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Green Nanotechnology and Functional Foods: Emerging Opportunities in Human Health

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ABSTRACT: Green nanotechnology has evolved as a novel and eco-friendly platform to improve the development of functional foods and human health. The present review is designed to highlight the recent developments in the synthesis of food-grade nanomaterials (food nanoparticles) with plant extract, microorganisms, algae, and other natural resources, with emphasis on their application in functional food systems in an environmentally friendly manner. Green synthesis of nanoparticles and nano-delivery systems with bioactive compounds like polyphenols, flavonoids, carotenoids, vitamins, probiotics, and essential fatty acids improves stability, solubility, and bioavailability, and helps with the controlled release of these compounds, thus enhancing their nutritional and therapeutic value. The review also covers the scope of the challenges and opportunities of Green Nanotechnology in improving the quality, shelf life, and antimicrobial packaging, as well as in designing intelligent food systems. The biomedical applications and antioxidant and anti-inflammatory properties of nanotechnology in functional foods for the prevention and management of chronic diseases are also summarized. Safety evaluation, toxicological aspects, regulatory concerns, new technical developments, and current and future research challenges are also critically discussed. Overall, green nanotechnology offers the potential to produce sustainable, safe, and (2nd) generation functional food for promoting precision nutrition and health.

1. INTRODUCTION AND GLOBAL PERSPECTIVE

Green nanotechnology is a new science emerging as a transformative interdisciplinary science, which combines the concepts of green chemistry, nanoscience, biotechnology, and sustainable engineering, to create environmentally friendly nanomaterials for various applications in healthcare, food sciences, agriculture, and environmental management. Green nanotechnology is based on the use of biological resources such as medicinal plants, edible herbs, fruits and vegetables, microorganisms, algae, enzymes, and natural polymers as reducing, stabilizing, and capping agents in the synthesis of nanoparticles, which is quite different from the traditional physicochemical methods that rely on toxic chemicals, high energy consumption, and toxic by-products (1). This environmentally friendly approach not only reduces unwanted environmental effects but also allows for improved biocompatibility and functional characteristics of nanomaterials, which are especially suitable for foods for human consumption. Meanwhile, the prevalence of chronic non-communicable diseases, the ageing population, nutrient deficiencies, and rising awareness of consumers about the importance of prevention in healthcare have positioned functional foods on the global agenda (2). The definition of functional foods is that they contain ingredients that have biological activity and provide benefits to the body beyond their nutritional content, such as polyphenols, flavonoids, carotenoids, dietary fibres, omega-3 fatty acids, probiotics, prebiotics, peptides, vitamins and minerals, which help to improve health and reduce the risk of disease. Many such bioactive components are, however, poorly soluble in water, unstable during processing and storage in foods, and do not get absorbed in the gut, and thus have restricted therapeutic applications (3). The creative approaches of green nanotechnology are facing these challenges by providing an innovative and novel system of nanoencapsulation of food grade, as well as a system of nano emulsion, nanoliposomes, polymeric nanoparticles, and other biodegradable nanocarriers to protect sensitive bioactive molecules, stabilize them, improve their controlled release, and enhance their intestinal absorption and internalization by cells (4). These advances have contributed to the development of new-generation functional foods that have more desirable nutritional properties, sensory characteristics, shelf life, and efficacy to support human health, and nutrient delivery is precisely controlled (5). The development of nanotechnology-based functional foods is the most emerging trend in the nanotechnology field, where the research and industrial interest in this area has been boosted due to the investments in green nanotechnology, precision nutrition, and natural/clean label foods worldwide, and the growing demand for such products. Furthermore, the capacity of functional foods with nanoparticles to enhance the antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory activities could be beneficial in the prevention and treatment of a wide range of conditions, including cardiovascular diseases, diabetes, obesity, cancer, neurodegenerative disorders, gastrointestinal dysfunctions, and immune-related diseases(6). These are welcome developments, but there are still important challenges to tackle, including nanoparticle safety, toxicological assessment, regulation, consumer acceptance, large-scale production and commercialization, and these will require multi-disciplinary research and, in a coordinated international effort, regulation. To conclude, the innovation of green nanotechnology into functional food is a sustainable solution for achieving human health and nutritional quality, and a future healthy, safe, and environmentally friendly food system (7).

