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RESEARCH ARTICLE

Harnessing Nanotechnology for Superior Fruit Crop Quality and Yield Enhancement

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ABSTRACT

Nanotechnology represents a groundbreaking frontier in agriculture, offering promising solutions for enhancing fruit crop quality and yield. Through the development of nanofertilizers, nanostimulants, and nanoscale delivery systems, nanotechnology can address critical challenges in nutrient management, stress resistance, and crop protection. However, the adoption of these innovations is not without challenges, including environmental risks, high production costs, regulatory uncertainties, and public acceptance issues. As research progresses, it is crucial to balance the benefits of nanotechnology with careful consideration of its potential impacts. Ensuring the safe and sustainable integration of nanotechnology in agriculture will require interdisciplinary collaboration, robust regulatory frameworks, and transparent communication with stakeholders. Ultimately, if these challenges are effectively addressed, nanotechnology has the potential to significantly contribute to the future of sustainable agriculture and global food security.

Key words: Nanotechnology, Nanofertilizers, Fruit crop quality, Yield enhancement, Sustainable agriculture

INTRODUCTION

The global demand for high-quality fruit crops has been escalating due to increasing consumer awareness about nutrition and the rising need for food security. As a result, enhancing the quality and yield of fruit crops has become a critical focus for agricultural researchers and industry stakeholders (Shoukat et al., 2024). Traditionally, improvements in fruit crop production have been driven by advancements in breeding techniques, chemical inputs, and cultivation practices. However, these methods often fall short of meeting the growing challenges posed by climate change, soil degradation, and the increasing prevalence of pests and diseases. In this context, nanotechnology has emerged as a promising solution, offering innovative approaches to optimize both the quality and yield of fruit crops (Zafar et al., 2024).

Nanotechnology involves the manipulation of materials at the nanoscale—typically between 1 and 100 nanometers—where unique physical and chemical properties can be harnessed to achieve specific outcomes (Azam et al., 2022). In agriculture, nanotechnology has been applied across various domains, including nutrient delivery, pest and disease management, and post-harvest preservation (Zafar et al., 2020; Razzaq et al., 2023). The ability to control the release and delivery of nutrients and agrochemicals at the nanoscale can significantly improve their efficiency and reduce environmental impacts. For instance, nano-fertilizers have been shown to enhance nutrient uptake and utilization in plants, leading to improved growth and yield (Naderi & Danesh-Shahraki, 2013). Additionally, nanopesticides offer targeted pest control, minimizing the need for broad-spectrum chemicals and reducing the risk of resistance development among pests (Kah et al., 2013).

The application of nanotechnology in fruit crop production is particularly promising given the economic importance of fruits and the challenges associated with their cultivation. Fruits are highly perishable and sensitive to environmental conditions, making them vulnerable to post-harvest losses and quality degradation. Nanotechnology offers solutions for extending shelf life and maintaining the quality of fruits during storage and transportation. For example, the use of nanomaterials in packaging can create barriers to gases and moisture, reducing spoilage and preserving the sensory and nutritional qualities of fruits (De Azeredo, 2009). Moreover, nanoparticles can be

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used to develop coatings that protect fruits from microbial contamination and mechanical damage, further enhancing their marketability and consumer appeal (Emamifar et al., 2010).

Another critical area where nanotechnology can contribute to fruit crop production is in improving disease resistance and stress tolerance. The increasing incidence of plant diseases, exacerbated by climate change, poses a significant threat to fruit crops. Nanoparticles can be engineered to deliver antimicrobial agents directly to the site of infection or to induce systemic resistance in plants, thereby reducing the reliance on chemical pesticides (Gogos et al., 2012). Additionally, the application of nanoscale materials can enhance the plants' ability to withstand abiotic stresses such as drought, heat, and salinity, which are becoming more prevalent due to changing climatic conditions (Rai et al., 2015).

Despite the potential benefits, the adoption of nanotechnology in agriculture, particularly in fruit crop production, is still in its nascent stages. Challenges such as the high cost of nanomaterials, potential environmental and health risks, and the need for regulatory frameworks to ensure their safe use must be addressed. Research is ongoing to develop cost-effective and environmentally friendly nanomaterials that can be integrated into existing agricultural practices. Moreover, a comprehensive understanding of the long-term impacts of nanotechnology on ecosystems and human health is essential to ensure its sustainable application in agriculture (Shahid et al., 2023).

