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# Nano-Innovations for a Greener Future- Merging Chemistry and Sustainability

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**ABSTRACT**

Precision agriculture offers an effective way to lower farming costs while boosting crop yields, addressing many challenges faced in conventional farming. Innovative techniques are now available to improve these practices, with nanotechnology playing a key role. By enabling control at the nanoscale, nanotechnology allows for highly accurate interventions. For example, certain nanoparticles can be designed to reduce damage to non-target plant tissues, aiding in early disease detection and treatment. It also enhances the ability of plants to absorb nutrients. When properly applied, machine-driven biological nanotechnology has the potential to transform agricultural systems. By targeting specific nanoparticles that can minimize damage to no target plant, nanotechnology can be used for disease detection and treatment, as well as increasing plant nutrient enhancement ability. Active ingredients with a nano size can have a higher efficiency and penetration. Nanotechnology can significantly enhance precision farming by enabling more accurate, efficient, and sustainable agricultural practices. Nanotechnology can be used in precision farming in various ways, nanoparticles can carry fertilizers, pesticides, or herbicides directly to specific plant parts or affected areas. This reduces waste, minimizes environmental impact and also the nano sensors can detect soil conditions, plant health, moisture levels, and disease presence in real time. This data helps farmers make precise decisions about irrigation, fertilization, and pest control. Not only this but Seeds coated with nanomaterials can have improved germination rates, controlled nutrient release, and better resistance to environmental stress. This book chapter aims to determine the use of nano chemistry in sustainability of agriculture and precision farming.

***Keywords:*** *nanofertilizers, nanopesticides, nanosensors nanofertilizers, nanopesticides, nanosensors*

## 1. INTRODUCTION

Agroecology has an important role to play in the attainment of the United Nations' "Zero Hunger" goal (Target 2) of its 17 Sustainable Development Goals (SDGs), which is the eradication of hunger, food security, better nutrition, and sustainable agriculture. Yet, agri-food systems across the globe are faced with an unprecedented challenge brought about by a speeding population, climate variability, soil erosion, declining water supply, and increasing energy demand (FAO, 2017; United Nations, 2023). These are supported by imbalances that arise from unequal distribution of food supplies and inefficiencies in international supply arrangements, wherein there are millions of people who are still malnourished amidst developments in food production technology.

Global food systems remain under severe pressure up to 2024. World food demand is projected to be more than 50% higher with the world's population exceeding 10 billion by 2050, particularly in sub-Saharan Africa and South Asia (FAO, 2020; World Bank, 2022). Currently, there are approximately 735 million hungry people, and the number can grow exponentially with or without extreme and revolutionary measures (FAO et al., 2023). Besides that, agriculture has already consumed about 70% of the world's freshwater withdrawals, consumes over two quadrillion BTUs of energy annually, and consumes about 187 million tonnes of fertilizers and 4 million tonnes of pesticides annually (Kah et al., 2019; Ray et al., 2022). This input dependence is not environmentally sound and contributes to greenhouse gas emissions, biodiversity loss, and contamination of water bodies and soils.

All these problems can be solved by agricultural sustainable intensification—more with less and less environmental cost. Here, nanotechnology presented as an emerging inter-disciplinary science with the potential to revolutionize the agriculture sector and enhance food security (Kah et al., 2019; Dasgupta et al., 2020; Alengebawy et al., 2021). The recent developments in nanoscience hold the vast potential to boost crop productivity in a smart delivery system, improved nutrient use efficiency, tolerance to abiotic stress, disease diagnosis, and targetted release of agrochemicals to save resources and reduce environmental pollution (Sekhon et al., 2021; Gogos et al., 2020).

Nanotechnology is the engineering and manipulation of material at the nanometer scale (1–100 nm), where distinctive physicochemical properties such as extensive surface area, reactivity, and regulated release can be exploited for agri-applications (Parisi et al., 2015; Fraceto et al., 2020). Over the past decade, studies have focused on the ability of nanomaterials (NMs) to develop nanofertilizers, nanopesticides, nanosensors, and nanocarriers with controlled release, soil purification, and promotion of plant growth (Shang et al., 2021; Kumar et al., 2023). The technologies allow precision agriculture with site-specific and resource-saving crop management practices.