2. FUNDAMENTALS OF GREEN NANOTECHNOLOGY IN FOOD SCIENCE

New developments in sustainable materials and nanoscience have completely transformed the use of green nanotechnology in food science and have created a new range of food and health applications with safe and functional nanotechnology. (7) Green nanotechnology is the synthesis of nanoparticles using renewable natural biological materials such as medicinal plants, edible herbs, fruits, vegetables, fungi, bacteria, algae, enzymes, proteins, and natural polysaccharides without using energy-intensive technologies and toxic chemicals that are used in the conventional synthetic methods (8). In the biosynthesis process, naturally occurring phytochemicals like polyphenols, flavonoids, terpenoids, alkaloids, proteins, and carbohydrates act as reducing and stabilizing agents, developing excellent biocompatibility and environmental compatibility (9). Several synthesis parameters, such as pH, temperature, precursor concentration, reaction time, and biological extract composition, affect the functional performance of these nanomaterials and are known to affect particle size, morphology, crystallinity, and surface characteristics (10). The synthesis of nanoparticles in a green way has been given great attention; some of the nanoparticles synthesized are silver, gold, zinc oxide, selenium, Fe3O4 (iron oxide), silica, polymeric nanoparticles, lipid nanoparticles, and nanocellulose, which have shown interesting physicochemical and biological properties and are being employed in a wide range of applications in the food sector (7). The structural and functional attributes of their products are usually assessed by employing advanced analytical methods such as ultraviolet-visible spectroscopy, Fourier-transform infrared spectroscopy, X-ray diffraction, scanning electron microscopy, transmission electron microscopy, dynamic light scattering, zeta potential analysis, and X-ray photoelectron spectroscopy to ensure quality, stability, and reproducibility (12). These nanomaterials have been used in food science to develop novel solutions to stabilize, improve the solubility, and bioavailability of vulnerable bioactives via nanoencapsulation, nanoemulsions, nanoliposomes, and biodegradable nanocarriers (11). These delivery systems can prevent degradation of vitamins, antioxidants, polyphenols, carotenoids, probiotics, omega-3 fatty acids, and other nutraceutical ingredients during processing, storage, and digestion in the gastrointestinal tract, allowing for a controlled and targeted release of the ingredients in the digestive tract (9). Green nanotechnology has also helped in the development of food packaging with antimicrobial properties, edible coatings, smart nanosensors, and food preservation technologies, which prolong shelf life, decrease the risk of microbial contamination, and preserve the nutritional value without adding synthetic preservatives to the food (11). Moreover, the use of agri-residues and food processing wastes as renewable feedstocks aligns with principles of the circular bioeconomy, resource efficiency and sustainable manufacturing. The shift in consumer preference to natural, clean label, and health-promoting food products provides a scientifically sound foundation for the creation of next-generation functional foods developed using green nanotechnology, which provides benefits for both the environment and the nutritional and health benefits of consumers. Future developments in nanobiotechnology, food engineering, and precision nutrition will further advance the incorporation of green nanotechnology into the modern food system, thereby improving human health, safety, and food production, and contributing to sustainable development (11).

3. FUNCTIONAL FOODS, NUTRACEUTICALS, AND HEALTH-PROMOTING PHYTOCHEMICALS

Growing consumer awareness of the relationship between diet and health has transformed functional foods and nutraceuticals into major components of preventive nutrition and modern healthcare (13). Functional foods are consumed not only to satisfy nutritional requirements but also to provide physiological benefits that reduce the risk of chronic diseases through the presence of naturally occurring bioactive compounds (14). Nutraceuticals, including dietary supplements, botanical extracts, probiotics, prebiotics, functional beverages, and fortified foods, have gained widespread acceptance because of their ability to improve metabolic health, strengthen immunity, and support overall well-being (15). These health-promoting properties are primarily attributed to phytochemicals such as polyphenols, flavonoids, phenolic acids, carotenoids, alkaloids, terpenoids, glucosinolates, lignans, and saponins, which exhibit potent antioxidant, anti-inflammatory, antimicrobial, anticancer, cardioprotective, neuroprotective, and immunomodulatory activities (16). However, the practical application of many phytochemicals is often limited by poor water solubility, low chemical stability, rapid degradation during food processing and storage, insufficient gastrointestinal absorption, and limited systemic bioavailability (17).