Nanotechnology holds significant promise for enhancing the quality and yield of fruit crops, addressing some of the most pressing challenges in modern agriculture. By improving nutrient delivery, enhancing disease resistance, and extending post-harvest shelf life, nanotechnology can contribute to the sustainable production of high-quality fruits. However, realizing the full potential of nanotechnology in agriculture will require continued research, innovation, and the development of appropriate regulatory frameworks. As the global population continues to grow and the demand for nutritious food increases, the role of nanotechnology in fruit crop production is likely to become increasingly important (Ahmed et al., 2023).

Overview of Nanotechnology in Agriculture

Nanotechnology has emerged as a transformative tool in various industries, including medicine, electronics, and environmental sciences. In recent years, its application in agriculture has gained considerable attention due to its potential to address several challenges faced by modern farming practices. The integration of nanotechnology in agriculture offers innovative solutions that can enhance crop production, improve resource use efficiency, and reduce environmental impacts. This overview delves into the fundamental concepts of nanotechnology and explores its broad applications in agriculture, laying the foundation for understanding its role in fruit crop quality and yield enhancement.

At its core, nanotechnology involves the manipulation of materials at the nanoscale, typically ranging from 1 to 100 nanometers. At this scale, materials exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts. These properties include increased surface area, reactivity, and quantum effects, which can be harnessed for various agricultural applications (Khot et al., 2012). The versatility of nanomaterials, such as nanoparticles, nanofibers, and nanocomposites, has paved the way for their use in developing advanced agricultural products, including nanofertilizers, nanopesticides, and nanosensors.

One of the primary applications of nanotechnology in agriculture is in the development of nanofertilizers. Traditional fertilizers often suffer from low nutrient use efficiency, leading to excessive application rates and environmental pollution. Nanofertilizers, on the other hand, can be engineered to release nutrients in a controlled manner, improving their uptake by plants and reducing losses to the environment. This targeted delivery system not only enhances crop growth and yield but also minimizes the environmental footprint of fertilizer use (Liu & Lal, 2015). For example, studies have demonstrated that nanofertilizers can improve the efficiency of nitrogen use in crops, resulting in higher productivity with lower input costs (DeRosa et al., 2010).

In addition to nanofertilizers, nanopesticides represent another significant application of nanotechnology in agriculture. Conventional pesticides often require large quantities to be effective, which can lead to environmental contamination and the development of pesticide resistance in pests. Nanopesticides are designed to overcome these limitations by delivering active ingredients more effectively and with greater precision. The enhanced surface area and reactivity of nanoparticles allow for better adhesion to plant surfaces, improved penetration into pest cells, and prolonged activity (Kah et al., 2013). As a result, nanopesticides can achieve the same or greater levels of pest control with lower doses, reducing the risk of environmental damage and resistance development.

Nanotechnology also plays a crucial role in precision agriculture, an approach that uses advanced technologies to optimize farming practices based on real-time data. Nanosensors are at the forefront of this innovation, providing farmers with detailed information about soil health, plant growth, and environmental conditions. These sensors can detect specific molecules or environmental factors at extremely low concentrations, enabling early diagnosis of plant stress, nutrient deficiencies, or pest infestations (Monreal et al., 2016). By integrating nanosensors into precision agriculture systems, farmers can make data-driven decisions that improve crop management, reduce input costs, and enhance overall productivity.

Furthermore, nanotechnology is contributing to the development of smart delivery systems for agrochemicals. These systems use nanoparticles to encapsulate and protect active ingredients, allowing for their controlled release over time or in response to specific triggers, such as changes in temperature, pH, or moisture levels (Torney et al., 2007). Such precision in the delivery of agrochemicals not only increases their effectiveness but also reduces the need for repeated applications, lowering costs and minimizing environmental impact.

Despite the promising potential of nanotechnology in agriculture, its widespread adoption is still in its early stages. Several challenges must be addressed to fully realize its benefits. These include the high cost of production, potential toxicity of nanomaterials to non-target organisms, and the need for regulatory frameworks that ensure the safe and sustainable use of nanotechnology in farming (Servin & White, 2016). Additionally, more research is needed to understand the long-term effects of nanomaterials on soil health, crop growth, and environmental ecosystems.

