International Journal of
Nanoscience and Nanotechnology

Short Communication

2025, Volume 21, Issue 1

Nanofertilizers: A New Approach to Horticultural Nutrition

Marina T. Stojanova[1*], Dragutin A. Djukic[2], Monika Stojanova[3]

Received 1/4/2025
Accepted 2/28/2025

DOI: 10.22034/ijnn.2025.2049877.2622

International Journal of Nanoscience and Nanotechnology

Abstract

Nanotechnology offers transformative potential in agriculture and horticulture, revolutionizing crop production, plant health, and resource management. Its dynamic influence is particularly evident in enhancing vegetable yields through targeted nutrient delivery. Nanofertilizers, which utilize nanoparticles with higher surface tension than conventional fertilizers, provide plants with slow-release, efficient nutrient availability. This improves nutrient uptake, reduces waste, and promotes more sustainable farming practices. Nanofertilizers are specifically designed to optimize plant growth, fertility, and pollination in flowers, resulting in higher yields and improved quality in horticultural crops. By enhancing the availability and use efficiency of nutrients, nano fertilizers reduce nutrient fixation and enhance overall productivity.

This review focuses on the significance of nanotechnology development, nanomaterials, and nano fertilizers, highlighting their potential to improve productivity and quality in horticultural crops. It also explores how nanoparticles can enhance plant resilience, particularly in response to environmental changes, supporting food security for the growing global population. By providing targeted, efficient solutions, nanotechnology offers promising strategies for ensuring the long-term sustainability and health of horticultural production systems. The application of nanofertilizers in enhancing both crop quality and environmental sustainability positions nanotechnology as a key innovation for the future of agriculture.

Keywords: Nanotechnology, Nanosensors, Nano Fertilization, Smart Agriculture, Digitalization in Horticulture

How to cite this article
Stojanova MT, Djukic DA, Stojanova M. Nanofertilizers: A New Approach to Horticultural Nutrition. Int. J. Nanosci. Nanotechnol., 2025;1: 49-58. DOI: 10.22034/ijnn.2025.2049877.2622

1. Introduction

Nanotechnology is a rapidly evolving field that involves the study, design, synthesis, and application of materials at the nanoscale, typically smaller than 100 nanometers. These nanomaterials exhibit unique physicochemical properties that differ significantly from their bulk counterparts, including enhanced reactivity, increased surface area-to-volume ratio, and improved functionalities [1-3]. Due to these attributes, nanotechnology is explored across multiple disciplines, including medicine, environmental science, and agriculture [4].

In the agricultural sector, nanotechnology offers transformative solutions by enhancing nutrient absorption, improving fertilizer use efficiency, and reducing environmental impacts. Conventional fertilizers often suffer from low nutrient use efficiency due to leaching, volatilization, and fixation losses, which contribute to environmental pollution and increased production costs [5]. In contrast, nanofertilizers, designed as controlled-release delivery systems, provide controlled release kinetics, enhance nutrient uptake, and minimize losses by targeting plant cells more efficiently [6].

Nanofertilizers have emerged as a promising alternative to traditional mineral fertilizers, offering significant advantages in nutrient delivery and absorption. Unlike conventional fertilizers, which often lead to excessive nutrient runoff and environmental pollution, nanofertilizers improve nutrient use efficiency by ensuring slow and controlled release, reducing leaching into water bodies, and minimizing greenhouse gas emissions associated with fertilizer production and application. Additionally, nanofertilizers enhance soil health by preventing the accumulation of toxic salts and excessive chemical residues, which are common drawbacks of mineral fertilizers. Their ability to improve nutrient bioavailability also means that lower quantities are required, leading to cost savings for farmers and decreased dependency on synthetic fertilizers [7].

Horticultural production, in particular, can greatly benefit from nano fertilization. Horticultural crops, including fruits, vegetables, and ornamentals, require

[1] *University of Ss. Cyril and Methodius, Faculty of Agricultural Sciences and Food, Skopje, North Macedonia.*

[2] *University of Kragujevac, Faculty of Agronomy, Cacak, Serbia.*

[3] *Association for Scientific-research, Educational and Cultural Activities "Open Science", Ohrid, North Macedonia.*

E-mail: mstojanova@fznh.ukim.edu.mk

precise nutrient management to maximize yield, improve quality, and enhance resistance to biotic and abiotic stresses. Nanofertilizers provide a highly efficient mechanism for delivering essential nutrients, such as nitrogen, phosphorus, and potassium in a more targeted manner, reducing nutrient wastage and optimizing plant uptake. Additionally, their role in enhancing plant resilience to diseases, drought, and other environmental stresses makes them an invaluable tool for sustainable horticultural practices. Implementing nanofertilizers in horticulture could significantly contribute to increased productivity, higher nutritional quality of produce, and reduced dependency on chemical inputs, thereby promoting eco-friendly and cost-effective farming systems.

Advances in nanotechnology have enabled the synthesis of nanoparticles using various fabrication methods, including physical, chemical, biological, and hybrid techniques. These methods allow for the development of customized nanofertilizers that improve nutrient bioavailability while reducing negative environmental impacts. Different types of nanomaterials, such as nanoparticles of essential metals, nanoscale phosphorus, and silica nanoparticles, have demonstrated potential in enhancing soil fertility and plant resilience [7].

Despite the promising advantages of nanofertilizers, significant challenges remain regarding their large-scale implementation, cost-effectiveness, and potential long-term environmental and ecological impacts. While several studies have explored the benefits of nanofertilizers, existing literature primarily focuses on their physicochemical properties, synthesis methods, and short-term efficiency [7, 8]. However, there is a critical gap in comprehensive reviews addressing the long-term sustainability, regulatory considerations, and comparative economic feasibility of nanofertilizers relative to conventional fertilizers. Additionally, further investigation is needed into their impact on soil microbiota, plant health, and potential bioaccumulation risks.

Furthermore, nanofertilizers could play a crucial role in mitigating environmental pollution caused by excessive fertilizer use. The controlled release of nutrients from nanofertilizers minimizes nutrient runoff into water bodies, reducing eutrophication and associated ecological disturbances. Recent research has highlighted the potential of nanosensors to monitor soil nutrient levels and optimize fertilizer application, thereby increasing precision agriculture practices [9]. However, concerns regarding nanoparticle toxicity, soil persistence, and interactions with microbial communities warrant further investigation to ensure their safe and sustainable use in agriculture.

