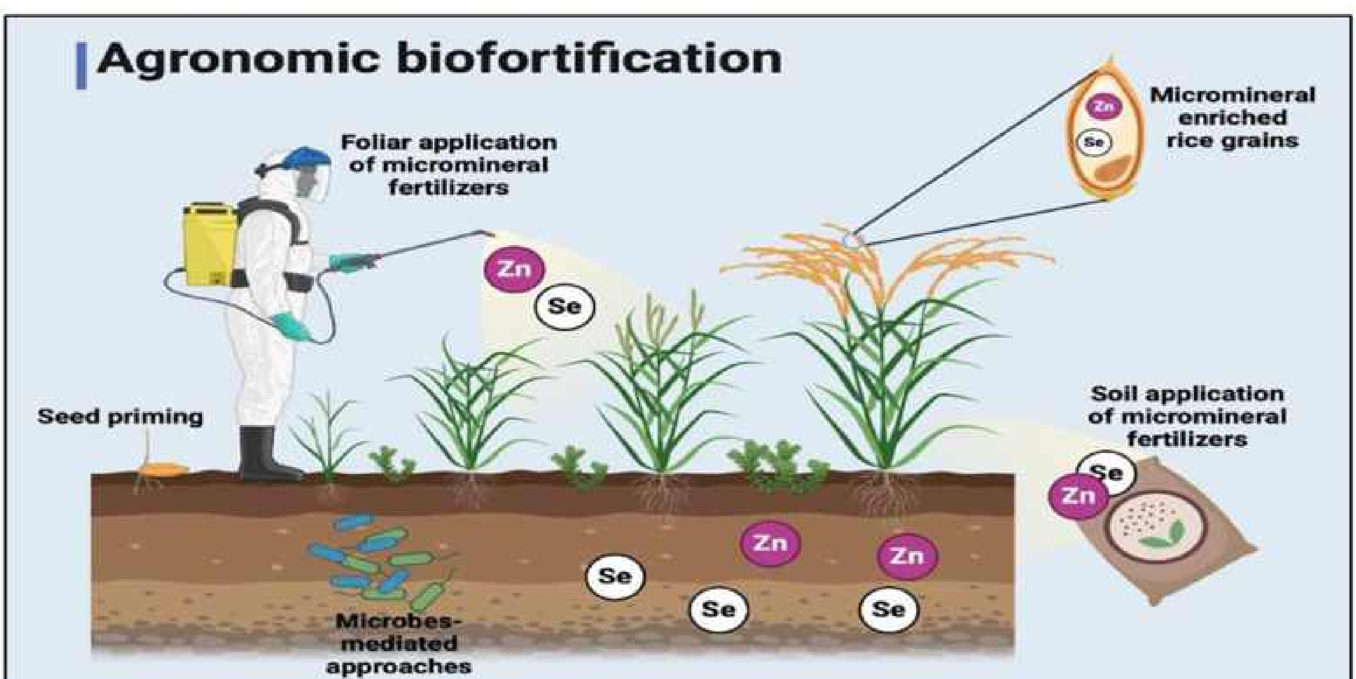

Fig. 8. Agronomic biofortification[12].

Table 6
Impact of different nanofertilizers on multiple crops, including the effective dose ranges for each.[32]

Nanofertilizers	Range of Doses	Plant/Crop	Effect	References
Nano-N	25–100 %	*Oryza sativa* L.	Boosted the number of tillers per plant, height and dry weight	94
Nano-potash	1500–2500 mg/L	*Arachis hypogea* L.	Enhanced shoot length, stem biomass, biological yield, and number of flowers per plant	95
Zn NPs	5–20 mg/L	*Allium cepa* L.	Reduced root growth.	96
Nano SiO_2+Nano TiO_2	100–500 ppm	*Capsicum annuum* L.	Significant increase in seed germination	97
ZnONPs	100 mg/kg	*Cucumis sativus* L.	Inhibited growth	98
ZnONPs	20 mg/L	*Triticum aestivum* L.	Enhanced biological yield and grain production	99
ZnONPs	10 mg/L	*Cyamopsis tetragonologa* L. *Taub*	Increased growth biological yield and nutrient contents	100
Nano-Fe_2O_3	500–1000 mg/L	*Cuminum cyminum* L.	Enhanced stem length and iron concentration	101