In addition, biosensors and diagnostic kits based on nanotechnology are facilitating real-time tracking of pathogen detection, plant health, and soil quality—crucial to regulation of biotic and abiotic stresses further induced by climatic variability (Zhao et al., 2021). Of significant interest, green and biogenic nanomaterials are at the center of attention owing to their reduced toxicity and improved compatibility with sustainable agriculture (Verma et al., 2022). But long-term fate, migration, and environmental effects of NMs in soil-plant systems are matters requiring enormous environmental risk assessment and governmental regulation (Singh et al., 2024; Keller et al., 2021).

Faced with ever-mounting research literature, there is not much in the way of general reviews which bring together fresh information, issues, and nanotechnology's varied functions towards agriculture in a general, integral way. It is the aim of this review to fill this knowledge gap by providing an overview of recent reviews on nano-agriculture, beginning with applications of nanomaterials as nanofertilizers, nanopesticides, nanobiosensors, and nanoremediation agents. It also elaborates on the NMs-soil-plant interactions, likely risks, and their impacts on the quality of the soil, plant health, nutrient uptake, and defense mechanism. Through the aggregation and integration of novel evidence, this review stands to be used as a tool to researchers, policymakers, and agriculturalists for the alignment of nanotechnology with sustainable development and food security goals.

## 2. APPLICATION OF NANOMATERIALS IN AGRICULTURE:

### 2.1 Nanofertilizers:

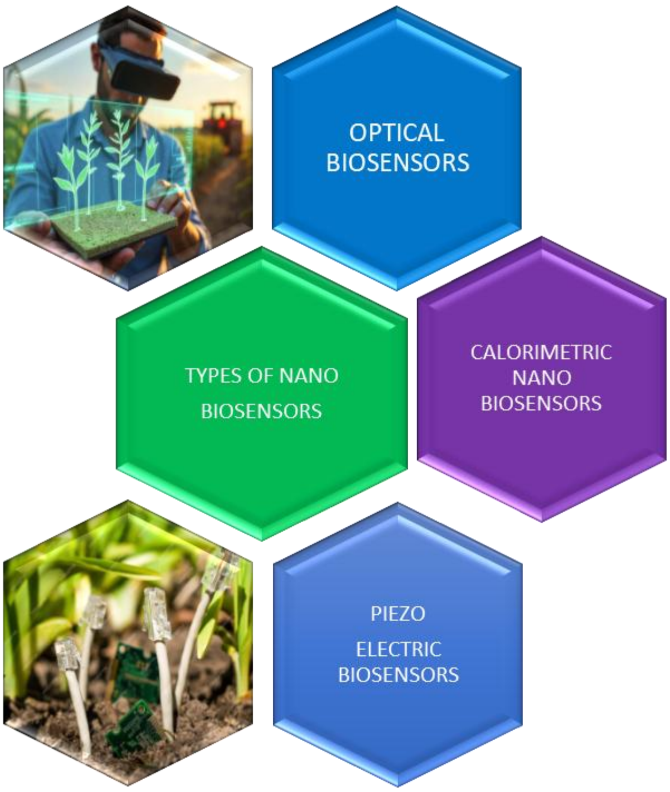
For example, 50–70% of the nitrogen applied by conventional fertilizers is lost to the environment (DeRosa, 2010). Therefore, development of alternate strategies to ensure sustainable use of nutrients is gaining significant attention among the scientific community. Nanotechnology is used to reduce the losses of mobile nutrients, to develop slow-release fertilizers, and to improve the accessibility of poorly-available nutrients.