This review aims to bridge this research gap by providing an in-depth analysis of the role of nanotechnology in fertilizer development, emphasizing its benefits, challenges, and potential applications in horticultural crop production. By synthesizing recent advancements and evaluating emerging concerns, this study offers valuable insights into the practical implementation of nanofertilizers to improve agricultural sustainability and food security. Understanding these aspects is crucial for developing policies, regulatory frameworks, and future research directions to ensure the responsible and effective use of nanofertilizers in modern agriculture.

2. The Science Behind Nanofertilizers

The application of fertilizers has long been recognized as a crucial factor in enhancing plant growth and yield. Modern synthetic fertilizers provide essential macronutrients, such as nitrogen, phosphorus, and potassium, along with secondary nutrients required for plant development. While synthetic fertilizers have significantly improved agricultural productivity, their excessive use leads to environmental pollution, soil degradation, and reduced long-term sustainability. Over-reliance on chemical fertilizers can result in nutrient imbalances, decreased soil microbial activity, and the leaching of harmful substances into water bodies, contributing to eutrophication and soil acidification [6].

Conventional agriculture relies heavily on chemical fertilizers to enhance crop yield and quality. The Green Revolution played a pivotal role in increasing food production through the widespread adoption of synthetic fertilizers. However, it is estimated that more than 50% of applied chemical fertilizers and pesticides remains unused, accumulating in the soil and surrounding ecosystems [10]. This inefficiency not only leads to economic losses but also poses serious environmental hazards. The growing awareness of these negative impacts has prompted extensive research into alternative approaches, such as biofertilizers, microbial consortia, and innovative nutrient management strategies [11].

The role of fertilizers extends beyond simply increasing yield; they influence various physiological and biochemical processes that affect plant development, fruiting, and overall quality. However, excessive or improper fertilizer application can disrupt plant metabolism, induce nutrient deficiencies, alter vegetative and generative organ development, and even cause phytotoxicity [12, 13]. Long-term overuse of mineral fertilizers depletes soil organic matter, weakens soil structure, and increases greenhouse gas emissions, necessitating the urgent adoption of more sustainable fertilization practices [14].

Given these concerns, advanced agricultural technologies are being developed to create more efficient and environmentally friendly fertilizers. One such approach involves the use of nanotechnology to produce smart fertilizers, known as nanofertilizers. These formulations leverage nanoscale materials to enhance nutrient delivery, improve soil fertility, and reduce environmental contamination. Nanofertilizers can mitigate many of the drawbacks associated with conventional fertilizers, including nutrient loss through leaching, volatilization, and runoff [15].

Nanotechnology involves the manipulation of materials at the atomic and molecular levels, leading to the development of nanostructured fertilizers that optimize nutrient uptake and utilization. Nanofertilizers can be designed to release nutrients in a controlled manner, ensuring a sustained supply of essential elements to crops. This targeted delivery system minimizes nutrient wastage, enhances photosynthesis, boosts crop productivity, and improves overall plant health while significantly reducing the frequency of fertilizer application and its associated environmental burden [16].

A key advantage of nanofertilizers is their high surface area-to-volume ratio, which enables more efficient nutrient absorption and reduces soil toxicity [1]. Unlike traditional fertilizers, nanofertilizers facilitate the gradual release of nutrients, ensuring that plants receive the necessary elements at different growth stages. This controlled-release mechanism enhances nutrient use efficiency and prevents excessive accumulation of nutrients in the soil, mitigating the risks of environmental pollution [17].

Nanofertilizers play a crucial role in modern agriculture by providing effective formulations and delivery mechanisms that ensure optimal uptake and utilization by plants. By leveraging nanoparticles (NPs) made from various metals and metal oxides, we can enhance nutrient use efficiency and environmental quality while avoiding detrimental chemical alterations. The smaller size of nanoscale particles allows them to be absorbed differently compared to bulk particles or ionic salts, offering significant advantages [17].

The mechanisms of action of nanofertilizers differ from those of conventional fertilizers due to their unique physicochemical properties (Table 1). Their small particle size enables better penetration into plant tissues, leading to more efficient nutrient transport. Nanofertilizers can be absorbed through the roots, leaves, and stomatal openings, allowing for multiple application methods, including foliar spraying, fertigation, and soil incorporation. Once absorbed, nanoparticles interact with plant cells to enhance enzymatic activities, promote chlorophyll synthesis, and stimulate metabolic pathways essential for plant growth [8].

In horticultural production, nanofertilizers offer significant advantages by improving nutrient efficiency, reducing input costs, and minimizing environmental pollution. Horticultural crops, which include fruits, vegetables, and ornamental plants, require precise nutrient management to achieve optimal growth and quality. The application of nanofertilizers in horticulture enhances root development, increases stress resistance, and improves post-harvest quality. Additionally, nanoscale formulations of essential nutrients, such as iron, manganese, and zinc, have demonstrated superior bioavailability and uptake efficiency in horticultural crops, ensuring higher yields and improved produce quality [7].

Nanofertilizers can be categorized into three main types [1]:

- **Nanoscale Fertilizer**: Conventional fertilizers reduced to nanoparticle size, increasing their reactivity and bioavailability.
- **Nanoscale Additive Fertilizer**: Traditional fertilizers combined with nanomaterials to improve nutrient efficiency.
- **Nanoscale Coating Fertilizer**: Nutrients encapsulated within nanofilms or incorporated into porous nanomaterials, ensuring slow and targeted release.

These novel fertilizers incorporate essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), iron (Fe), and manganese (Mn), which are either bound to nanocarriers or formulated as nano-sized particles. The use of polymer coatings, clay-based encapsulation, and biopolymer matrices further enhances their stability and efficiency. By optimizing nutrient bioavailability, nanofertilizers contribute to improved crop resilience and soil fertility while minimizing nutrient loss [11, 18].

Intrinsic factors that influence the efficacy of nanoparticles (NPs) include their surface properties, such as coatings and particle size, which affect their stability, solubility, and interaction with plant tissues. Meanwhile, extrinsic factors encompass soil characteristics, including texture, pH levels, and organic matter content, all of which play a crucial role in determining nutrient availability and uptake efficiency. The mode of absorption, whether through the roots or leaves, directly impacts the bioavailability and distribution of nanofertilizers within the plant, ultimately shaping their agronomic effectiveness [19].