4.4. Tackling global food safety challenges with nanofertilizers

Food safety remains a significant global concern, with foodborne pathogens, pesticide residues, and environmental pollutants posing substantial risks to human health. Nanofertilizers offer a promising solution to these issues by improving crop quality, boosting resistance to pathogens, and reducing the need for chemical pesticides and fertilizers. By enhancing nutrient use efficiency, nanofertilizers contribute to healthier crops that are less vulnerable to diseases and pests, thereby decreasing the reliance on chemical treatments.[102]

Moreover, nanofertilizers enable the controlled release of nutrients, providing crops with a steady supply of essential nutrients over time. This continuous supply helps maintain optimal growing conditions and reduces the potential for crop stress. Well-nourished and healthy plants are more resilient to infections, resulting in higher-quality, safer food for consumers.[103]

5. Exploring future directions and research priorities for nanofertilizer technology

As precision agriculture continues to evolve, the need to use minimal yet highly efficient nutrient inputs has become increasingly essential. This demand poses a significant challenge for conventional fertilizers, which often fall short in terms of efficiency and environmental sustainability. In contrast, nanofertilizers, owing to their distinct physicochemical characteristics, offer a compelling alternative by addressing several limitations associated with traditional fertilizer formulations. Extensive research has been conducted globally to explore the influence of nanomaterials on plant physiology and development, with findings indicating both beneficial and adverse effects. While many studies highlight improved nutrient uptake, growth promotion, and stress resilience, others, particularly early investigations, have reported phytotoxic effects, often associated with high concentrations or specific nanoparticle types. To date, no definitive global consensus exists regarding their net impact, as outcomes are highly context-dependent. Moreover, the broader ecological implications, including effects on soil microbiota, water systems, and non-target organisms, remain an area of active investigation. Thus, a cautious, evidence-based approach is essential to ensure both agricultural benefits and environmental safety.[104] However, many early investigations contributed to the widespread perception of nanomaterials as predominantly phytotoxic.

This initial conclusion largely stemmed from experiments that employed high concentrations of nanomaterials with brief exposure durations, particularly those involving micronutrient-based nanoparticles. Given that micronutrients are required in trace amounts, even slight deviations beyond optimal levels can result in toxicity. More recent findings, however, indicate that nanomaterials, when applied judiciously, can promote plant growth, increase crop yields, and enhance resistance to various abiotic and biotic stressors. As a result, the focus is gradually shifting towards macro-nutrient-based nanofertilizers, which are applied in larger quantities and are thus more aligned with broader agricultural applications.

The advancement of macronutrient nanofertilizers, along with comprehensive ecological assessments, could have a profound impact on the sustainability of modern agriculture. However, despite their importance, research on the interactions between nanofertilizers and the diverse microbial communities in the soil and rhizosphere remains insufficient. While available studies indicate that nanofertilizers can have both beneficial and detrimental effects on soil and plant-associated microbes, these outcomes are highly context-dependent, influenced by the type of nanoparticle, dosage, exposure duration, and soil composition. What remains particularly underexplored is the impact of nanofertilizers on endophytes, microorganisms that reside within plant tissues and perform vital ecological roles in supporting plant health, growth, and resilience.

Moreover, there is a critical knowledge gap regarding the influence of nanofertilizers on the entire plant microbiome, especially for major crops cultivated at a commercial scale. It remains unclear how these materials may alter the composition, diversity, and functionality of microbiomes and how such changes could affect crop productivity and ecosystem dynamics. Additionally, interactions between nanofertilizers and bio-inoculants, such as growth-promoting bacteria and beneficial fungi commonly applied in field conditions, warrant in-depth investigation at the ecosystem level. Gaining a holistic understanding of these interactions will be crucial for optimizing nanofertilizer formulations, dosages, and application strategies for large-scale agricultural use.