Nanofertilizers can be produced by incorporating nutrients within nanomaterials (DeRosa, 2010). These fertilizers enhance both the productivity and quality of crops by improving nutrient uptake efficiency, which helps lower production expenses and supports sustainable farming practices. A detailed review of nanofertilizer data conducted by Kah et al. (2018) showed that these fertilizers offer an average performance improvement of 18–29% over traditional fertilizers. Furthermore, the use of phosphate-based nanofertilizers has been associated with a 32% increase in growth rate and a 20% rise in soybean (Glycine max L.) seed yield compared to conventional fertilizer treatments (Liu and Lal, 2014). Nanofertilizers also boost plant metabolic activities and nutrient absorption, which is made possible through nanoscale pores and specific molecular transport systems present in the plant's cuticle. Enhancing the efficiency of fertilizer use and minimizing nutrient losses to the environment are essential steps toward eco-friendly agriculture (Liu & Lal, 2014). Traditional nitrogen-based fertilizers typically exhibit use efficiencies ranging between 30% and 60%, whereas approximately 8–90% of phosphorus from conventional phosphate fertilizers becomes chemically immobilized in soil, rendering it inaccessible to plants (Giroto et al., 2017). In contrast, nanocomposites, such as those combining urea and hydroxyapatite, have shown promise in releasing nitrogen in a controlled manner, reducing ammonia volatilization, and ensuring a steady supply of phosphorus over a four-week period (Giroto et al., 2017). The overall application rate of fertilizers can be reduced through the use of slow-release formulations.Ideally, nanofertilizers should release nutrients precisely when and where plants require them, thus preventing nutrient losses through leaching or gaseous emissions. This targeted release can potentially be guided by plant-derived signals (DeRosa, 2010). Such "smart" fertilizers might be realized by understanding the signaling interactions between plant roots and soil microorganisms (Mastronardi et al., 2015). Studies have shown that engineered nanomaterials (NMs) can notably enhance fertilizer efficiency by allowing for reduced application rates, whether applied to soil or foliage, while also minimizing environmental release compared to traditional formulations (Adisa et al., 2019). According to a review by Kah et al. (2019), the use of nano-enabled fertilizers holds promise, and their adoption is unlikely to face regulatory challenges in many developed nations. This information which is available gives an evidence that nanofertilizers have far better efficiency than fertilizers, thus reducing the amount of fertilizers applied. This decreases the environmental impacts due to nutrient losses. This innovation is very timely to ensure food security of world.

**2.2 Nano-Biosensors in Soil-Plant Systems:**

Nanobiosensors play a crucial role in ensuring food safety by identifying harmful substances such as pesticides, heavy metals, pathogens, and veterinary residues in food items. They are also valuable tools for tracking food processing, storage, and transportation conditions to help prevent spoilage and preserve quality. There are various kinds of biosensors (Fig.1).

These sensors represent an evolution of traditional biosensors by incorporating nanomaterials, enabling detection of target substances at extremely low concentrations with enhanced precision and speed (Sun et al., 2006). Due to their miniaturized form and high sensitivity, nano-biosensors support real-time monitoring and early diagnosis in agricultural systems, contributing to better management of water, soil, fertilizers, and pesticides, which ultimately leads to improved crop productivity. The nanostructured materials used in these sensors serve as bio-receptors and are immobilized on transducer surfaces. When the target analyte interacts with the biological element, the transducer converts this interaction into a measurable signal. The exceptional properties of nano-biosensors—such as high surface area-to-volume ratio, superior electron transfer rates, enhanced sensitivity, and prolonged operational life—make them more effective than conventional sensors (Scognamiglio, 2013). Key advantages of nano-biosensors include their ability to be functionalized, miniaturized, and integrated into complex detection systems. These features enable the simultaneous detection (multiplexing) of multiple biological targets and enhance the overall performance and reliability of nanoscale sensing systems in agricultural applications.




Detecting soil contaminants at an early stage can help mitigate their harmful impacts. One of the major global challenges is the accumulation of toxic metal ions in agricultural soils and crops beyond safe limits, posing significant risks to human health. These metal ions are typically identified using optical sensors, which function through chemical interactions and rely on electromagnetic radiation. The sensors detect changes in optical characteristics caused by the interaction between the analyte and immobilized organic dyes in the sample, which correlate with the concentration of the target substance. Organo-phosphates, neonicotinoids, carbamates, and atrazines are among the most prevalent pesticide groups. Due to their low degradation and persistence in soil, even trace amounts can remain for extended periods. Nano-biosensors are utilized to detect these compounds, leveraging piezoelectric transducers combined with antigen-antibody interactions (Ivask et al., 2002; Přibyl et al., 2006), enzyme inhibition mechanisms, the binding affinity of nanomaterials, and targeted antibodies. However, the effectiveness of these sensors can vary depending on detection thresholds and the high cost of antibody development, which currently exists for only around 10% of the 800 active pesticide compounds (Aragay et al., 2012; Liu et al., 2013). As a result, enhancing the performance of nano-biosensors through sample pre-treatment and multiple testing is essential to broaden their practical use.