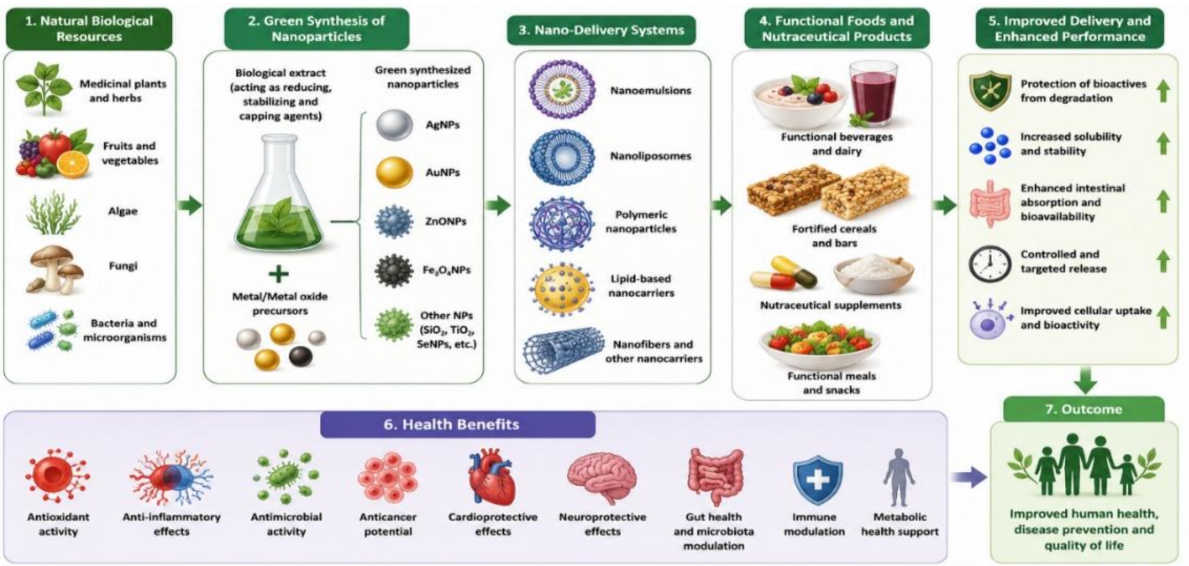

Figure 1. Conceptual framework illustrating the integration of green nanotechnology with functional foods for human health.

Green nanotechnology has emerged as an innovative strategy to overcome these challenges through the development of environmentally friendly nano-delivery systems that protect sensitive bioactive compounds while improving their stability, controlled release, cellular uptake, and biological efficacy (18). Plant-mediated nanoparticles, nanoemulsions, nanoliposomes, polymeric nanoparticles, lipid-based nanocarriers, and nanofibers have demonstrated considerable potential for enhancing the delivery of nutraceutical ingredients without compromising food safety or environmental sustainability (14). These advanced nanocarriers facilitate the incorporation of phytochemicals into a wide range of functional food products, thereby improving nutritional quality, shelf life, sensory characteristics, and therapeutic performance (13). Furthermore, nano-enabled functional foods have shown significant promise in supporting the prevention and management of cardiovascular diseases, diabetes, obesity, cancer, gastrointestinal disorders, neurodegenerative diseases, and immune dysfunction through enhanced bioavailability and targeted delivery of bioactive molecules (15). The overall relationship between natural biological resources, green synthesis of nanoparticles, nano-delivery systems, functional food development, and their subsequent health-promoting effects is summarized in Figure 1, which illustrates the conceptual framework linking sustainable nanotechnology with functional foods for improved human health and disease prevention (14). Consequently, the integration of green nanotechnology with functional foods represents a multidisciplinary and sustainable approach for developing next-generation nutraceutical products that address global nutritional challenges while advancing precision nutrition, food innovation, and public health (18).

