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Nanofertilizers for Sustainable Crop Production: Recent Advances, Nutrient Use Efficiency, and Agricultural Applications

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ABSTRACT

Nanofertilizers have emerged as an innovative technology for improving crop productivity and promoting sustainable agricultural development. Unlike conventional fertilizers, nanofertilizers provide controlled and targeted nutrient delivery, thereby enhancing nutrient use efficiency and minimizing nutrient losses through leaching, volatilization, and runoff. Their unique physicochemical properties improve nutrient availability, root absorption, plant metabolism, and stress tolerance, leading to increased crop yield and reduced environmental pollution. Recent advancements in nanotechnology have facilitated the development of smart nanofertilizers with controlled-release mechanisms and precision nutrient management. These nano-enabled fertilizers support sustainable farming by reducing fertilizer consumption while maintaining soil fertility and crop productivity. Despite their considerable advantages, concerns regarding nanoparticle toxicity, environmental persistence, and regulatory frameworks remain challenges for large-scale adoption. This review summarizes recent advances in nanofertilizer technology, nutrient use efficiency, agricultural applications, environmental benefits, current limitations, and future research directions for sustainable crop production.

Keywords: *Nanofertilizers, Sustainable Agriculture, Crop Production, Nutrient Use Efficiency, Precision Agriculture, Nanotechnology, Plant Nutrition.*

1. Introduction

The rapid increase in global population, climate change, declining soil fertility, and limited natural resources have intensified the need for sustainable agricultural practices that ensure food security while minimizing environmental degradation [1,2]. Modern agriculture relies heavily on chemical fertilizers to increase crop productivity; however, excessive fertilizer application has resulted in nutrient losses, soil degradation, groundwater contamination, greenhouse gas emissions, and reduced nutrient use efficiency [3,4]. These environmental and economic concerns have encouraged researchers to develop innovative fertilizer technologies that improve nutrient availability while reducing ecological impacts.

Nanotechnology has emerged as one of the most promising approaches for enhancing agricultural productivity through the development of nanofertilizers [5,6]. Nanofertilizers are nano-sized nutrient formulations or nanomaterial-based delivery systems that improve nutrient availability, controlled release, and nutrient uptake by plants. Their high surface area, enhanced reactivity, and controlled-release characteristics enable nutrients to be supplied according to crop requirements, thereby minimizing nutrient losses and improving fertilizer efficiency [7,8]. Recent advances in nanotechnology, biotechnology, and precision agriculture have significantly expanded the applications of nanofertilizers in crop production [9,10].

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Various nano-based fertilizers containing nitrogen, phosphorus, potassium, zinc, iron, and other micronutrients have demonstrated improved nutrient uptake, enhanced photosynthesis, increased biomass production, and greater tolerance to abiotic stresses such as drought and salinity [11,12]. In addition, nanofertilizers contribute to sustainable agriculture by reducing fertilizer application frequency, minimizing environmental pollution, and improving soil health [13,14]. Despite these advantages, several concerns remain regarding nanoparticle toxicity, long-term environmental accumulation, food safety, and regulatory approval [15,16]. Comprehensive risk assessment and standardized safety guidelines are therefore necessary before widespread commercialization [17,18].

2. Overview of Nanofertilizers

Nanofertilizers are advanced fertilizer formulations that utilize nanotechnology to improve nutrient delivery and fertilizer efficiency [5,6]. They may consist of nutrients encapsulated within nanoparticles, nutrients coated with nanomaterials, or nano-sized particles that directly supply essential plant nutrients. Common nanofertilizers include nitrogen, phosphorus, potassium, zinc, iron, copper, and silica-based nanoformulations [7,11]. Compared with conventional fertilizers, nanofertilizers provide slow and controlled nutrient release, reducing nutrient losses while improving plant uptake efficiency [2,8]. Their small particle size facilitates better interaction with plant roots and leaves, resulting in enhanced nutrient absorption and improved crop growth [12,13]. These characteristics make nanofertilizers an important component of precision agriculture and sustainable farming systems [9,14].

3. Recent Advances in Nanofertilizer Technology

Recent developments in nanotechnology have significantly improved the design and performance of nanofertilizers [5,10]. Nanoencapsulation techniques protect nutrients from rapid degradation and allow their gradual release according to plant demand [6,7]. Polymeric nanocarriers, metal oxide nanoparticles, carbon-based nanomaterials, and biodegradable nanoformulations have been developed to improve nutrient stability and bioavailability [8,11]. Smart nanofertilizers capable of responding to environmental conditions such as soil moisture, temperature, and pH are also being investigated for precision nutrient management [14]. Furthermore, the integration of nanotechnology with artificial intelligence, the Internet of Things (IoT), and precision agriculture enables real-time nutrient monitoring and site-specific fertilizer application, improving agricultural productivity while reducing environmental impacts [18].