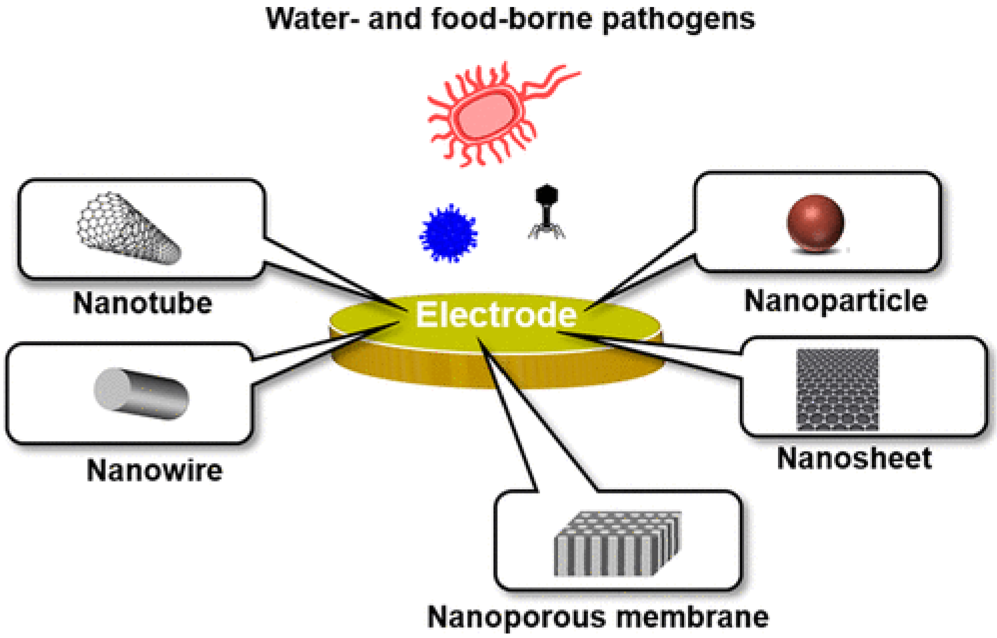



**Fig.2. Nano-biosensor detecting water contaminants**

Urea is extensively applied in agriculture and serves as a key source of nitrates, nitrites, and urease—common water contaminants linked to environmental concerns (Mura et al., 2015; Delgadillo-Vargas et al., 2016). To detect these substances in both soil and water, nano biosensors using microfluidic impedance-based and colorimetric assays have been developed (Fig.2).

Nanotechnology has also been used to in electronic noses (e-noses) regarded as artificial intelligent systems and next generation of sensors. They have been frequently applied in agriculture to monitor the production processes and to assess the plant diseases, insect infestations and soil/water contaminants (Hu et al., 2019). Although, use of nano-technology has opened new revolution in smart farming and reduced associated risks, wide use of nanomaterials -based agriculture and food products and less-likely immobilized nano-sensors have raised concerns on human and environmental health. Complexity of nano-bio-eco-interactions limits monitoring their behaviour in soils. Therefore, a holistic approach is recommended to understand these interactions in soil-plant-air and ultimately in food chain

## 3. IMPACT OF NANOMATERIALS ON PLANT DEVELOPMENT

The interaction between nanomaterials and plants often results in various morphological and physiological changes, which are influenced by both the type and concentration of the nanomaterial applied (Siddiqui et al., 2015). Depending on these factors, nanomaterials can have either beneficial or harmful (phytotoxic) effects on plant systems (Aslani et al., 2014; Siddiqui et al., 2015).

Certain nanomaterials act as growth enhancers by improving seed germination and supporting subsequent plant development (Nadiminti et al., 2013; Aslani et al., 2014). For example, treatment of soybean seeds with nano-sized $TiO_2$ and $SiO_2$ led to an increase in nitrate reductase activity, boosting seed germination, with the combined use showing better results (Lu et al., 2002). Application of $TiO_2$ nanoparticles (0.25%) in spinach enhanced nitrogen assimilation and photosynthesis, promoting growth with a 44% increase in dry biomass compared to untreated plants (Zheng et al., 2005; Yang et al., 2006). Similarly, pre-germinated wheat seeds soaked in multiwalled carbon nanotubes (MWCNTs) solutions (40–160 µg $L^{-1}$) for four hours showed improved root development and higher biomass, although some trials reported no observable effect (Wang et al., 2012). Indian mustard seeds treated with oxidized MWCNTs (2.3–46.0 µg $L^{-1}$) demonstrated enhanced germination uniformity and increased root and shoot lengths (Mondal et al., 2011). In watermelon (Citrullus lanatus), $Fe_2O_3$ nanoparticles stimulated seed germination and improved overall plant growth and fruit development (Li et al., 2013). Additionally, tomato seed exposure to low levels of $SiO_2$ nanoparticles improved germination rates (Siddiqui and Al-Whaibi, 2014).