By understanding and optimizing these factors, nanofertilizers can be tailored to maximize nutrient use efficiency while minimizing environmental losses, making them a promising tool for sustainable agriculture.

One of the most promising applications of nanofertilizers is in precision agriculture, where targeted nutrient delivery maximizes efficiency while reducing the environmental footprint of fertilization practices. Research has demonstrated that nanofertilizers significantly improve the growth, yield, and nutritional quality of various crops, including horticultural species. Due to their ability to enhance nutrient uptake and promote plant health, nanofertilizers are increasingly regarded as a sustainable alternative to conventional fertilizers [20, 21].

For instance, studies have shown that zinc oxide nanoparticles (ZnO-NPs) are more effective than traditional zinc sulfate ($ZnSO_4$) fertilizers for enhancing wheat germination and growth. Furthermore, ZnO-NPs exhibit lower toxicity than $ZnSO_4$ at higher concentrations, making them a safer alternative for plant nutrition. Similarly, research on common beans treated with ZnO-NPs indicates that they do not pose health risks to consumers, reinforcing the potential of nanofertilizers in food production [22, 23].

However, despite their numerous benefits, the widespread adoption of nanofertilizers faces certain challenges. Concerns regarding their production costs, long-term environmental impact, and potential toxicity require further investigation. The movement and fate of nanoparticles in soil and water ecosystems must be thoroughly assessed to ensure their safe and sustainable use. Additionally, regulatory frameworks governing the use of nanotechnology in agriculture need to be established to address potential risks and standardize quality control measures [26].

While nanofertilizers offer significant potential for enhancing nutrient use efficiency and minimizing environmental harm, their widespread adoption requires

Table 1. Property comparison between nanofertilizers and conventional products [24].

Property	Nanofertilizer	Challenges
Controlled release	can control the speed and doses of nutrient solution release	Reactivity and composition variations due to environmental factors
Nutrient loss	Leakage and waste caused by application of fertilizers can be reduced	Environmental effects after the conclusion of the nanofertilizer life cycle
Duration of release	can extend the duration of nutrient release in comparison with regular fertilizers	Phytotoxicity effects due to the dose and time of exposure
Efficiency	The uptake ratio is increased and the release time of nanostructures is reduced	Long-term environmental effects, as well as chronic effects on final consumers
Solubility and dispersion	Absorption and fixation of nutrients by the soil are improved, increasing their bioavailability	Complete ecotoxicological profiles, taking into account the consequences for health and the environment

Table 2. Impact of different micronutrient nanofertilizers on various horticultural crops [25].

Micronutrients Delivered as Nanoparticles	Dose Used (mg/L)	Crops	Effect on Plant Growth and Development
Zinc (Zn)	1000 1000 100, 200, 500	Cucumber Spinach Chilli pepper	Root tip deformation and growth inhibition; Reduces plant growth; Improves germination.
Iron (Fe)	50–2000 10 and 20	Cucumber Lettuce	Enhances biomass production and activities of antioxidant enzymes in dose-depended manners; Reduces chlorophyll contents and growth but increases activities of the antioxidant enzyme.
Copper (Cu)	130, 660 0–1000 50–500 100, 250, 500 100–500	Lettuce Cucumber Tomato Bean Garden pea	Increases shoot and root length ratio; Reduces growth and increases antioxidant enzymes; Improves fruit firmness and antioxidant content; Causes of growth inhibition and nutrition imbalance; Reduces the growth of plants, enhances the production of ROS and the peroxidation of lipid.

a more nuanced evaluation of their limitations and challenges. One key concern is their long-term impact on soil microbiota and ecosystem health. Although nanofertilizers reduce nutrient loss, their interactions with beneficial soil microorganisms remain poorly understood. Some studies suggest that nanoparticles, depending on their composition and concentration, may disrupt microbial communities essential for soil fertility and plant growth [18]. Further research is needed to assess their potential ecotoxicological effects.

Another critical issue is the economic feasibility of nanofertilizers compared to conventional fertilizers. Despite their efficiency, the production of nano-based fertilizers involves complex synthesis techniques that may increase costs, limiting their accessibility to small-scale farmers. Additionally, the effectiveness of nanofertilizers in field conditions remains a subject of debate. Many studies demonstrating their benefits have been conducted under controlled environments, but real-world agricultural settings present variables such as soil heterogeneity, climatic fluctuations, and water availability, which can influence their performance [27].

Regulatory and safety concerns also warrant attention. Unlike traditional fertilizers, nanofertilizers require rigorous evaluation of their environmental fate, potential bioaccumulation, and long-term effects on human health. Standardized testing protocols and clear regulatory frameworks are still lacking, making it difficult to assess the risks associated with their large-scale application [18].

Therefore, while nanofertilizers hold promise for revolutionizing modern agriculture, a comprehensive assessment of their economic viability, environmental safety, and long-term sustainability is essential before they can be widely implemented. Addressing these concerns through interdisciplinary research and policy development will be crucial in ensuring their responsible and effective use in agricultural systems.

3. The Role of Nanofertilizers in Horticultural Production

Horticulture is a vital branch of agriculture that includes various specialized fields such as pomiculture (fruit tree cultivation), olericulture (vegetable cultivation), viticulture (grapevine cultivation), floriculture (flower production, including medicinal varieties), and general gardening (the cultivation of flowers, herbs, and vegetables). Horticultural crops encompass vegetables, fruits, mushrooms, and medicinal plants, playing a crucial role in human nutrition. Recent advancements in nutritional science emphasize the importance of fruits and vegetables in maintaining health and preventing diseases, as reflected in dietary guidelines like the "healthy eating plate."

However, meeting the growing demand for high-quality horticultural produce is becoming increasingly challenging due to population growth and changing dietary habits [28]. Horticultural crops, often classified as super-intensive, produce substantial yields, particularly in controlled environments like greenhouses. These crops require high soil fertility due to their biological characteristics, such as relatively small root masses supporting large vegetative structures. Their productivity is influenced by genetic traits, environmental conditions, and agricultural practices. As such, horticulture necessitates substantial nutrient inputs to sustain optimal yields and product quality.