Nanotechnology for Fruit Crop Quality Enhancement

Improving Nutritional Content

The nutritional quality of fruit crops is a critical factor that influences consumer preferences and market value. Nanotechnology offers innovative solutions to enhance the nutritional content of fruits by improving nutrient uptake and utilization within plants. One of the key mechanisms through which nanotechnology achieves this is by developing nanofertilizers that are more efficient than traditional fertilizers. Nanofertilizers are engineered to release nutrients in a controlled and sustained manner, ensuring that plants receive a steady supply of essential elements such as nitrogen, phosphorus, and potassium throughout their growth cycle (Shoukat et al., 2024). This enhanced nutrient availability leads to improved metabolic processes within the plant, resulting in fruits with higher concentrations of vitamins, minerals, and antioxidants.

In addition to macronutrients, nanotechnology can also enhance the bioavailability of micronutrients, which are vital for the synthesis of key biochemical compounds in fruits. For instance, iron, zinc, and selenium are essential for the synthesis of enzymes and antioxidants that contribute to the nutritional quality of fruits (Khot et al., 2012). Nanoparticles of these micronutrients can be tailored to improve their solubility and uptake by plants, leading to increased concentrations in the edible parts of the fruit. This not only boosts the nutritional profile of the fruit but also addresses micronutrient deficiencies in human diets, contributing to better public health outcomes.

Enhancing Shelf-Life and Post-Harvest Quality

The post-harvest phase is a critical period in the lifecycle of fruit crops, as it determines the quality, safety, and marketability of the produce. Post-harvest losses due to spoilage, microbial contamination, and physiological deterioration are significant challenges that affect the profitability of fruit crops. Nanotechnology offers promising solutions to extend the shelf-life of fruits and maintain their quality during storage and transportation.

One of the primary ways nanotechnology contributes to extending shelf-life is through the development of advanced packaging materials. Nanocomposites, which incorporate nanoparticles into polymer matrices, have been shown to improve the barrier properties of packaging materials against gases such as oxygen and carbon dioxide (De Azeredo, 2009). These barriers slow down the respiration rate of fruits, reducing the production of ethylene, a hormone that accelerates ripening and spoilage. By controlling the internal atmosphere of the packaging, nanotechnology helps preserve the freshness and sensory attributes of fruits, such as texture, flavor, and color.

In addition to improving packaging materials, nanotechnology can be used to create antimicrobial coatings that protect fruits from microbial spoilage. These coatings often incorporate nanoparticles with inherent antimicrobial properties, such as silver, zinc oxide, or titanium dioxide, which are effective against a wide range of bacteria and fungi (Emamifar et al., 2010). When applied to the surface of fruits, these coatings form a protective barrier that inhibits the growth of spoilage organisms, thereby reducing post-harvest losses and enhancing food safety.

Disease Resistance and Pest Management

Fruit crops are particularly susceptible to a wide range of diseases and pests, which can severely impact yield and quality. Traditional methods of pest and disease management, such as chemical pesticides and fungicides, often have limited effectiveness and can lead to the development of resistance among pathogens and pests. Nanotechnology offers innovative strategies for enhancing disease resistance and pest management in fruit crops, providing more effective and sustainable solutions (Zafar et al., 2022).

One of the key applications of nanotechnology in this context is the development of nanopesticides, which are formulations that incorporate nanoparticles or nanomaterials to improve the efficacy of active ingredients. Nanopesticides can enhance the solubility, stability, and bioavailability of active compounds, allowing for more targeted and efficient delivery to the site of infection or infestation (Kah et al., 2013). This targeted approach not only improves the effectiveness of pest and disease control but also reduces the amount of chemicals needed, minimizing the environmental impact and the risk of resistance development.

In addition to nanopesticides, nanotechnology can also be used to develop nanofungicides, which are designed to combat fungal infections in fruit crops. Fungal diseases, such as powdery mildew and downy mildew, are major threats to fruit production and can lead to significant crop losses. Nanofungicides, which often include metal oxide nanoparticles like copper oxide and zinc oxide, have shown promise in inhibiting the growth of fungal pathogens by disrupting their cellular processes (Mehwish et al., 2023). These nanomaterials can be engineered to provide sustained release of the active ingredient, ensuring long-lasting protection against fungal infections.