4. ECO-FRIENDLY SYNTHESIS AND CHARACTERIZATION OF FOOD-GRADE NANOMATERIALS

However, the synthesis of food-grade nanomaterials in an eco-friendly way has become a significant research focus in sustainable food nanotechnology, because it can produce safe (and bio-compatible and biodegradable) nanoparticles from renewable biological resources instead of toxic chemicals (18). Plant extracts, edible herbs, fruits and vegetables, fungi, algae, bacteria, yeasts, enzymes, proteins, and polysaccharides are important components of green synthesis, which use them as natural reducing, stabilizing, and capping agents, and remove the need for toxic solvents or high-energy processing conditions (19). The phytochemicals (polyphenols, flavonoids, terpenoids, alkaloids, sugars, amino acids, and proteins) not only reduce the metal ions to the stable nanoparticles but also prevent the aggregation and stabilize the nanoparticles (20). The concentration of the precursors, pH, temperature, reaction time, and composition of the biological extracts used as the precursors for the nanomaterial have a strong influence on the physicochemical properties of food-grade nanomaterials such as particle size, morphology, crystallinity, surface charge, porosity, and dispersibility (21). Nanomaterials are commonly synthesized, such as silver, gold, zinc oxide, selenium, iron oxide, silica, lipid nanoparticles, polymeric nanoparticles, nanocellulose, and protein-based nanocarriers, which are being widely used in the food industry to deliver nutrients, preserve food, create antimicrobial packaging, and for nanoencapsulation of bioactive compounds (22). Before being incorporated into food products, comprehensive characterization is a necessary step to ensure the quality, stability, functionality, and safety of these products. Advanced analytical techniques like UV–Vis, FTIR, XRD, SEM, TEM, DLS, zeta potential/EDX, AFM and XPS are commonly used to determine the structural, optical, chemical and surface properties of synthesized nanomaterials (23). These characterization techniques could provide valuable information: composition of the nanoparticles, size distribution of nanoparticles, crystallinity, functional groups, presence of elements, and long-term stability, etc., that will allow for the reproducibility and ensure approval for food applications. Therefore, with such eco-friendly synthesis and extensive physicochemical characterization, it is a sound foundation for the future design of excellent food-grade nanomaterials which can enhance the safety, stability, bioavailability, and functional properties of food products, as well as the environmentally friendly production.

5. NANO-BASED DELIVERY SYSTEMS FOR FUNCTIONAL FOOD BIOACTIVES

One of the most important challenges in the development of functional foods is the delivery of bioactive compounds to the gastrointestinal tract because most of the phytochemicals can be poorly bioavailable after ingestion, due to limited gastrointestinal absorption, stability, and water solubility (24). Nano-based delivery systems have been proven to be a viable option because of the ability to protect the bioactive ingredients from degradation, improve the solubility and/or stability, and control the release of the bioactive ingredients in nano-scale carriers (25). The introduction of biodegradable materials from natural resources like plant polysaccharides, proteins, lipids, chitosan, alginate, cellulose, and starch into the development of food-grade nanocarriers has led to increased safety and environmental sustainability of green nanotechnology applied to food packaging (26). The most used delivery systems are nanoemulsions, nanoliposomes, solid lipid nanoparticles, polymeric nanoparticles, nanogels, and protein-based nanocarriers, which contribute to the enhancement of the bioavailability of vitamins, polyphenols, flavonoids, carotenoids, probiotics, omega-3 fatty acids, and other nutraceutical compounds. These nanocarriers can also provide better food quality via effective protection of sensitive food ingredients during processing and storage, or by targeted delivery of nutrients and long-lasting physiological action. The major types of green-synthesized nanoparticles are summarized in Table 1, which includes the natural sources, synthesis strategy, and application in functional food systems. The incorporation of a sustainable nano delivery system with functional foods, therefore, could be a novel approach to optimize the nutritional quality, therapeutic action, and consumer acceptance of the future foods while simultaneously fostering environmentally friendly food production (27).

Table 1. Types of Green-Synthesized Nanoparticles and Their Applications in Functional Foods

Nanoparticle	Natural Source	Green Synthesis	Functional Food Application
Silver (AgNPs)	Plant extracts	Plant-mediated reduction	Antimicrobial food packaging
Gold (AuNPs)	Herbs, algae	Phytochemical reduction	Nutraceutical delivery
Zinc oxide (ZnO)	Leaf and fruit extracts	Green precipitation	Food preservation and fortification
Selenium (SeNPs)	Garlic, yeast	Biological reduction	Antioxidant supplements
Iron oxide (Fe_3O_4)	Plant extracts	Green co-precipitation	Iron fortification
Lipid nanoparticles	Vegetable oils	Homogenization	Delivery of lipophilic nutrients
Polymeric nanoparticles	Chitosan, alginate	Ionic gelation	Bioactive compound encapsulation
Nanocellulose	Agricultural waste	Mechanical processing	Edible coatings and food packaging