Soil nutrient availability is often suboptimal due to intensified agricultural production, making fertilization essential. Beyond merely supplementing nutrient deficiencies, effective fertilization must consider nutrient dynamics and inter-element ratios to ensure sustainable production. In soils with adequate fertility, fertilization aims to maintain soil health, whereas in less fertile soils, it seeks to enhance nutrient availability. Key limiting factors in horticultural production include nutrient deficiency, water scarcity, and unsuitable soil pH. Consequently, soil fertility management, based on laboratory testing and agrochemical analysis, plays a critical role in optimizing plant nutrition and productivity [29].

Nanotechnology has emerged as a transformative tool in agriculture, particularly through the use of nanofertilizers (NFs) in fruit and vegetable production. Nanofertilizers have demonstrated the potential to enhance vegetative growth, reproductive development, and flowering, leading to increased yield, improved quality, and extended shelf life. By delivering essential nutrients at the molecular level, nanoparticles facilitate precise nutrient uptake, enhancing photosynthesis and biomass production [18, 25, 30]. This precise nutrient management reduces fertilizer losses, minimizes environmental contamination, and enhances sustainability in horticulture [31].

Essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients (Zn, Cu, Mn, Fe, Mo, and B) can be supplied in nano form, improving nutrient use efficiency (Figure 1). Nanomaterials exhibit high surface tension, preventing nutrient immobilization and enhancing slow-release properties, thereby reducing the environmental impact of synthetic fertilizers [32]. Studies have demonstrated that nanoparticles such as ZnO, SiO_2, CuO, and iron oxide positively influence plant growth, nutrient uptake, and yield [27, 33].

3.1. Nanosensors in Precision Horticulture

A nanosensor is any device capable of transmitting information about the properties and characteristics of nanoparticles from the nanoscale to the macroscopic level [34]. These sensors are essential for detecting and measuring various factors, such as temperature, humidity, and moisture. By leveraging the unique properties of nanomaterials, nanosensors can identify and quantify physical characteristics on the nanoscale. They play a crucial role in monitoring physical quantities and converting them into detectable signals for analysis [31].

Additionally, nanosensors enable real-time monitoring that can reduce environmental pollution and lower production costs. This is achieved by minimizing the overuse of pesticides and fertilizers in crop production.

Integrating nanosensors into traditional farming practices promotes smart agriculture, making it more environmentally sustainable and energy-efficient [34].

The use of nanosensors in agriculture leads to smart farming techniques, which help mitigate excessive pesticide and fertilizer use, thereby reducing pollution and production costs. These advancements make agriculture more energy-efficient and environmentally friendly, supporting sustainable practices.

Smart agricultural practices in horticulture include: (i) nanoformulation-based fertilizers and pesticide delivery systems, which improve nutrient dispersion and wettability; (ii) nanodetectors to identify pesticide or fertilizer residues; and (iii) remote sensing systems to

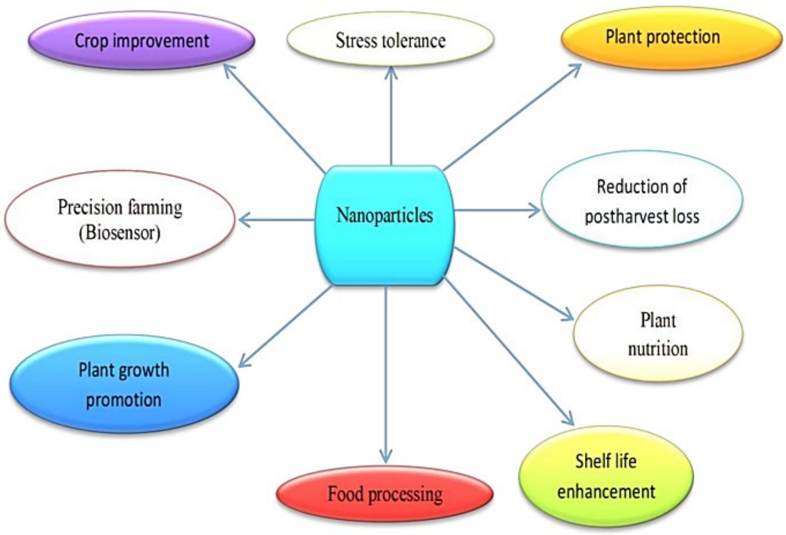

Figure 1. The role of nanoparticles in enhancing agricultural productivity and the quality of horticultural crops [25].

monitor disease incidence and crop growth. Nanosensors are widely used in horticulture to measure soil moisture content, assess nutrient needs, and detect pesticide residues [25].

Furthermore, nanosensors are vital for monitoring plant nutrient levels. Smart delivery systems based on these sensors improve the efficiency of natural resource use, such as water, nutrients, and agrochemicals, through precision farming techniques. As such, the application of nanosensors is highly beneficial for improving crop yields by monitoring nutrient levels and optimizing resource utilization [32].

In horticulture, nanosensors are transforming crop monitoring and management practices. These small devices, made from nanomaterials, gather real-time data on critical factors affecting crop health and productivity. Nanosensors are particularly valuable for monitoring soil conditions, including moisture levels, nutrient content, and pH, with remarkable accuracy. These data enable horticulturists to optimize irrigation schedules, ensure timely nutrient delivery, and maintain ideal soil conditions for optimal crop growth [31].

The use of nanosensors in horticultural production provides several advantages. One of the most notable benefits is the ability to monitor soil and plant conditions with unprecedented precision. By providing real-time data, nanosensors allow farmers to make informed decisions that can enhance crop yield and health. This results in more efficient use of water, fertilizers, and pesticides, leading to cost savings and reduced environmental impact. Moreover, nanosensors can help detect issues like nutrient deficiencies or pest infestations at an early stage, enabling timely interventions and minimizing crop loss [35].

However, there are some challenges associated with the widespread adoption of nanosensors in horticulture. One disadvantage is the high initial cost of implementing such technology, which may be prohibitive for small-scale farmers. Additionally, the long-term environmental impacts of using nanomaterials in agricultural settings are still not fully understood. Although nanosensors hold great promise, further research is needed to assess their potential risks and to ensure their safe integration into agricultural systems. Despite these challenges, the advantages of nanosensor technology in enhancing agricultural productivity and sustainability make it a promising tool for the future of horticultural production [36].