Nanomaterials have significant utility in in vitro culture systems as well. ZnO nanoparticles, for instance, were found to enhance the growth of tobacco (Nicotiana tabacum L.), showing superior effects compared to traditional Zn sources. This treatment also increased protein content in the callus tissue (Mazaheri-Tirani and Dayani, 2020). Foliar application of ZnO nanoparticles (10 mg $L^{-1}$) on cluster bean (Cyamopsis tetragonoloba) improved leaf chlorophyll, total soluble protein, and phosphorus content (Raliya and Tarafdar, 2013). Enhanced seed germination and nitrogen fixation capacity have also been reported following nanomaterial treatments (Hong et al., 2005; Yang et al., 2006). In sugarcane (Saccharum officinarum L.), foliar application of $SiO_2$ nanoparticles (5–15 nm; 300 g $L^{-1}$) under cold stress improved growth by maintaining efficient photosynthetic electron transport and photoprotection mechanisms (Elsheery et al., 2020).

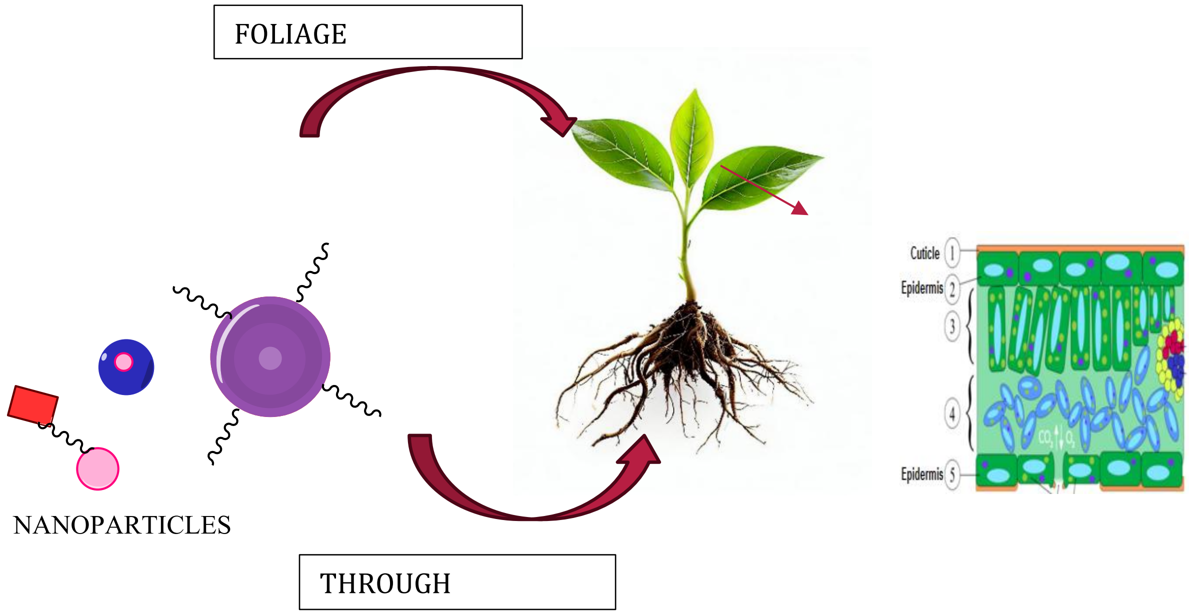



Fig. 3. Uptake and translocation mechanisms of nanoparticles in plant through leaf and roots. (A) uptake of nanomaterial by foliage application (i) nanomaterial penetrates into leaf cuticle(B) nanomaterial uptake by plant roots when applied through irrigation (i) penetration of nanomaterial into root hairs through irrigation.