Table 1: Major Types of Nanofertilizers and Their Agricultural Applications

Type of Nanofertilizer	Examples	Primary Agricultural Application	Major Benefits
Nitrogen-Based Nanofertilizers	Nano-urea	Controlled nitrogen delivery to crops	Improved nitrogen use efficiency, reduced volatilization and leaching losses
Phosphorus-Based Nanofertilizers	Nano-phosphate	Enhanced phosphorus availability and uptake	Improved root development, nutrient absorption, and plant growth
Potassium-Based Nanofertilizers	Nano-potash	Efficient potassium nutrition	Enhanced stress tolerance, water-use efficiency, and crop productivity
Micronutrient Nanofertilizers	Nano-zinc (Zn), Nano-iron (Fe), Nano-copper (Cu)	Correction of micronutrient deficiencies	Improved photosynthesis, enzyme activity, and overall plant metabolism
Polymeric Nanofertilizers	Chitosan-based nanofertilizers	Controlled and targeted nutrient delivery	Sustained nutrient release, enhanced nutrient use efficiency, and reduced environmental pollution

Table 2: Advantages and Limitations of Nanofertilizers in Sustainable Agriculture

Aspect	Advantages	Limitations
Nutrient Delivery	Controlled, targeted, and sustained nutrient release	High production and formulation costs
Nutrient Use Efficiency	Enhanced nutrient uptake and reduced nutrient losses	Limited long-term and large-scale field validation
Crop Productivity	Improved plant growth, yield, and crop quality	Performance may vary depending on crop species, soil properties, and environmental conditions
Environmental Impact	Reduced nutrient leaching, runoff, and greenhouse gas emissions	Potential accumulation and persistence of nanoparticles in soil and aquatic ecosystems
Precision Agriculture	Facilitates site-specific and precision nutrient management	Requires advanced application equipment and monitoring systems
Safety and Regulatory Issues	Reduced fertilizer consumption and environmental contamination	Lack of standardized regulatory frameworks and comprehensive long-term toxicity assessments

4. Nutrient Use Efficiency

Nanofertilizers significantly improve nutrient use efficiency (NUE) by delivering nutrients in a controlled and sustained manner according to plant requirements [2,4]. Conventional fertilizers often suffer from nutrient losses through leaching, volatilization, fixation, and surface runoff, resulting in low fertilizer use efficiency and environmental pollution [3,5]. In contrast, nanofertilizers release nutrients gradually, ensuring continuous nutrient availability throughout different stages of plant growth [6,8]. Their nanoscale size enhances interaction with plant roots and leaves, leading to greater nutrient absorption and translocation within plant tissues [10,11]. Improved nutrient use efficiency not only increases crop productivity but also reduces fertilizer consumption, production costs, and nutrient losses, making agriculture more sustainable [12,16].

5. Agricultural Applications

Nanofertilizers are increasingly used in a wide variety of agricultural crops, including cereals, fruits, vegetables, legumes, oilseed crops, and horticultural plants [7,9]. Nano-based formulations of nitrogen, phosphorus, potassium, zinc, iron, and other micronutrients have demonstrated significant improvements in seed germination, root development, photosynthesis, flowering, and crop yield [8,10]. Foliar application and soil application of nanofertilizers improve nutrient uptake while minimizing fertilizer wastage [2,14]. Nanofertilizers also enhance plant tolerance to abiotic stresses such as drought, salinity, heat, and nutrient deficiency by improving antioxidant activity and physiological processes [11,17]. Their integration with precision agriculture enables site-specific nutrient management, increasing productivity while conserving natural resources [5,19].

6. Environmental Benefits

The use of nanofertilizers offers several environmental advantages compared with conventional fertilizers [4,6]. Controlled nutrient release reduces nitrate leaching, phosphorus runoff, and greenhouse gas emissions associated with excessive fertilizer application [3,12]. Improved nutrient uptake minimizes fertilizer accumulation in soil and water bodies, thereby protecting aquatic ecosystems and reducing environmental pollution [1,13]. Nanofertilizers also contribute to improved soil fertility by maintaining nutrient balance and supporting beneficial soil microorganisms [9,15]. These environmental benefits make nanofertilizers an important component of climate-smart and sustainable agricultural systems [18].

7. Challenges and Future Prospects

Despite their promising applications, several challenges limit the widespread adoption of nanofertilizers **[5,13]**. High production costs, limited commercial availability, lack of standardized manufacturing methods, and insufficient long-term safety studies remain major concerns [14,16]. The potential toxicity of nanoparticles to soil microorganisms, aquatic organisms, and human health also requires comprehensive investigation before large-scale commercialization [11,17]. Future research should focus on developing biodegradable nanomaterials, environmentally friendly formulations, and internationally accepted regulatory guidelines [18].

Advances in artificial intelligence, Internet of Things (IoT), biosensors, and precision agriculture are expected to improve nutrient management and support the next generation of smart nanofertilizers [9].

8. Conclusion

Nanofertilizers have emerged as an innovative solution for improving nutrient use efficiency and promoting sustainable crop production. Their controlled nutrient release, enhanced bioavailability, and efficient nutrient delivery improve plant growth while reducing fertilizer losses and environmental pollution. Recent advances in nanotechnology have expanded the applications of nanofertilizers in precision agriculture, stress management, and climate-resilient farming systems. Although challenges related to nanoparticle safety, environmental risks, and regulatory approval remain, continuous research is contributing to the development of safer and more sustainable nanofertilizer technologies. Future integration of nanotechnology with digital agriculture, artificial intelligence, and smart farming practices is expected to improve global food security while supporting environmentally sustainable agricultural production.

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