3.2. Case Studies on NanoFertilizer Application

In horticulture, nanofertilizers are employed to promote vegetative growth, enhance pollination, and improve flower fertility, ultimately leading to higher yields and better product quality in fruit trees. When nano-calcium (nano-Ca) is applied to blueberries under saline stress, it boosts vegetative growth and increases leaf chlorophyll content (Table 2). Similarly, spraying nano-boron on mango tree leaves positively impacts overall fruit yield and chemical composition, likely due to an increase in chlorophyll levels and essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), manganese (Mn), magnesium (Mg), boron (B), zinc (Zn), and iron (Fe) in the leaves [25].

Nanofertilizers are released slowly, specifically targeting plants and ensuring efficient delivery. For instance, ZnO nanoparticles have been shown to improve peanut (*Arachis hypogaea*) yields. Similarly, applying SiO_2 nanoparticles boosts plant biomass and increases biomolecule contents, such as chlorophyll, proteins, and phenols, in maize grains. Carbon nanotubes, even at low concentrations, promote root growth in hexaploid wheat, enhance seed germination and seedling growth in mustard (*Brassica juncea*), black gram (*Phaseolus mungo*), and rice *(Oryza sativa*), and increase cell growth by 16% in tobacco (*Nicotiana tabacum*).

Research indicates that combining nano-nitrogen (Nano-N) and nano-zinc (Nano-Zn) with conventional nitrogen fertilizers can significantly improve crop yield, soil nutrient availability, and microbial biomass in cropping systems [37]. In horticultural production, nanofertilizers have been shown to enhance the growth and productivity of potatoes [38] and tomatoes [39], with potassium nanofertilizers increasing fruit yield and quality.

In cabbage, nano-hydroquinone and nano-theophenols were found to improve nitrogen, phosphorus, and potassium absorption, increasing nitrogen use efficiency and yield by over 40% [40]. Similarly, Shebl et al. [7] reported that nano oxides of zinc, manganese, and iron, synthesized using green chemistry methods, significantly improved squash plant growth and yield. Foliar application of manganese and iron nano oxides enhanced fruit quality by increasing organic matter, protein, and lipid content.

A study on sweet peppers revealed that applying copper oxide nanoparticles at a concentration of 100 ppm enhanced root dry weight, shoot fresh weight, and plant height compared to the control group [41].

Nanofertilizers have also been explored in cucumber production, offering an alternative to traditional mineral fertilizers. The application of zinc and sulfur nanoparticles in broad bean cultivation has mitigated micronutrient deficiencies, particularly zinc deficiency, which can cause physiological disorders like little leaf syndrome [32, 42, 43]. Moreover, nanofertilizers enhance seed germination and early seedling growth by facilitating water and nutrient uptake, benefiting crops such as onion, spinach, tomato, and potato [33].

3.3. Critical Perspective and Challenges

While nanofertilizers offer promising benefits in horticultural production, their adoption comes with challenges. One major concern is the potential environmental impact of nanoparticle accumulation in soil and water systems. Although nanofertilizers reduce nutrient runoff and improve efficiency, long-term ecological effects remain unclear. Some studies suggest that excessive nanoparticle concentrations could disrupt soil microbial communities, altering nutrient cycling and soil health.

Additionally, the cost and accessibility of nanofertilizers may limit widespread adoption, particularly for small-scale farmers. The production of nanofertilizers requires sophisticated technology and quality control measures to ensure safe and effective formulations. Furthermore, regulatory frameworks for nano-based agricultural inputs are still evolving, necessitating comprehensive risk assessments before large-scale implementation.

Despite these challenges, nanofertilizers hold significant potential for addressing the increasing demand for sustainable horticultural production. By improving nutrient use efficiency, reducing fertilizer losses, and enhancing crop quality, they represent a valuable tool for modern agriculture. Future research should focus on optimizing nanofertilizer formulations, assessing their long-term environmental impact, and developing cost-effective production methods to enhance accessibility.

Nanofertilizers represent a groundbreaking innovation in horticultural production, offering numerous benefits in terms of yield improvement, nutrient efficiency, and sustainability. Their ability to provide precise and controlled nutrient release makes them a viable alternative to traditional fertilizers. However, concerns regarding environmental impact, cost, and regulatory challenges must be addressed to ensure their safe and widespread application. With continued research and responsible implementation, nanofertilizers have the potential to revolutionize horticultural practices, supporting the growing demand for high-quality, sustainable food production.

3.4. Benefits of Nanotechnology in Horticulture

According to research by Mehta et al. [31], the benefits of nanotechnology in horticulture include:

- **Precision in Nutrient Delivery**: Nanoscale carriers ensure that plants receive optimal nutrients, which reduces fertilizer usage and minimizes environmentally harmful nutrient runoff. This approach helps reduce the negative environmental impact of traditional fertilizers by improving the efficiency of nutrient uptake, thus promoting sustainable agricultural practices.
- **Enhanced Pest Control**: Nanopesticides penetrate insect exoskeletons and plant tissues more effectively, allowing for targeted pest control. This targeted approach minimizes pesticide application, reducing the amount of chemicals needed and consequently lowering the environmental impact, which is crucial for preserving biodiversity and protecting ecosystems.
- **Improved Soil Quality**: Nanomaterials enhance soil structure and moisture retention, leading to better aeration, reduced soil erosion, and increased drought resistance in crops. This results in healthier plant growth and the potential for higher yields, especially in regions prone to drought or soil degradation, thereby enhancing the resilience of agricultural systems.
- **Extended Shelf Life of Produce**: Nanotechnology regulates gas exchange, moisture, and temperature within packaging materials, which extends the shelf life of harvested fruits and vegetables, reduces food waste, and maintains product quality. By slowing down the degradation process, it ensures that produce stays fresh for longer periods, benefiting both farmers and consumers by reducing losses during transport and storage.
- **Promotion of Sustainable Practices**: Nanotechnology supports sustainable horticultural practices by reducing chemical usage, optimizing resource utilization, and minimizing environmental impact. By increasing the efficiency of inputs like water, nutrients, and pesticides, nanotechnology helps move agriculture toward more sustainable, resource-efficient practices, making it a key technology for the future of farming.
- **Real-Time Monitoring**: Nanosensors and monitoring systems provide real-time data on soil and environmental conditions, enabling precise decision-making and efficient resource allocation. This enhances crop management by providing actionable insights, which improves productivity while minimizing unnecessary inputs, such as water, fertilizers, and pesticides.
- **Controlled Release of Beneficial Agents**: Nanotechnology facilitates the controlled release of beneficial microorganisms or biopesticides, supporting natural pest control methods and reducing dependence on chemical pesticides. This innovation promotes eco-friendly pest management, decreasing the overall chemical load in agricultural systems and supporting the shift toward integrated pest management (IPM) strategies.
- **Improved Plant Health and Productivity**: The overall health and productivity of plants are enhanced through nanotechnology, resulting in increased crop yields and improved crop quality. By optimizing nutrient delivery and improving plant resilience to stressors, such as pests or environmental fluctuations, nanotechnology helps meet the growing global demand for food production.
- **Efficient Water Use**: Nanoscale sensors and moisture management technologies promote efficient water use in irrigation, helping conserve this vital resource in agriculture. As water scarcity becomes an increasingly pressing issue, nanotechnology can play a crucial role in ensuring that crops receive the right amount of water at the right time, thus reducing water wastage.
- **Tailored Crop Management Solutions**: Nanotechnology offers precision and flexibility in crop management by allowing solutions to be customized to meet specific horticultural needs. By offering personalized interventions based on real-time data, nanotechnology enables farmers to address unique challenges for each crop, optimizing productivity and sustainability.

