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HARNESSING NANOTECHNOLOGY AS A TOOL FOR GLOBAL FOOD SECURITY: A REVIEW

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ABSTRACT

The challenge of food security, which is the reliable access to adequate, safe, and nutritious food, is disturbing globally in this 21st century, especially due to rapid population growth, climate change, and low agricultural productivity. Traditional approaches alone are insufficient to sustainably meet projected food demand increases by 2050. As a result of the bottleneck, the need for researchers and industries to explore innovative technologies, like nanotechnology, the manipulation and application of materials at the nanometer scale (1–100 nm), where unique physicochemical properties allow new functions unattainable by bulk materials, to transform the agricultural and food systems in ways that enhance productivity, improve safety, reduce waste, and ensure equity in food access. Nanotechnology refers to the manipulation and application of materials at the nanometer scale (1–100 nm), where unique physicochemical properties allow new functions unattainable by bulk materials. Nanotechnology is emerging as a transformative tool in global food security, offering innovative solutions to agricultural challenges and improving food quality, safety, shelf life, and nutritional value. By manipulating materials at the nanoscale, unique physicochemical properties can be exploited to enhance food processing, preservation, packaging, and quality monitoring. This review examines the role of nanotechnology in both agricultural and food industrial sectors, how it can be harnessed, as well as concerns and future prospects.

Keywords: Nanotechnology, Food security, Sustainable solution

INTRODUCTION

Food security is the reliable access to sufficient, safe, and nutritious food to meet dietary needs and food preferences for an active and healthy life (FAO, 2022). Currently, the issue of food security has become a fundamental challenge to humanity in this century (Savary *et al*., 2012; Shittu *et al*., 2023; FAO *et al*., 2023). This is mainly due to rapid population growth, climate change, agricultural resource constraints, conflict, political instability, economic inequality, and poverty, according to Elmer and White (2018), IPCC (2022), and FAO *et al*. (2023). Also, land degradation, low mechanization, water scarcity, pests, diseases, and post-harvest losses threaten food security (Ayanlade and Radeny, 2020).

It is projected that by 2050, an additional 70% of food production will be required to meet the needs of a growing human population, which will rise from an estimated six (7.6) billion to nine (9.7) billion people (Godfrey *et al*., 2010; Bedington, 2010; Ditta and Arshad, 2016; UN, 2022). Use of traditional approaches (agricultural practices/technologies) alone are not capable of sustainably meeting projected food demand; as a result, scientists, policymakers, and industry are exploring innovative technologies, including nanotechnology, to transform the agricultural and food systems in ways that enhance productivity, improve safety, reduce waste, and ensure food access (Ansari, 2023; Kuchipudi *et al*., 2025).

Nanotechnology (NT) is a broad-based science involving manipulation of matter in a variety of ways to generate new understanding of how materials can be developed at the nanoscale level to solve many problems in various fields (Scrinis and Lyons, 2007; Koka *et al*., 2019). It is the science and engineering of materials at the nanoscale (1–100 nm) that have unique physiochemical and biological properties due to their reduced small size (Ahmed *et al*., 2016; Khan *et al*., 2017; Terna, and Oshinowo, 2019; Igiehon *et al.*, 2020). The unique properties allow new functions unattainable by bulk materials, like enhanced reactivity, strength, or sensing capability, which can be harnessed in food and agriculture sectors (Ansari, 2023; Kuchipudi *et al*., 2025).

Nanotechnology offers transformative solutions by enhancing efficiency, precision, and sustainability across the entire food value chain from primary production to consumption that directly address food availability, access, utilization, and stability (Mahmoud and Alwan, 2025). The use of nanotechnology has been reported in different ways in agricultural and food sciences. This review article is aimed at exploring applications of NT as a potential means of revolutionizing agricultural and food industrial sectors in ways of optimizing fertilizer and pesticide efficiency, improving nutrient delivery, enabling precision farming, mitigating environmental impacts, and enhancing crop yields, nanocapsulation, nanodelivery of active ingredients, and nanopackaging to meet the demand for food.

The Issue of Food Security

Despite global efforts, food insecurity persists, with over 700 million people experiencing hunger worldwide (FAO *et al.*, 2023). Africa, including Nigeria, accounts for a disproportionately high burden of food insecurity, with more than 20% of its population undernourished (Conway, 2012; Jones *et al.*, 2013; World Bank, 2022; FAO *et al*., 2023). Food security is built on four interrelated pillars that include food availability, accessibility, utilization, and stability (FAO, 2008; Pinstrup-Andersen, 2009; Barrett, 2010). Addressing it, therefore, requires multidimensional and systems-based approaches.