Nanotechnology for Yield Enhancement in Fruit Crops

Nanotechnology offers transformative potential for enhancing the yield of fruit crops by addressing some of the fundamental challenges in modern agriculture, including efficient resource utilization, stress management, and crop protection. Yield enhancement is a critical focus in fruit crop production, as it directly impacts food security and the economic viability of agricultural systems. This section explores how nanotechnology can contribute to yield enhancement in fruit crops through innovative applications such as nanofertilizers, nanostimulants, and nanoscale delivery systems for agrochemicals.

Nanofertilizers for Optimized Nutrient Delivery

Traditional fertilization methods often suffer from inefficiencies, with a significant portion of applied nutrients being lost to leaching, volatilization, or other forms of environmental dissipation before they can be absorbed by plants. This inefficiency not only results in lower crop yields but also contributes to environmental pollution. Nanofertilizers represent a groundbreaking solution to this problem by improving the efficiency of nutrient delivery and uptake. These fertilizers are engineered at the nanoscale to provide a slow and controlled release of nutrients, tailored to the specific needs of the crop throughout its growth stages (Liu & Lal, 2015). A list of nanofertilizers and their advantages/disadvantages have been summarized in Table 1 (Yadav et al., 2023).

Table 1: Comparative Analysis of Controlled-Release Nanofertilizers (Yadav et al., 2023)

Nanofertilizer Type	Advantages	References	Disadvantages	References
Carbon-Based	- Promotes plant growth - Increases water and nutrient retention - Helps during drought conditions	(Bijali and Acharya, 2020)	- Time-consuming synthesis methods	(Zhu et al., 2022)
Chitosan-Based	- Biodegradable - Adjustable size - Easy to modify - Protects biomolecules from environmental factors	(Shukla et al., 2013; Liu et al., 2022)	- Hydrophilicity - Weak mechanical properties - Low gas permeability - Low encapsulation efficiency	(Yu et al., 2021)
Clay-Based	- Large surface area - Nanolayer reactivity - Regulates the release of anions	(Mishra et al., 2013)	- Can inhibit leaf growth - May affect transpiration	(Asli and Neumann, 2009)
Nanocapsule-Based	- Controlled nutrient release - Efficient nutrient delivery - Reduced risk of leaching	(Li, 2015; Gupta et al., 2021)	- Requires complex synthesis processes - Material limitations	
Nanogel-Based	- Highly soluble - Biodegradable - Non-toxic - Improves water retention	(Win et al., 2021)	- Challenges in optimizing biodistribution - Issues with degradation mechanism - Potential component toxicity	(Neamtu et al., 2017)
Polyurethane-Based	- Controlled nutrient release - Improved water-holding capacity - Reduced soil erosion	(Aththanayaka et al., 2022)	- Weak chemical and thermal stability - Rapid elimination - Short polymer lifespan due to acid monomer formation	(Wen et al., 2005)
Starch-Based	- Renewable energy source - Effective nutrient delivery - Minimal chemical waste	(Mishra and Khare, 2021)	- Expensive and time-consuming - Unstable nature	(Rahman et al., 2021)
Zeolite-Based	- Improved nutrient delivery - Tailored nutrient provision - Reduced fertilization cost	(Al-Juthery et al., 2021)	- Requires specific formulations and synthesis processes for optimal results - Limited in managing anionic nutrients	(Morales-Díaz et al., 2017)

Nanofertilizers can enhance nutrient use efficiency by ensuring that a higher proportion of the applied nutrients are absorbed by the plants, thereby increasing growth rates and overall yield. For instance, research has shown that the application of nanofertilizers in fruit crops such as strawberries and tomatoes leads to improved growth performance and higher fruit yields compared to conventional fertilizers (Rai et al., 2015). The increased surface area and reactivity of nanoparticles allow for better interaction with root systems, facilitating greater uptake of essential nutrients like nitrogen, phosphorus, and potassium.

Moreover, nanofertilizers can be designed to include micronutrients that are crucial for various physiological processes in fruit crops. These micronutrients, such as zinc, iron, and copper, play key roles in enzymatic functions, photosynthesis, and stress resistance. By delivering these nutrients more effectively, nanofertilizers contribute to healthier plants that are more capable of achieving their full yield potential. This optimized nutrient management not only boosts fruit production but also enhances the quality of the harvest, making it a valuable tool for both small-scale and commercial farmers.