Despite their benefits, nanomaterials can also exhibit toxicity depending on various factors such as dosage, particle size, chemical composition, and exposure conditions (Mazaheri-Tirani and Dayani, 2020; Noori et al., 2020). For instance, Yusefi-Tanha et al. (2020) observed that smaller CuO nanoparticles (25 nm) were more toxic to soybean than their larger counterparts (50 and 250 nm), with a linear dose-response relationship in smaller particles, unlike the nonlinear pattern seen with larger ones.

The phytotoxic effects of nanoparticles primarily influence seed germination, biomass production, leaf count, and root elongation (Lin and Xing, 2007; Racuciu and Creanga, 2007; Doshi et al., 2008; Lee et al., 2010). In some cases, exposure can lead to reduced growth, impaired germination, or even plant death (Yang et al., 2017). Negative consequences include stunted growth (Colman et al., 2013), disruption of subcellular processes (Zheng et al., 2005), oxidative damage to membranes (Noori et al., 2020), lowered photosynthetic efficiency (Barhoumi et al., 2015), chromosomal alterations (Raskar and Laware, 2014), impaired water transport (Martinez-Fernández et al., 2016), reduced phytohormone levels (Rai et al., 2012), and changes in gene expression profiles (García-Sánchez et al., 2015).

## 4. DISCUSSION AND CONCLUSION

Nanotechnology is one of the newly evolved strengths of contemporary agriculture that matches increasing demand for sustainable food production and use of resources-saving strategies. Use of nanomaterials (NMs) such as nanofertilizers, nanopesticides, and nanobiosensors is a flagship input to precision agriculture that provides solutions for the flagship agronomic challenges such as loss of nutrients, pest resistance, and environmental pollution (Fraceto et al., 2020; Kah et al., 2019). According to this review, nanomaterials improve nutrient use efficiency, reduce ecological impacts, and allow real-time measurement of the plant-soil system to ensure productivity and sustainability.

Recent research has shown that use of nano-enabled sensors and agrochemicals can greatly improve crop yield and quality by facilitating controlled release, site-directed delivery, and alleviation of stress (Kumar et al., 2023; Zhao et al., 2021). For example, smart nanofertilizers allow precise control of nutrient release by environmental or plant stimuli, which eliminates input loss and greenhouse emissions (Ray et al., 2022). Likewise, nanosensors and e-noses are great diagnostic tools for the diagnosis of early diseases, pest management, and soil contamination, closing the gap between conventional agriculture and smart agriculture (Hu et al., 2019).

Despite their promises, there are still some limitations and challenges. Their environmental fate, bioavailability, and matrix toxicity are little understood, particularly under field-literate conditions. NMs positive and negative effects on the plant system have been reported based on particle size, concentration, composition, and mode of exposure (Yusefi-Tanha et al., 2020; Singh et al., 2024). Adversarial effects like oxidative stress, chromosomal aberrations, and disruption of plant hormone signaling are some of the driving powers behind guided and accurate application (Mazaheri-Tirani & Dayani, 2020; García-Sánchez et al., 2015).

To realize the full growth potential of nanotechnology application to agriculture, multiple research fields and policy areas to be addressed have been established. At first, larger field tests are required on large scales to confirm the lab data and prove replicability and scalability in various climatic and soil conditions. Secondly, integration of nanotechnology, plant biology, environmental chemistry, and toxicology must be established in the development of safe, multi-dimension, and biodegradable nanomaterials. Third, setting up strong regulatory procedures and risk assessment guidelines will provide human and environmental security innovation (Keller et al., 2021; Dasgupta et al., 2020).

Apart from that, nanotechnology has the potential to trigger bioremediation and environment management as a whole via contaminant degradation or sequestration in agroecosystems (Verma et al., 2022). Nanocomposites tailored for a specific application, i.e., particular pesticide degradation or heavy metal immobilization against soil pollution, could be possible. All these advances can be adapted to the UN's SDGs, i.e., Zero Hunger, Clean Water, and Climate Action.

Finally, though nanotechnology has massive potential to be harnessed in future sustainable agriculture, its use should be carefully made so that a balance is met between caution and innovation. Green synthesis, hazard assessment, and collaborative approach in knowledge sharing will be pivotal in continuing efforts at safe exploitation of its benefits. There must be a convergent, collective, and ethics-driven shift by scientists, policymakers, business stakeholders, and farmers to transform nanotechnology into a cornerstone of sustainable food systems in the 21st century.

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