Harnessing Nanotechnology as an Option

Nanotechnology operates as an enabling technology, complementing biotechnology, precision agriculture, and smart food systems (He *et al*., 2019; Kah *et al*., 2023). NT integrates across the entire food supply chain, from farm production and crop protection, through processing and packaging, to distribution and consumption (Gustafson *et al*., 2016; Mahmoud and Alwan, 2025). The basic goals of NT in food security are to increase agricultural productivity sustainably; improve food quality and nutritional value; reduce post-harvest losses and spoilage; enhance food safety and traceability; and support resource-efficient and climate-resilient food systems (Rajiv *et al*., 2013; Tripathi *et al*., 2017; Mahmoud and Alwan, 2025).

Applications of Nanotechnolgy in Agricultural Sector

The effective use of nanotechnology in the agriculture sector is multidirectional and has the potential to change the entire scenario of agriculture (United States Department of Agriculture (USDA) 2003; Ditta, 2012; Thul *et al.*, 2013; Peters *et al*., 2016; Kah *et al*., 2023). Its applications in agricultural productivity improvements are central to food security (Qaim, 2020; Kah *et al*., 2023). Below are the following ways NT has been used in the field of agriculture.

Nanofertilizers

Nanofertilizers are nutrient formulations engineered at the nanoscale to improve nutrient delivery and uptake (Kuchipudi *et al*., 2025). The basic mechanism of action of nanofertilizer usage is to control and slow nutrient release, increase surface area that will enhance plant absorption, and reduce leaching and volatilization losses (Solanki *et al*., 2015; Raliya *et al*., 2020; Dimkpa and Bindraban, 2023). This will be beneficial to plants in ways of higher nutrient use efficiency, reduced fertilizer application rates, and lower environmental pollution. Notably, studies have shown that nanofertilizers can improve crop yield by 15–30% compared to conventional fertilizers (Raliya *et al*., 2020; Dimkpa and Bindraban, 2023).

Nanopesticides

Pesticides such as DDT, which cause extreme environmental hazards and have increased public and regulatory awareness of the use of chemicals in farming, therefore lead to the use of user-friendly and eco-friendly nano-delivery systems (Dimetry and Hussein, 2016). Nanoparticle pesticides enhance effectiveness, reduce required doses, and minimize environmental impact by more precisely targeting pests and reducing harm to nontarget organisms (Sun *et al*., 2019; Kuchipudi *et al*., 2025). Nanoemulsions, nanoencapsulates, nanocontainers, and nanocages were some of the nanopesticide delivery techniques proven to be effective in plant protection programs (Lyons and Scrinis, 2009; Bouwmeester *et al.,* 2009).

According to Yan *et al.* (2005), these nanomaterials exhibited useful properties such as stiffness, permeability, crystallinity, thermal stability, solubility, and biodegradability needed to formulate the nanopesticides that offer a large specific surface area for increased affinity to the target. Nanopesticides can reduce the rate of application because the quantity of product actually being effective is at least 10-15 times smaller than that applied with classical formulations (Chittaranjan *et al.*, 2013). The use of nanopesticides using nano-carriers to deliver active ingredients precisely to target pests, thereby significantly reducing chemical residues in food and the environment, supporting sustainable agriculture (Qaim, 2017; Kumar *et al*., 2022).

Nanodiagnostics

Nanodiagnostics is the application of nanotechnology in disease detection, monitoring, and prognosis; it is highly sensitive, rapid, and specific in the detection of biological targets (pathogens) at molecular and cellular levels (Valenzuela *et al*., 2023). It was reported that these nano-devices can identify plant-related health issues even before they become visible to the farmers and, at the same time, provide remedial measures (Prasad *et al*., 2014). This nano-enabled diagnostics has transformed diagnostics in medicine, environmental monitoring, food safety, and agriculture, with growing relevance in point-of-care and low-resource settings (Kumar *et al*., 2021).