The benefits of nanotechnology in horticulture are vast and transformative. By improving nutrient delivery, pest control, and water use efficiency, nanotechnology not only boosts crop productivity but also enhances environmental sustainability. It facilitates the move toward precision agriculture, where every input is optimized to meet the plant's needs, leading to reduced waste, lower costs, and less environmental degradation. Moreover, the ability to extend the shelf life of produce can significantly reduce food waste, which is a growing global concern [44].

3.5. Limitations and Risks of Nanotechnology in Horticulture

Despite its numerous benefits, the adoption of nanotechnology in horticulture also presents certain limitations and challenges. One major concern is the toxicity and potential environmental impact of nanomaterials. While they may offer enhanced performance, their long-term effects on soil health, water quality, and ecosystems are still not fully understood. The introduction of nanoparticles into the environment could lead to unintended consequences, such as bioaccumulation in organisms or disruption of natural microbial communities in soil. Therefore, rigorous testing and long-term studies are required to assess their safety and potential environmental risks [31, 45].

Another limitation is the economic feasibility of nano-based solutions, particularly for small-scale farmers. The initial investment in nanofertilizers, pesticides, and sensors can be high, which might limit access to these technologies for farmers in low-income regions. Thus, while the benefits are clear, the cost factor could hinder widespread adoption, especially in developing countries where access to advanced technologies is often limited [46].

Furthermore, regulatory considerations are crucial when implementing nanotechnology in commercial agriculture. There is currently a lack of comprehensive regulations governing the use of nanomaterials in agriculture. For nanofertilizers and pesticides to be widely accepted, they must undergo rigorous safety protocols and approval processes to ensure they do not pose risks to human health or the environment [47]. This includes determining acceptable limits for nanoparticle exposure and ensuring that these products meet safety standards before they are introduced to the market. The lack of clear regulatory guidelines and certification processes for nano-based agricultural products poses a significant challenge to their commercialization.

3.6. Future Perspectives

The integration of nanotechnology into horticultural production presents a transformative approach to nutrient delivery, crop management, and post-harvest preservation. Nanofertilizers, in particular, offer a promising solution for enhancing crop productivity while minimizing environmental impact. By enabling precise, controlled nutrient release, these advanced fertilizers improve nutrient uptake efficiency, reduce waste, and optimize resource utilization, including water and fertilizers. As a result, they contribute to higher crop yields and more sustainable agricultural practices [44, 45, 48].

Beyond fertilization, nanotechnology is revolutionizing horticulture by enhancing the quality and shelf life of fruits, vegetables, and cut flowers. Nanomaterials facilitate the efficient delivery of nutrients and protective agents, reducing the excessive use of chemical fertilizers and pesticides. Additionally, nanosensors play a crucial role in monitoring soil moisture, detecting pesticide residues, diagnosing crop diseases, and assessing nutrient deficiencies, thereby supporting precision agriculture.

Despite these advantages, the improper use of nanomaterials could pose risks to plants and the environment. Ongoing research is essential to ensure their safe and effective application while addressing regulatory concerns regarding their long-term impact. As nanotechnology continues to advance, it is expected to become an integral component of modern horticultural practices, promoting cost-effective, environmentally friendly, and high-quality food production. Ultimately, the widespread adoption of nanotechnology in horticulture could contribute significantly to global food security by improving efficiency and reducing post-harvest losses.

4. Conclusion

Nanotechnology offers tremendous potential for revolutionizing horticultural production through the development of nanofertilizers. These advanced fertilizers promote plant growth and improve crop yield with superior-quality traits. They also play a critical role in reducing nitrogen leaching, maintaining soil health, and supporting the long-term enhancement of soil microorganisms, which ultimately contribute to more sustainable agricultural practices. Additionally, the energy conservation benefits of nanofertilizers, alongside potential economic improvements, make them a valuable tool for the future of agriculture.

Research into nanofertilizers is paving the way for more sustainable agricultural and horticultural systems, offering numerous benefits for the production of high-quality, high-yield crops. The potential of nanofertilizers to improve nutrient uptake efficiency and reduce environmental impact aligns with the growing demand for sustainable farming practices. However, it is essential to address the complexities surrounding their use. While the absorption, biotransformation, and translocation of nanoparticles within plants may offer significant benefits, they also pose potential risks. These risks include unintended interactions within the plant or ecosystem, which require further investigation.

Several challenges need to be overcome for the widespread adoption of nanofertilizers, including significant research gaps, a lack of standardized formulations, insufficient monitoring protocols, and unclear regulatory guidelines. One of the most pressing issues is that there are still not enough research articles on the practical application of nanofertilizers in the production of various crops. This gap in knowledge limits the ability to fully assess the effectiveness and safety of these products across different agricultural systems. These limitations, alongside concerns regarding long-term environmental impact, risk management, and safety, must be addressed to ensure the responsible use of nanotechnology in agriculture.