6. ROLE OF GREEN NANOTECHNOLOGY IN IMPROVING NUTRITIONAL QUALITY AND FOOD STABILITY

In functional foods, which are focused on imparting a health advantage, one of the most successful approaches to enhance the stability, protection and bioavailability of the bioactive compounds is green nanotechnology (28). Loss of many food components and phytochemicals during food processing, storage, and gastrointestinal digestion has been reported, leading to losses of nutritional and biological activity, such as vitamins, polyphenols, carotenoids, flavonoids, omega-3 fatty acids, and probiotics (29). The protective matrix of the green-synthesized nanocarriers does not allow them to be degraded by heat, light, oxygen, moisture, or enzymes, and guarantees the stability and activity of these sensitive compounds over the product's shelf life (30). In addition, by enhancing solubility, dispersibility, and bioavailability of poorly soluble bioactives, nanoencapsulation technologies can lead to greater intestinal absorption and greater physiological advantages following consumption (31). Green nanotechnology is employed to solve food stability issues by developing biodegradable antimicrobial packaging, edible packaging, and active packaging with antimicrobial activity to inhibit the growth of food-borne microbes and to reduce the food product oxidation rate and preserve the food product's freshness without the addition of synthetic food preservatives. The use of sustainable nanomaterials (based on plant-based biomolecules, natural polymers, and agricultural residues) in clean-label food production and environmentally responsible food production methods is also positive. Therefore, green nanotechnology, its inclusion in functional foods, is a sustainable solution and ensures the nutritional value, shelf life, food safety, and bio delivery efficiency of bioactive compounds, promoting good health to the consumers and producing healthier food products (25).

7. BIOMEDICAL AND THERAPEUTIC POTENTIAL OF NANO-ENABLED FUNCTIONAL FOODS

Nano-enabled functional foods are in the spotlight due to the enhanced biomedical effect of naturally occurring bioactive foods with the use of advanced and sustainable nano-delivery technologies (27). The use of green synthesized nanocarriers with phytochemicals, vitamins, carotenoids, polyphenols, probiotics, and essential fatty acids after oral delivery enhances the release, bioavailability, solubility, and stability of these components to maximize their therapeutic effects (28). The increased absorption from the intestine and increased uptake into cells allow these bioactive compounds to have more potent antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory effects, which help prevent and manage certain chronic diseases (29). Nano-based functional foods are shown to have potential applications in cardiovascular diseases, diabetes mellitus, obesity, cancer, gastrointestinal diseases, and neurodegenerative diseases, such as regulation of oxidative stress, inflammatory pathway, metabolic homeostasis, and immune function (30). Furthermore, systems for targeted delivery can be used to ensure the sustained release of bioactive molecules encapsulated in them, preventing degradation during food processing and digestion, and enhancing their biological activity (31). Other interactions between nano delivery systems and the intestinal microbiota include a role in gut health, nutrient absorption, and boosting the intestinal barrier function, which in turn promotes overall physiology (32). Nano-enabled functional foods and their effects on human health outcomes are summarized in the relationships between the integrated pathways of nutrient delivery, cell protection, and disease prevention, as shown in Figure 2 (33). These are only a few examples of the potential of nano-enabled functional foods as an important innovation of functional nutrition, which offers sustainable and effective ways to prevent diseases, promote health, and develop novel dietary interventions using natural bioactive compounds as functional food ingredients (34).