Nanobiosensors

Nanobiosensors enable precision farming; it is a process of maximizing crop yields and minimizing the input/usage of pesticides, fertilizers, and herbicides through efficient monitoring procedures (Rai and Ingle, 2012; Gul *et al.*, 2014; Faroogui *et al*., 2016). It is designed to utilize remote sensing devices, computers, and global satellite positioning systems to analyze various environmental conditions in order to determine the best environmental conditions for the growth of plants and identify problems related to crops and their environment (Prasad *et al*., 2014; Aitieri *et al*., 2015). The development of small sensors and monitoring devices using nanotechnology will enhance productivity in agriculture by providing accurate information, thus helping in making better decisions (Prasad *et al*., 2014).

Nanomaterials influence soil properties to enhance moisture retention or pollutant remediation, contributing to improved plant growth in stressed environments (Ansari, 2023). Nanosensors integrated with IoT (internet of things) platforms help farmers optimize irrigation and fertilizer application, increasing crop health and yield while conserving resources (Elmer and White, 2024; Mahmoud and Alwan 2025). These innovations can reduce dependency on traditional chemical inputs and bolster climate-resilient farming practices essential for future food security.

Nano-antimicrobial Agent

Several inorganic nanoparticles, such as copper oxide nanoparticles (NPs), silver NPs, titanium oxide NPs, gold NPs, magnesium NPs, and zinc oxide NPs, have shown potential as new antimicrobial agents for the management of phytopathogens affecting agricultural crops (Gul *et al*., 2014; Shittu *et al*., 2023). Studies have reported the extensive use of silver nanoparticles and other metallic/metallic oxide nanoparticles as antimicrobial agents against several pathogenic fungi and bacteria (Park *et al*., 2006; Kim *et al*., 2009; Esteban-Tejeda *et al*., 2010; Malandrakis *et al*., 2019; Fatemifard *et al.*, 2024; Hussain *et al*., 2024).

Post-harvest Management

A significant proportion of global food is lost to spoilage, decay, or inefficient storage; the use of a nanotechnology-based approach mitigates these challenges to a large extent as nanocoatings and nanocomposites protect fruits, vegetables, and grains during storage and transport (HLPE, 2014; Kanmani and Rhim, 2014; Ansari, 2023). Its functions are to delay ripening, reduce microbial growth, and improve the mechanical strength of packaging. This is particularly critical in tropical regions where storage infrastructure is limited (Qaim, 2017; Adeyemi *et al*., 2024). Such systems reduce post-harvest losses, which account for nearly 30% of global food production (FAO, 2022).

Applications Nanotechnology in Food Industry

Nanotechnology plays a key role in the food industry (Martirosyan and Schneider, 2014; Dasgupta and Ranjan, 2018). It addresses hidden hunger (micronutrient deficiency), especially in developing regions (McClements, 2020). There are several reports of nanotechnology having the potential to revolutionize the food industrial sector (Thakur and Kumar, 2018). These are some of the applications of NT in the food industry.

Nanoencapsulation of Nutrients

Nanoencapsulation involves entrapping bioactive compounds such as vitamins, antioxidants, probiotics, omega-3 fatty acids, and necessary bioactive ingredients within nanocarriers to protect them from degradation and improve bioavailability (Augustin and Hemar, 2009; McClements and Xiao, 2014). Nanoencapsulation techniques are widely used to enhance stability, controlled release in the digestive system, and improved absorption of nutrients (Acosta, 2009; Katouzian and Jafari, 2016; Emamhadi *et al.*, 2020). Nutrients, primarily vitamins, are encapsulated and targeted into the bloodstream via NT, and these selected foods and drinks exhilarated with NPs are found to be taste and appearance unaffected (Thakur and Kumar, 2018).

Food Safety and Quality

Conventional food processing and preservation techniques often face limitations related to nutrient loss, microbial spoilage, and chemical degradation (Floros *et al*., 2010; Zhong and Wang, 2019). Nanotechnology offers novel approaches to address these challenges by enhancing functionality and efficiency at the molecular level (Chaudhry *et al.*, 2008; Roco, 2011; Dasgupta *et al*., 2015; McClements, 2020). The use of nanosensors in food safety and quality are faster, highly sensitive, and portable; these sensors operate through optical, electrochemical, or colorimetric signals triggered by molecular interactions (Kumar *et al*., 2017; Chen *et al*., 2019). Nanosensors enable real-time detection of the presence of contaminants like pathogenic bacteria (*E. coli*, *Salmonella*), mycotoxins, aflatoxin, heavy metals, and pesticide residues at extremely low concentrations in food products (Ding *et al*., 2020; Zhang *et al*., 2022; Thurner and Alatraktchi, 2023). Also, nanocoating of materials helps in self-purification and disinfection for improved food quality (Thakur and Kumar, 2018; Kim *et al*., 2020).