In conclusion, while integrating nanotechnology into horticulture represents a promising opportunity for sustainable agriculture and addressing the challenges of global food security, the path forward requires a balanced approach. This includes continued research, clear regulatory frameworks, and effective risk management to ensure that nanofertilizers are both safe and effective. By optimizing resource use, enhancing crop productivity, and reducing environmental impact, nanotechnology has the potential to transform horticultural practices, ultimately contributing to a more sustainable and efficient food production system.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

1. Mejias JH, Salazar F, Amaro PL, Hube S, Rodriguez M, Alfaro M. Nanofertilizers: A Cutting-Edge Approach to Increase Nitrogen Use Efficiency in Grasslands. Front Environ Sci. 2021;9:635114. https://doi.org/10.3389/fenvs.2021.635114
2. Majid A. Lepidium meyenii Walp (Maca) Roots Extract Assisted Green Synthesis of Zinc Nanoparticles and Their Antioxidant and Anticancer Activities. Int J Nanosci Nanotechnol. 2023;19(4):21-33. https://doi.org/10.22034/ijnn.2023.2002709.2377
3. John T, Parmar KA, Kotval SC, Jadhav J. Synthesis, Characterization, Antibacterial and Anticancer Properties of Silver Nanoparticles Synthesized from Carica papaya Peel Extract. Int J Nanosci Nanotechnol. 2021;17(1):23-32.
4. Beegum SA, David SB. Investigation of Antimicrobial Activity of Plant-Mediated Green Synthesis of Silver Nanoparticles. Int J Nanosci Nanotechnol. 2022;18(4):265-74. https://doi.org/10.22034/ijnn.2022.697997
5. Wangdi K. Production of Nano fertilizer-A mini Review. Int J Eng Appl Sci Technol. 2019;4(3):2455-2143. https://doi.org/10.33564/IJEAST.2019.v04i03.001
6. Nisar S, Sadique S, Kazerooni EG, Majeed U, Shehzad MR. Physical and chemical techniques to produce nano fertilizers. Int J Chem Biochem Sci. 2019;15:50-7.
7. Shebl A, Hassan A, Salama DM, Abd El-Aziz ME, Abd Elwahed MSA. Green Synthesis of Nanofertilizers and Their Application as a Foliar for Cucurbita pepo L. J Nanomater. 2019;2019:3476347. https://doi.org/10.1155/2019/3476347
8. Kumar A, Singh K, Verma P, Singh O, Panwar A, Singh T, et al. Effect of nitrogen and zinc nanofertilizer with the organic farming practices on cereal and oil seed crops. Sci Rep. 2022;12:6938. https://doi.org/10.1038/s41598-022-10843-3
9. Dubey A, Mailapalli DR. Nanofertilisers, nanopesticides, nanosensors of pest and nanotoxicity in agriculture. In: Lichtfouse E, editor. Sustainable Agriculture Reviews. Vol 19. Cham: Springer; 2016. p. 307-30. https://doi.org/10.1007/978-3-319-26777-7_7
10. Rajput VD, Singh A, Minkina T, Rawat S, Mandzhieva S, Sushkova S, et al. Nano-enabled products: Challenges and opportunities for sustainable agriculture. Plants (Basel). 2021;10(12):2727. https://doi.org/10.3390/plants10122727
11. Nongbet A, Mishra AK, Mohanta YK, Mahanta S, Ray MK, Khan M, et al. Nanofertilizers: A Smart and Sustainable Attribute to Modern Agriculture. Plants (Basel). 2022;11(19):2587. https://doi.org/10.3390/plants11192587
12. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea-Torresdey JL. Interaction of nanoparticles with edible plants and their possible implications in the food chain. J Agric Food Chem. 2011;59(8):3485-98. https://doi.org/10.1021/jf104517j
13. Stojanova TM, Djukic D, Stojanova M, Şatana A. Nutrition, Quality and Biological Potential of the Grapevine. New York: Nova Science Publishers; 2024. https://doi.org/10.52305/ZUEH8540
14. Stojanova TM. Nutrition of Horticultural Plants. Skopje: Academic Press; 2022.
15. Tyagi J, Ahmad S, Malik M. Nitrogenous fertilizers: Impact on environment sustainability, mitigation strategies, and challenges. Int J Environ Sci Technol. 2022;19:11649–11672 https://doi.org/10.1007/s13762-022-04027-9
16. Mandal D, Lalrinchhani A. Nanofertilizer and its application in horticulture. J Appl Horticult. 2021;23(1):70-7. https://doi.org/10.37855/jah.2021.v23i01.14
17. Verma KK, Song XP, Joshi A, Tian DD, Rajput VD, Singh M, et al. Recent Trends in NanoFertilizers for Sustainable Agriculture under Climate Change for Global Food Security. Nanomaterials (Basel). 2022;12(1):173. https://doi.org/10.3390/nano12010173
18. Manzoor MA, Xu Y, lv Z, Xu J, Wang Y, Sun W, et al. Nanotechnology-based approaches for promoting horticulture crop growth, antioxidant response and abiotic stresses tolerance. Plant Stress. 2024;11:100337. https://doi.org/10.1016/j.stress.2023.100337
19. El-Ramady H, Abdalla N, Alshaal T, El-Henawy A, Elmahrouk M, Bayoumi Y, et al. Plant Nano-nutrition: Perspectives and Challenges. In: Gothandam KM, Ranjan S, Dasgupta N, Ramalingam C, Lichtfouse E, editors. Nanotechnology, Food Security and Water Treatment. Cham: Springer International Publishing; 2018. p. 129-61. https://doi.org/10.1007/978-3-319-70166-0_4
20. Iqbal MA. Nano-fertilizers for sustainable crop production under changing climate: A Global Perspective. In: Sustainable Crop Production. London: IntechOpen; 2019.
21. Upadhyay PK, Singh VK, Rajanna GA, Dwivedi BS, Dey A, Singh RK, et al. Unveiling the combined effect of nano fertilizers and conventional fertilizers on crop productivity, profitability, and soil well-being. Front Sustain Food Syst. 2023;7:1260178. https://doi.org/10.3389/fsufs.2023.1260178
22. Du W, Yang J, Peng Q, Liang X, Mao H. Comparison study of zinc nanoparticles and zinc sulphate on wheat growth: from toxicity and zinc biofortification. Chemosphere. 2019;227:109-16. https://doi.org/10.1016/j.chemosphere.2019.03.162
23. Shaban EE, Elbakry HFH, Ibrahim KS, El Sayed EM, Salama DM, Farrag ARH. The effect of white kidney bean fertilized with nano-zinc on nutritional and biochemical aspects in rats. Biotechnol Rep (Amst). 2019;23:e00357. https://doi.org/10.1016/j.btre.2019.e00357
24. Silva SL, Cortes RA, Luqueño FF, Valdez FL. Design and Production of Nanofertilizers. In: Nanobiotechnology. Cham: Springer Nature Switzerland AG; 2018. p. 2. https://doi.org/10.1007/978-3-319-96719-6_2
25. Rana RA, Siddiqui MN, Skalicky M, Brestic M, Hossain A, Kayesh E, et al. Prospects of Nanotechnology in Improving the Productivity and Quality of Horticultural Crops. Horticulturae. 2021;7(10):332. https://doi.org/10.3390/horticulturae7100332
26. Ardali TR, Soleimanpour L, Mamani L, Chorom M. Opportunities and Future Perspective of Nanofertilizers and Controlled Release Nanofertilizers in Agriculture. J Water Environ Nanotechnol. 2024;9(2):223-47. https://doi.org/10.22090/jwent.2024.02.08
27. Subramanian KS, Manikandan A, Thirunavukkarasu M, Rahale CS. Nano-fertilizers for balanced crop nutrition. In: Rai M, Raghuram N, Chakrabarti R, editors. Nanotechnologies in Food and Agriculture. Cham: Springer; 2015. p. 69-80. https://doi.org/10.1007/978-3-319-14024-7_3
28. Postolache S, Sebastião P, Viegas V, Postolache O, Cercas F. IoT-Based Systems for Soil Nutrients Assessment in Horticulture. Sensors (Basel). 2023;23(1):403. https://doi.org/10.3390/s23010403
29. Stojanova TM, Djukic D, Stojanova M, Şatana A. Digitalization of Plant Nutrition Using IoT-techniques. Newcastle upon Tyne: Cambridge Scholars Publishing; 2025.
30. Zahedi SM, Karimi M, da Silva JAT. The use of nanotechnology to increase quality and yield of fruit crops. J Sci Food Agric. 2020;100(1):25-31. https://doi.org/10.1002/jsfa.10010
31. Mehta A, Yadav A, Kumar A, Manish K. Role of nanotechnology in horticulture: An overview. Int J Adv Biochem Res. 2024;8(1):702-8. https://doi.org/10.33545/26174693.2024.v8.i1i.481
32. Saisupriya P, Saidaiah P. Application of Nanotechnology in Vegetable Crops. Just Agric. 2021;2(2). Available from: https://www.justagriculture.in
33. Kumar MR, Bahadur V, Prasad VM. Role of Nanotechnology in horticulture. Agri Allis J. 2023;5(6). Available from: https://www.agriallis.com
34. Anushi JS, Sharma R, Thapliyal V, Behera SD, Ulla HMTU, Haokip SW, et al. Nanotechnology in Horticulture: A Blossoming Frontier