Nanostimulants for Enhanced Growth and Stress Resistance

Beyond the basic provision of nutrients, nanotechnology also offers solutions for enhancing the overall growth and stress resilience of fruit crops through the use of nanostimulants. Nanostimulants are materials that, when applied to plants, stimulate various physiological processes, leading to improved growth rates, greater biomass accumulation, and increased fruit yield. These stimulants often include nanoparticles of elements like silicon, which have been shown to reinforce plant cell walls, enhance photosynthetic efficiency, and improve water use efficiency (Siddiqui & Al-Whaibi, 2014).

Nanostimulants can also play a critical role in helping fruit crops cope with abiotic stresses, such as drought, salinity, and temperature fluctuations. By bolstering the plant's natural defense mechanisms, these nanomaterials can reduce the negative impacts of stress on growth and yield. For example, the application of silicon nanoparticles has been demonstrated to enhance drought tolerance in fruit crops by improving water retention and reducing oxidative stress within plant tissues (Ghorbanpour et al., 2015). This increased resilience enables plants to maintain higher productivity levels even under suboptimal growing conditions, contributing to more stable and reliable yields.

Additionally, nanostimulants can be used to promote earlier flowering and fruiting, which can be particularly advantageous in regions with short growing seasons or in controlled environments like greenhouses. By accelerating key developmental processes, nanostimulants help maximize the productive potential of fruit crops, leading to increased harvests and potentially higher profits for farmers.

Nanoscale Delivery Systems for Agrochemicals

Efficient and targeted delivery of agrochemicals is essential for maximizing the yield of fruit crops while minimizing the environmental impact of farming practices. Traditional methods of applying pesticides, herbicides, and growth regulators often result in significant wastage, with a large portion of the chemicals not reaching their intended targets. This inefficiency not only reduces the effectiveness of the treatment but also leads to environmental contamination and the potential development of resistance in pests and diseases.

Nanotechnology offers a solution to these challenges through the development of nanoscale delivery systems for agrochemicals. These delivery systems utilize nanoparticles to encapsulate and protect the active ingredients, ensuring that they are released in a controlled manner at the site of action (Kah et al., 2013). This targeted approach reduces the amount of chemical required, thereby lowering costs and minimizing the environmental footprint of agricultural practices.

One of the key advantages of nanoscale delivery systems is their ability to penetrate plant tissues more effectively than conventional formulations. This improved penetration allows for better absorption of the active ingredients, leading to enhanced efficacy and reduced need for repeated applications. For example, nanopesticides have been shown to provide more effective pest control in fruit crops, leading to higher yields and better crop quality (Gogos et al., 2012). Similarly, the use of nanocarriers for the delivery of growth regulators can promote more uniform fruit development and ripening, resulting in increased yield consistency.

Challenges and Limitations

While nanotechnology holds great promise for enhancing fruit crop quality and yield, it also presents a range of challenges and limitations that must be carefully considered. These issues stem from the complexity of nanoscale materials, their interactions with biological systems, and the broader environmental, economic, and regulatory implications of their use in agriculture.

One of the primary challenges in the application of nanotechnology in agriculture is the potential environmental impact of engineered nanoparticles. Nanoparticles, due to their small size and high reactivity, can interact with soil, water, and air in ways that are not yet fully understood. There is concern that these particles could accumulate in the environment, potentially leading to unforeseen ecological consequences. For example, nanoparticles could alter soil microbial communities, which play a crucial role in nutrient cycling and plant health, or they might be taken up by non-target organisms, leading to bioaccumulation and potential toxicity in the food chain (Grillo et al., 2015). These environmental concerns necessitate comprehensive risk assessments and long-term studies to better understand the fate and behavior of nanoparticles in agricultural ecosystems.

Another significant limitation is the high cost of developing and producing nanomaterials, which can be a barrier to widespread adoption, particularly in resource-limited regions. The production of high-quality, uniform nanoparticles requires advanced technology and infrastructure, which can be expensive to establish and maintain. As a result, the cost of nanotechnology-based agricultural inputs, such as nanofertilizers and nanopesticides, may be prohibitive for small-scale farmers, limiting the accessibility and equity of these innovations. Moreover, the economic viability of nanotechnology in agriculture is still being debated, as the long-term benefits need to outweigh the initial investment costs for it to be sustainable on a large scale (Gruère et al., 2011).