Shelf-life Extension

Nanotechnology-based packaging extends shelf life as nanoparticles with antimicrobial properties are incorporated into food matrices or packaging materials to inhibit microbial growth (Thakur and Kumar, 2018; Nacas *et al.*, 2019). Reports have it that silver, zinc oxide, and chitosan nanoparticles disrupt microbial cell membranes, generate reactive oxygen species, and interfere with cellular metabolism (Rai *et al*., 2009; Duncan, 2011). These mechanisms significantly reduce food spoilage and extend shelf life without compromising sensory quality (Silvestre *et al*., 2011; Mashad and Pan, 2015; Thakur and Kumar, 2018).

Smart and Active Packaging

Nanocomposite packaging materials combine polymers with nanoparticles to improve mechanical strength, gas barrier properties, and thermal stability (Sorrentino *et al*., 2007; Rhim *et al*., 2013; Pereda *et al.*, 2018). Clay nanoparticles, nanocellulose, and metal oxides are commonly used to prevent oxygen and moisture transmission, thereby maintaining food freshness and quality (Arora and Padua, 2010; Azeredo *et al*., 2017). Smart packaging integrated with nanosensors enhances traceability and quality assurance across the food supply chain (Zhao *et al*., 2020).

The packaging materials are integrated with nanosensors to detect the oxidation process in food, and in such packaging materials, when oxidation occurs in the foodstuff, the nanosensor indicates with colour change and provides information about the contamination of the foodstuffs like milk and meat (Thakur and Kumar, 2018). Also, nano-food packaging is an excellent opportunity to use high-performance and lightweight nanomaterials to replace non-degradable plastic packaging materials (Emamhadi *et al.*, 2020; Topuz and Uyar, 2020; Ashfag *et al*., 2022).

Nanofortifed Functional Foods and Texture Modification

The use of nanotechnology enables the development of functional foods with health-promoting properties and also contributes to improved texture, appearance, and flavor. Zhao *et al*. (2023) reported nano-iron fortified foods (nano-calcium dairy products), an innovation that enhance food utilization and nutritional security. NPs emulsion is being used in ice cream production, and its use can improve the texture and uniformity of the ice cream (Kumar, 2015). Also, nanostructured ingredients improve viscosity and stability in beverages, dairy products and biofortification of food products (Solans and Solé, 2012; McClements, 2015; Bouis and Saltman, 2017).

Potential Concerns

While promising, the integration of nanotechnology in food security also faces significant concerns like the concerns of safety and toxicity that is the possibility for nanoparticles to migrate from packaging or food systems into human tissues raises health concerns, as the toxicity data remain limited (EFSA, 2018; Fadeel and Garcia-Bennett, 2010; Bryksa and Yada, 2012; Cushen *et al.*, 2012; Ansari, 2023). The issue of environmental impacts concerning the use of nanomaterials / nanoparticles persistence in soil or water could cause ecological consequences (Xiaojia *et al*., 2018; Mahmoud and Alwan, 2025). Regulatory frameworks are still evolving, there is lack of international consensus on assessment and standards for nanosafety, complicating global deployment evolving (Chaudhry *et al*., 2014; He *et al*., 2019; Mousavi Khaneghah *et al*., 2021; Ansari, 2023). Also, Consumer awareness, acceptance and trust are critical for market adoption, but many remain unaware or wary of nanoscale food technologies (Cormick, 2009; Chaudhry *et al*., 2014). Responsible innovation, risk assessment, and transparent regulation are essential (Arnaldi and Muratorio, 2013; Kah *et al*., 2023).

Future Prospects

The future of nanotechnology in food security is promising but requires focus on biodegradable, nanomaterials using green synthesis methods, interdisciplinary research for sustainable, safe, and scalable solutions, stronger regulation and safety assessment methods, Public engagement and education programs and Integration with artificial intelligence and smart systems may further revolutionize food quality

CONCLUSION

Nanotechnology offers powerful tools to strengthen food security by improving agricultural productivity, food safety, nutritional quality, and supply chain resilience. While challenges related to safety, regulation, and public acceptance remain, responsible and evidence-based deployment of nanotechnology can significantly contribute to sustainable and resilient global food systems.

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