Another area that requires urgent attention is the potential residual effects of nanofertilizers on edible plant parts and the subsequent implications for human health. Evaluating the fate of nanoparticles in the food chain is imperative for ensuring consumer safety and fostering public acceptance of nano-enabled agricultural technologies. Although nanofertilizers hold tremendous promise for transforming current farming practices, improving nutrient use efficiency, enhancing crop quality, and reducing environmental degradation, their long-term ecological and health-related impacts must be rigorously evaluated.[36]

As the global agricultural sector grapples with the dual challenge of feeding a growing population while maintaining environmental integrity, nanofertilizers emerge as a promising innovation with the potential to reshape food systems. Their application could lead to significant improvements in crop productivity and food quality while simultaneously reducing chemical runoff and environmental pollution. Nevertheless, unlocking the full benefits of nanofertilizer technology will require sustained investment in research, innovation, and interdisciplinary collaboration.[105] Moving forward, key priorities should include the development of smart delivery systems, understanding plant-nano interactions at the molecular and ecosystem levels, and ensuring the safety and regulatory compliance of nanofertilizers for broad adoption in agriculture.

5.1. Limitations and future outlook of nanofertilizers

Nanofertilizers (NFs) represent a significant innovation in agriculture, offering enhanced crop productivity and nutrient use efficiency.

They are increasingly being adopted across various agricultural sectors to support sustainable food production. However, despite their promising potential, several concerns persist regarding their safety for human health and the environment.

While expert evaluations generally suggest that food products containing nanoparticles (NPs) currently available on the market are likely safe for consumption, the deliberate introduction of nano-scale materials into agricultural systems demands thorough scrutiny.[106] Before NPs can be widely integrated into farming practices, their safety profiles must be rigorously assessed, particularly in high-concentration applications. Exposure to elevated levels of nanoparticles through nano-enabled food products could pose potential risks, especially when these materials enter the human body or environment in an uncontrolled manner.

A major concern lies in the unregulated release of nanomaterials into ecosystems and the food chain, which could lead to unintended consequences. Not all nanomaterials are universally safe across all contexts, and their interactions with biological systems can vary significantly. Given the potential for nanoparticles to penetrate biological barriers and accumulate in vital organs, it is essential to conduct in-depth toxicological evaluations. These studies should include both *in vivo* and *in vitro* experiments to ensure comprehensive safety assessments for human and environmental health.

Another limitation of nanofertilizer technology is its complexity in production and application. The manufacturing of nanomaterials requires sophisticated facilities and highly trained personnel, which can make the process prohibitively expensive for widespread adoption, particularly in low-resource settings. Furthermore, technical challenges related to formulation, dosage control, and scalability remain hurdles to the commercial deployment of nanofertilizers.

Despite these challenges, the agricultural sector remains a highly promising field for the application of nanotechnology. Integrating nanotechnology with material science and biomass transformation techniques has the potential to revolutionize agricultural practices, helping to meet the dual goals of food security and environmental sustainability.[16] By improving nutrient delivery efficiency and reducing chemical runoff, nanofertilizers can contribute significantly to sustainable agricultural intensification.

5.2. Progress in synthesis techniques and formulation strategies for nanofertilizers

The advancement of innovative, economical, and scalable techniques for the synthesis of nanofertilizers represents a pivotal direction for future research and development. Presently, many conventional synthesis processes are not only technologically intensive but also costly, which limits the broader implementation of nanofertilizers in agriculture. To address this limitation, researchers are increasingly exploring environmentally sustainable alternatives such as green synthesis methods. These techniques utilize biological agents, such as plant extracts, beneficial microorganisms, and biopolymers – to produce nanoparticles. Green synthesis holds significant promise as a cost-effective and eco-friendly approach, potentially lowering manufacturing costs and improving accessibility, particularly for smallholder farmers in developing regions.[107]

In parallel, significant emphasis is being placed on the formulation of nanofertilizers with precise and efficient nutrient delivery systems. One of the foremost goals is the development of controlled- or smart-release formulations that ensure nutrients are released in synchronization with crop growth stages and environmental conditions (Fig. 9). Such controlled delivery systems not only enhance nutrient use efficiency but also minimize nutrient losses through leaching, volatilization, or runoff, thereby reducing the environmental footprint of fertilization practices.

Future innovations in nanofertilizer formulation are expected to incorporate multi-nutrient strategies, where several essential nutrients are encapsulated within a single nano carrier. This multifunctional approach aims to improve nutrient synergy, reduce the frequency of fertilizer applications, and optimize resource use efficiency on farms. Moreover, the integration of functional additives, such as biostimulants, enzymes, or antimicrobial agents, within nanofertilizers may further elevate their role beyond nutrition, contributing to enhanced plant health and resilience.