In addition to environmental and economic concerns, there are also significant regulatory and safety challenges associated with the use of nanotechnology in agriculture. The regulatory frameworks for nanomaterials are still evolving, and there is a lack of standardized guidelines for their assessment and approval in many countries. This regulatory uncertainty can hinder the development and commercialization of nanotechnology products, as companies may face delays or additional costs in meeting compliance requirements. Furthermore, the safety of nanoparticles for human health remains a critical concern. Although some studies have shown that certain nanoparticles are safe for use in food and agriculture, others have raised questions about their potential toxicity, especially when ingested or inhaled (Dasgupta et al., 2015). Ensuring that nanotechnology applications in agriculture do not pose risks to consumers or agricultural workers will require rigorous testing and transparent communication of the risks and benefits.

Public perception and acceptance of nanotechnology in agriculture is another hurdle that must be addressed. The novelty of nanotechnology, combined with the general public's limited understanding of nanoscale science, can lead to apprehension or resistance to its use in food production. Misinformation and lack of awareness about the safety and benefits of nanotechnology can exacerbate these concerns, potentially leading to market rejection or stringent regulations that could stifle innovation. Engaging stakeholders, including farmers, consumers, and policymakers, through education and transparent communication is essential to building trust and acceptance of nanotechnology in agriculture (Kuzma & VerHage, 2006).

Lastly, the technical challenges associated with the large-scale application of nanotechnology in agriculture cannot be overlooked. Developing effective delivery systems for nanoparticles that can be easily integrated into existing agricultural practices remains a significant challenge. Ensuring that nanoparticles reach their intended targets, whether it be plant tissues or specific pests, requires precision in formulation and application techniques. Moreover, the potential for nanoparticles to interact with other agrochemicals or environmental factors adds another layer of complexity to their use in the field.

Conclusion

In conclusion, nanotechnology holds transformative potential for revolutionizing fruit crop production by significantly enhancing both quality and yield. The application of nanotechnology in agriculture is driven by the development of advanced nanofertilizers, nanostimulants, and nanoscale delivery systems for agrochemicals. Nanofertilizers, by optimizing nutrient delivery and absorption, address key issues related to nutrient inefficiency, leading to improved vegetative and reproductive growth, increased productivity, and enhanced fruit quality. Nanostimulants further contribute by promoting plant resilience to abiotic stresses such as drought and salinity, thereby supporting consistent crop performance and stability in yield. Nanoscale delivery systems for agrochemicals ensure precise and controlled release of pesticides and growth regulators, reducing waste and environmental impact while enhancing the effectiveness of these inputs.

Despite the promising advancements, several challenges must be addressed to fully realize the benefits of nanotechnology in agriculture. Environmental concerns related to the potential accumulation and toxicity of nanoparticles in soil, water, and non-target organisms require rigorous risk assessments and long-term studies. Understanding the fate and behavior of nanoparticles in agricultural ecosystems is crucial to mitigate any adverse environmental impacts. Additionally, the high costs associated with the production and application of nanotechnology-based products pose a significant barrier, particularly for small-scale farmers. The development of cost-effective manufacturing processes and scalable solutions is essential to make these technologies accessible to a broader audience.

Regulatory frameworks for nanomaterials are still evolving, and there is a need for standardized guidelines to ensure the safety and efficacy of nanotechnology applications in agriculture. Clear regulations and safety standards will facilitate the approval and commercialization of nanotechnology products, providing confidence to both farmers and consumers. Public perception and acceptance of nanotechnology also play a critical role in its adoption. Educating stakeholders and fostering transparent communication about the benefits and safety of nanotechnology will help build trust and support for these innovations.

Overall, the integration of nanotechnology into fruit crop production offers significant opportunities for advancing sustainable agriculture and addressing global food security challenges. To harness the full potential of nanotechnology, continued interdisciplinary research, collaboration, and innovation are essential. By overcoming existing challenges and leveraging the benefits of nanotechnology, the agricultural sector can achieve greater efficiency, productivity, and sustainability, ultimately contributing to a more secure and resilient food supply.

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