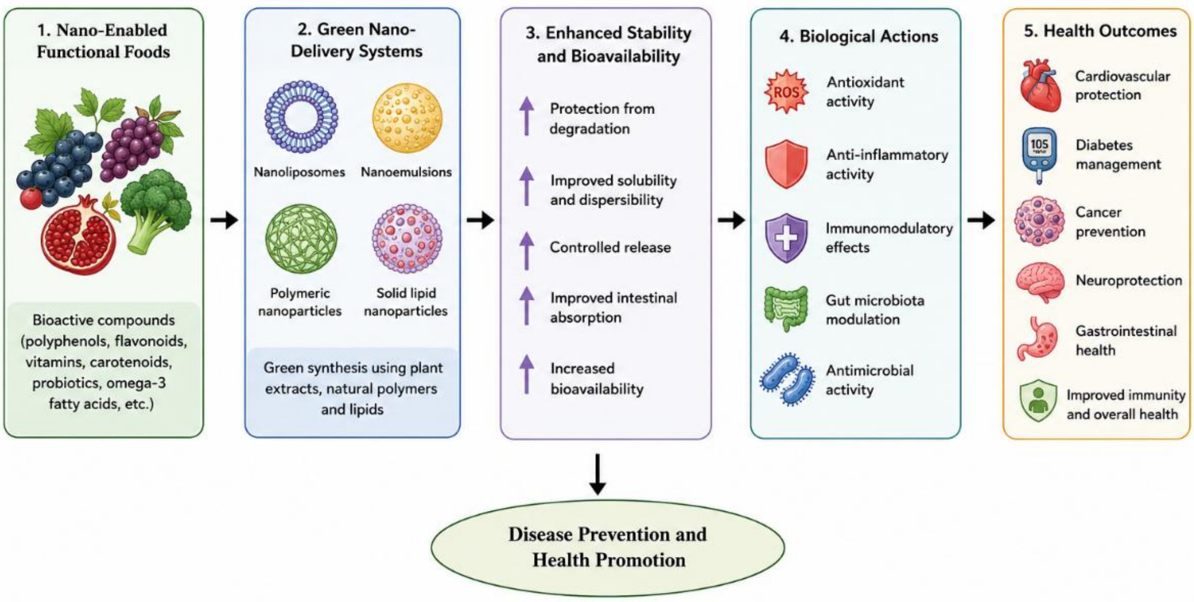

Figure 2. Mechanisms of action of nano-enabled functional foods in disease prevention and health promotion.

8. SAFETY EVALUATION, TOXICOLOGICAL ASPECTS, AND REGULATORY LANDSCAPE

Therefore, there is a need for a comprehensive and sound safety assessment of green nanotechnology in functional foods, as well as to guarantee consumer health and compliance with regulations. (34) Nanoparticles synthesized using green techniques are potential to be more biocompatible and less hazardous to the environment, but their toxicity can be different in terms of size, concentration, surface properties, dosage, and time of exposure (35). Thus, careful assessment of the toxicology in vitro, in vivo, and clinical testing is necessary before commercialization. Regulatory bodies, for instance, the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA), have developed guidelines to assess the safety, effectiveness, labelling, and quality of nano-enabled foods for their safe application in the food sector (36).

9. EMERGING INNOVATIONS AND FUTURE TRENDS IN NANO-FUNCTIONAL FOODS

Advances in nanobiotechnology, AI, and precision nutrition (34) will help make the future of nano-functional foods safer, more effective, and sustainable. Also, the innovations in the field are emerging, such as intelligent nano delivery systems, stimuli-responsive nanocarriers, edible nanosensors, etc. and biodegradable packaging to enhance food quality and nutrient delivery. The incorporation of machine learning and omics technologies is accelerating the formation of personalized functional foods, which are customized for each person's nutritional and health needs (36). Future studies are expected to focus on scaling up the green synthesis, clinical trials, harmonizing regulations, and sustainable manufacturing of safe and effective nano-enabled functional foods for future commercialisation globally (33).

10. CONCLUSIONS AND FUTURE OUTLOOK

Green nanotechnology has transformed functional food research by providing sustainable strategies to improve the stability, bioavailability, and therapeutic performance of natural bioactive compounds. Eco-friendly nano-delivery systems have demonstrated significant potential for enhancing nutritional quality, food safety, and disease prevention while reducing environmental impacts. Despite encouraging progress, further research is required to establish long-term safety, standardized production methods, and globally harmonized regulatory frameworks. Continued collaboration among food scientists, nanotechnologists, clinicians, and regulatory authorities will facilitate the translation of laboratory discoveries into commercially viable products, supporting healthier diets and advancing sustainable food systems for future generations.

ABBREVIATIONS

AgNPs, Silver nanoparticles; AuNPs, Gold nanoparticles; ZnO NPs, Zinc oxide nanoparticles; ROS, Reactive oxygen species; FTIR, Fourier-transform infrared spectroscopy; UV–Vis, Ultraviolet–visible spectroscopy; XRD, X-ray diffraction; SEM, scanning electron microscopy; TEM, Transmission electron microscopy; FDA, Food and Drug Administration.

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