In essence, ongoing developments in the synthesis and formulation of nanofertilizers aim to combine affordability, sustainability, and technological sophistication. These advancements will be instrumental in scaling up the use of nanofertilizers as a mainstream agricultural input, ultimately supporting global efforts to achieve sustainable food production.[107]

5.3. Smart nutrient delivery: merging nanofertilizers with precision agriculture

The fusion of nanofertilizers with precision agriculture techniques represents a forward-thinking strategy for improving nutrient management in modern farming systems. Precision agriculture leverages data-centric technologies, such as GPS mapping, remote sensing, and soil monitoring tools, to enhance decision-making and maximize input efficiency. By integrating nanofertilizers into these advanced systems, it becomes possible to tailor nutrient application precisely according to real-time crop and soil conditions.[108]

This synergy allows for the development of nanofertilizers that are capable of responding dynamically to environmental cues or specific soil parameters, releasing nutrients only when required. Such responsive nutrient delivery systems would significantly reduce fertilizer losses, enhance nutrient uptake by plants, and lessen the ecological footprint of fertilization practices.[107]

Looking ahead, research should prioritize the creation of intelligent nanofertilizer formulations that are compatible with precision monitoring technologies. These “smart” fertilizers could synchronize with sensor networks to automate and fine-tune nutrient release in real-time, ensuring optimal crop nutrition with minimal resource wastage (Fig. 10).

5.4. Evaluating the long-term ecological and health impacts of nanofertilizers

As the agricultural sector increasingly adopts nanofertilizers, there is a growing imperative to conduct comprehensive, long-term studies on their environmental and human health implications. Although early investigations have highlighted the advantages of nanofertilizers in enhancing nutrient efficiency and crop productivity, their prolonged effects on ecosystems remain inadequately explored. It is essential to investigate how nanoparticles behave once introduced into the environment – how they interact with soil components, their mobility in water systems, their potential for accumulation in living organisms, and their influence on non-target species, including beneficial soil microbes, pollinators, and other wildlife.[105]

Equally important is the evaluation of nanofertilizer safety for human health. Despite their role in promoting nutrient enrichment in crops, concerns persist regarding the extent to which nanoparticles may persist or accumulate in edible plant parts. Detailed toxicological assessments and food safety studies are necessary to understand possible risks associated with consumption. Therefore, long-term, field-based research that weighs the advantages against any potential hazards is vital to ensuring the sustainable and responsible use of nanofertilizers in agriculture.[63]

5.5. Navigating regulatory barriers and establishing safety standards for nanofertilizers

With the increasing adoption of nanofertilizers in modern agriculture, the establishment of robust regulatory frameworks and