for Sustainable Agriculture. Front Crop Sci. 2023;11:1668-73.
35. Ibrahim AA, Abd-Ellatif S, Abdel Razik ESS, Hamedo HA, Salem KFM. Nanosensors for Enhancing Plant Growth and Productivity. In: Al-Khayri JM, Alnaddaf LM, Jain SM, Penna S, editors. Innovative Methods in Horticultural Crop Improvement. Advances in Plant Breeding Strategies. Vol 2. Cham: Springer; 2024. https://doi.org/10.1007/978-3-031-61095-0_2
36. Liu C, Zhou H, Zhou J. The Applications of Nanotechnology in Crop Production. Molecules. 2021;26(23):7070. https://doi.org/10.3390/molecules26237070
37. Upadhyay PK, Dey A, Singh VK, Dwivedi BS, Singh T, Rajanna GA. Conjoint application of nano-urea with conventional fertilizers: an energy efficient and environmentally robust approach for sustainable crop production. PLoS One. 2023;18(4):e0284009. https://doi.org/10.1371/journal.pone.0284009
38. Hayyawi WA, Al-Uthery MN, Al-Shami Q. Impact of fertirigation of nano NPK fertilizers, nutrient use efficiency and distribution in soil of potato (Solanum tuberosum L.). Plant Arch. 2019;19(1):1087-96.
39. Ajirloo AR, Shaaban M, Motlagh ZR. Effect of K nanofertilizer and N bio-fertilizer on yield and yield components of tomato (Lycopersicon esculentum L.). Int J Adv Biol Biom Res. 2015;3(1):138-43.
40. Wang Q, Ebbs SD, Chen Y, Ma X. Trans-generational impact of cerium oxide nanoparticles on tomato plants. Metallomics. 2011;3(7):753-9. https://doi.org/10.1039/C3MT00033H
41. Abd-Alrahman HA, Aboud FS. Response of sweet pepper plants to foliar application of compost tea and dry yeast under soilless conditions. Bull Natl Res Cent. 2021;45:119. https://doi.org/10.1186/s42269-021-00578-y
42. Merghany M, Mohamed M, Shahein Mahmoud AS, Karima FA, Amany FR. Effect of nano-fertilizers on cucumber plant growth, fruit yield and its quality. Plant Arch. 2019;19(2):165-72.
43. Ghidan AY, Abdel MSK, Al-Antary TM. Effect of nanotechnology liquid fertilizers on yield and nitrogenous compounds of broad bean (Vicia faba L.). Fresenius Environ Bull. 2020;29(6):4124-8.
44. Ijaz M, Khan F, Ahmed T, Noman M, Zulfiqar F, Rizwan M, et al. Nanobiotechnology to advance stress resilience in plants: Current opportunities and challenges. Mater Today Bio. 2023;22:100759. https://doi.org/10.1016/j.mtbio.2023.100759
45. Rana L, Kumar M, Rajput J. Nexus between nanotechnology and agricultural production systems: challenges and future prospects. Discov Appl Sci. 2024;6:555. https://doi.org/10.1007/s42452-024-06265-7
46. Tang Y, Zhao W, Zhu G, Tan Z, Huang L, Zhang P, et al. Nano-Pesticides and Fertilizers: Solutions for Global Food Security. Nanomaterials (Basel). 2024;14(1):90. https://doi.org/10.3390/nano14010090
47. Yadav A, Yadav K, Abd-Elsalam KA. Exploring the potential of nanofertilizers for a sustainable agriculture. Plant Nano Biol. 2023;5:100044. https://doi.org/10.1016/j.plana.2023.100044
48. Conley DJ, Paerl HW, Howarth RW. Controlling eutrophication: nitrogen and phosphorus. Science. 2009;323(5917):1014-5. https://doi.org/10.1126/science.1167755