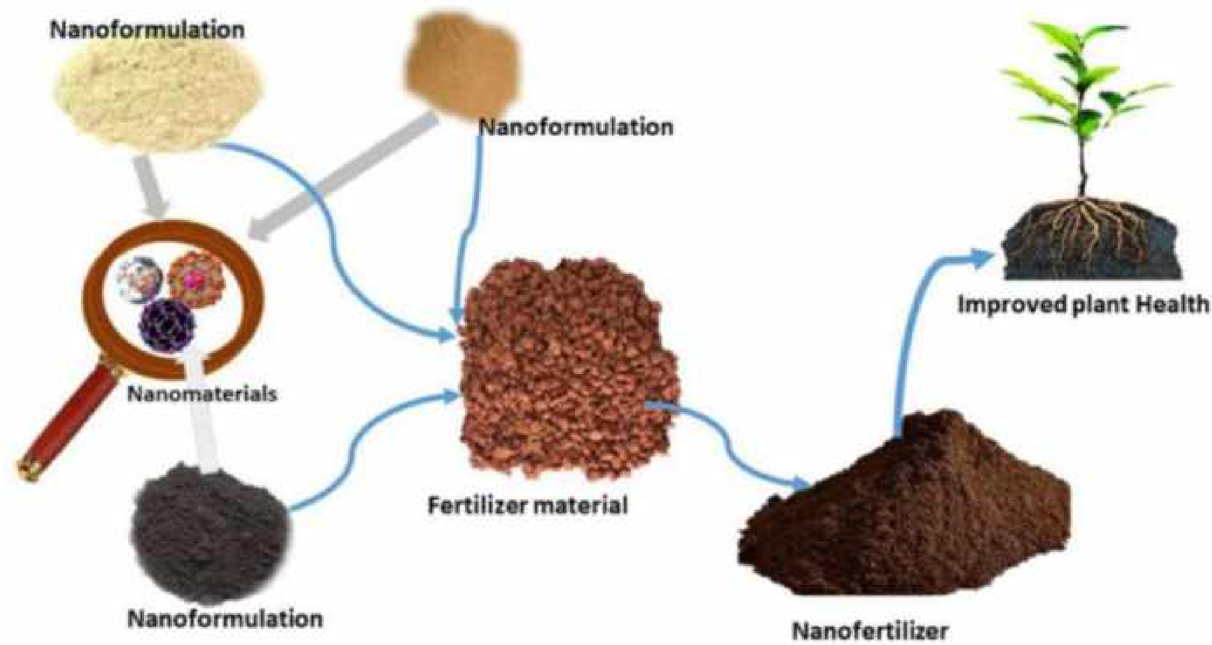

Fig. 9. Nano-engineered fertilizers for effective delivery and absorption of vital nutrients to support crop health[63].

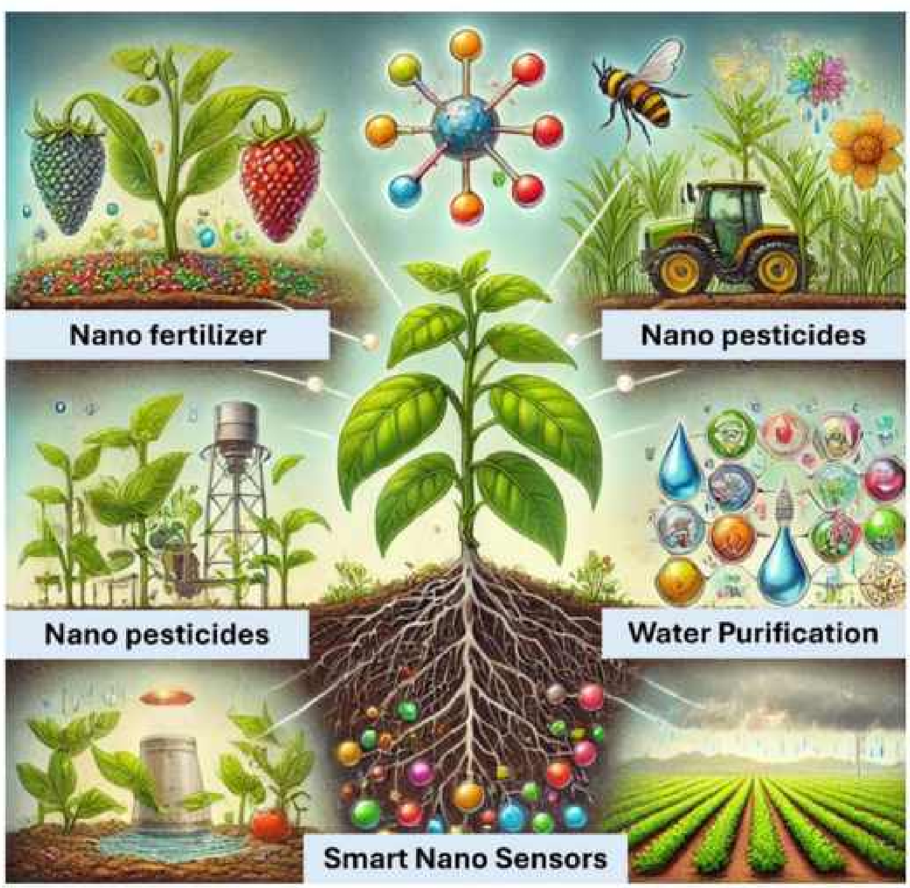

Fig. 10. Progress in agriculture driven by nanotechnology integration, including the use of nanofertilizers to enhance plant growth, nano-pesticides for targeted pest control, and smart nanosensors for precise soil monitoring[63].

standardized safety protocols has become a critical priority. At present, the absence of unified international regulations for the use of nanomaterials in farming presents a significant obstacle to their broader implementation. It is imperative that governments and international regulatory bodies collaborate to formulate comprehensive guidelines that oversee the manufacturing, evaluation, and deployment of nanofertilizers.

To support this process, there is a pressing need for the development of standardized testing methodologies tailored specifically to nanofertilizers. These should include validated procedures for assessing their environmental footprint, potential health risks to humans, and agronomic effectiveness. As nanotechnology continues to evolve, regulatory agencies must remain agile and responsive, ensuring that the application of nanofertilizers remains both safe and scientifically sound, avoiding unexpected hazards to ecosystems and human populations.[109]

Despite the growing interest in nanofertilizers, globally harmonized safety standards specifically tailored to their unique properties remain underdeveloped. Nonetheless, certain countries and international organizations have initiated steps toward regulatory oversight. India has pioneered this effort by including nanofertilizers such as nano urea in its Fertilizer (Control) Order (FCO), and by issuing safety and efficacy protocols through the Indian Council of Agricultural Research (ICAR) and the Department of Biotechnology (DBT).[110,111] In the European Union, nanomaterials are regulated under the REACH framework (Registration, Evaluation, Authorisation and Restriction of Chemicals), which, although not fertilizer-specific, requires detailed safety data for all chemical substances including those at the nanoscale.

Additionally, international bodies such as the OECD, FAO, and WHO have recognized the need for nano-specific guidelines and have initiated research and consultations on the environmental and health impacts of nanomaterials in agriculture. These early efforts reflect a growing global recognition of the need for clear, science-based regulatory standards to ensure the safe and effective integration of nanofertilizers into sustainable agricultural systems.[112]

6. Conclusion

Nanofertilizers represent a transformative advancement in agricultural science, offering the potential to significantly enhance crop yields, elevate food quality, and support environmental sustainability. Thanks to their nanoscale properties, such as targeted nutrient delivery, improved absorption, and controlled nutrient release, these fertilizers can help curb nutrient loss, enhance soil fertility, and reduce the adverse environmental consequences often associated with traditional fertilization methods. Moreover, nanofertilizers contribute to food safety and nutritional quality by minimizing the presence of chemical residues and increasing the concentration of beneficial micronutrients in crops. Their role in addressing global food security and improving dietary health makes them a valuable tool in the quest for a more resilient agricultural system.

Nevertheless, realizing the full potential of nanofertilizers comes with critical challenges. These include ensuring cost-effective and scalable production, validating environmental and human health safety, and creating coherent regulatory frameworks. Importantly, potential short- and long-term toxicological effects, such as phytotoxicity, nanoparticle accumulation in soil and plants, and impacts on soil microbial communities and human health, require further investigation to ensure safe application. Further scientific investigation is needed to explore their long-term ecological impacts and understand their interactions with soil microbiomes, plant systems, and food chains. Establishing standardized testing procedures and developing global safety regulations will be fundamental to ensuring their responsible use.

Looking to the future, research priorities should include the advancement of innovative synthesis techniques, especially eco-friendly methods, integrating nanofertilizers into precision agriculture systems, and further investigating their utility in biofortification to combat micronutrient deficiencies. If supported by sound policies and adequate investment, nanofertilizers could become central to sustainable agriculture and the mitigation of global hunger and malnutrition.

As agricultural practices evolve to meet the demands of an increasing population, nanotechnology will likely play a central role, not only in crop production but also in food processing, packaging, and storage. High-tech solutions enabled by nanomaterials have already demonstrated the ability to improve the taste, texture, and nutritional value of food while enhancing the bioavailability of active ingredients. However, it is vital to ensure that nanomaterials used in food and agriculture are properly regulated to avoid unintended risks to human and animal health. When considered as part of a broader system that includes sustainable practices, food safety regulations, and post-harvest quality control, nanofertilizers can meaningfully contribute to the production of safer, more nutritious food. As such, responsible development and deployment of nanotechnologies will be key to securing a safer, more efficient, and more sustainable global food system.

CRediT authorship contribution statement

Monika Stojanova: Writing – original draft, Methodology, Investigation, Data curation. **Sani Demiri:** Writing – original draft, Investigation, Data curation. **Marina T. Stojanova:** Writing – original draft, Methodology, Investigation, Data curation. **Dragutin A. Djukic:** Methodology, Investigation, Data curation. **Yalcin Kaya:** Methodology, Investigation, Data curation.

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