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Review Article

Application of Nanomaterials to Ensure Quality and Nutritional Safety of Food

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Nanomaterials (NMs) are emerging novel tools for preserving quality, enhancing shelf life, and ensuring food safety. Owing to the distinctive physicochemical characters, engineered NMs under varying sizes and dimensions have great potentials for application in the manufacturing, packaging, processing, and safety of quality agrifood. The promise of various kinds of novel NMs that are useful for food industries has opened a possibility of a new revolution in agroprocessing industries in both the emerging and advanced nations. The rapid advancement of nanoscience has provided a great impact on material science that has allowed researchers to understand every aspect of molecular complexity and its functions in life sciences. The reduced size of NMs that increase the surface area is useful in the specific target of different organs, and biodegradable nanospheres are helpful in the transport of bioactive molecules across the cellular barriers. However, nanotechnology creates a great revolution in several sections including agriculture and food industry and also reduces environmental pollution, while the toxicity of some NMs in the food industry poses a great concern to researchers for their greater application. However, most of the developed countries have regulatory control acts but developing countries do not have them yet. Therefore, for the safe use of NMs and also to minimize the health and environmental risks in both the developed and developing countries, it is indispensable to recognize the toxicity-constructed, toxicodynamic, and toxicokinetic features of NMs, which should carefully be emphasized at the home and industrial levels. The current study highlights the updates of the NMs to safeguard the quality and nutritional safety of foods at home and also at the industrial level.

1. Introduction

The food market demands new technologies, which are essential to keep market leadership in the food processing industry to produce fresh, authentic, convenient, and flavorful food products, prolonging the product's shelf life and freshness with improved food quality [1]. Over the past few decades, nanotechnology has increasingly been considered to be attractive technology that has revolutionized the food sector. Nanotechnology has brought a new industrial revolution, and both the developed and developing countries are interested in investing more in this technology [2]. It is a technology on the nanometer scale and deals with the atoms, molecules, or macromolecules with any exterior size (surface or internal structure) in the nanoscale (around 1 nm to 100 nm) [3].

The applications of nanotechnology in the food sector can be summarized in two main groups that are food nanostructured ingredients and food nanosensing. Food nanostructured ingredients encompass a wide area from food processing to food packaging. In food processing, these nanostructures can be used as food additives, carriers for smart delivery of nutrients, anticaking agents, antimicrobial agents, fillers for improving mechanical strength and durability of the packaging material, etc., whereas food nanosensing can be applied to achieve better food quality and safety evaluation [4].

Due to the surprisingly new properties of any molecule at the nanoscale, the NMs have been industrially used in many nanotechniques in the field of electronics, medicine, healthcare products, bioremediation, sensing, agriculture, and others [5–7]. Benefits of using NMs in agriculture consist of improvement of quality and safety of foodstuffs, shrinkage of the excessive use of synthetic agronomic inputs, enhancement of fascinating nanoscale nourishments from the soil, and so on [1, 2]. Food wastage is the foremost loss in the food industry. It is estimated that throughout the supply chain, ~1.3 billion metric tons of foodstuffs are misused annually, mostly due to the traditional postharvest practices and transportation, conventional storage, and delayed marketing accessibilities [8]. In today's competitive world, reduction of food wastage ensuring food for an ever-increasing population necessitates nanotechnology in agriculture. It has been observed that wastage of food materials due to spoilage is a regular phenomenon due to microbial contamination. NMs have shortened the storage duration and secured food materials under stored conditions [9]. Several lines of evidence suggest that nanotechnology (NT) plays a vital role in enhancing agricultural productivity and also enhancing product quality and safety, which lead to upholding healthier nations [10–12]. Various roles of NMs for enhancing agricultural productivity as well as food and nutritional safety are shown in Figure 1. Owing to the distinctive physiobiological characters, different sizes of engineered nanoparticles (Figure 2) have great potentials to ensure quality foodstuffs [13, 14]. Nanomaterials and their potential prospects and use are listed in Table 1.

NMs enhanced preservation ability and quality of foodstuffs. For example, the storage duration of vegetable tomato has been improved by the nanoencapsulated quercetin [28]. Besides, NMs also enhance the storage and packing duration of other fruits and vegetables [28]. Without boiling, nanoscale filters could remove the harmful bacteria from the milk and milk products, as well as water and beer [36]. Engineered nanoparticles enhance biological ability, sensitivity, consistency, and steadiness or conceal the unfriendly flavor and odor of food [37–39]. It is also portrayed in different research articles that nanoparticles can also provide flavor and color and regulate various enzymes and antibrowning agents, as well as antioxidant activity which improved the shelf life of processed foods [40]. Although a large frame of literature is available on the application of quality and nutritional safety of foods, no comprehensive review has so far been published according to our knowledge. In this present review, we have tried to summarize recently published research in the field of the application of NMs on foods and especially in food technology including application, toxicology, potential challenges, and regulations of uses of NMs to prepare a compressive insight in this field.

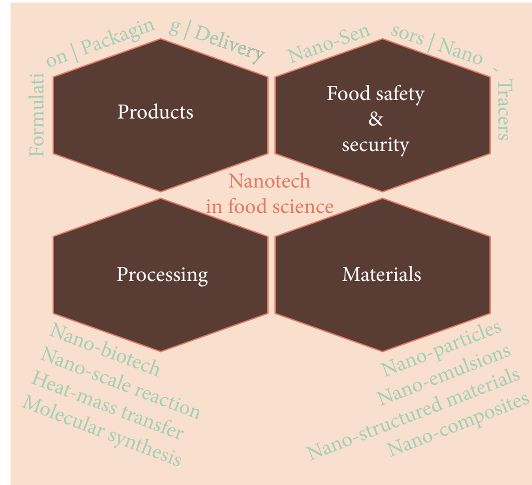

Figure 1: Various roles of nanomaterials for food quality and safety.

2. Application of Engineered Nanomaterials in Food-Related Areas

The application of engineered nanomaterials (ENMs) in food and allied industries is increasing at a brisk rate for its multipurpose use [41]. Global market values of NM-based products were estimated at around 20 billion euros [42], and these values are increasing at a rapid rate. The various uses and possible functions of ENMs in the food and agricultural sectors are briefly discussed below, and these will certainly help in ensuring food quality.

2.1. Engineered Nanomaterials in Agricultural Production Systems for Food Security. The agricultural sector provides a significant contribution to the economic growth of developing countries [43]. Sustainable allocation of food is firmly determined by the sustainable productivity of the agricultural production system. It is reported that at least 33% of

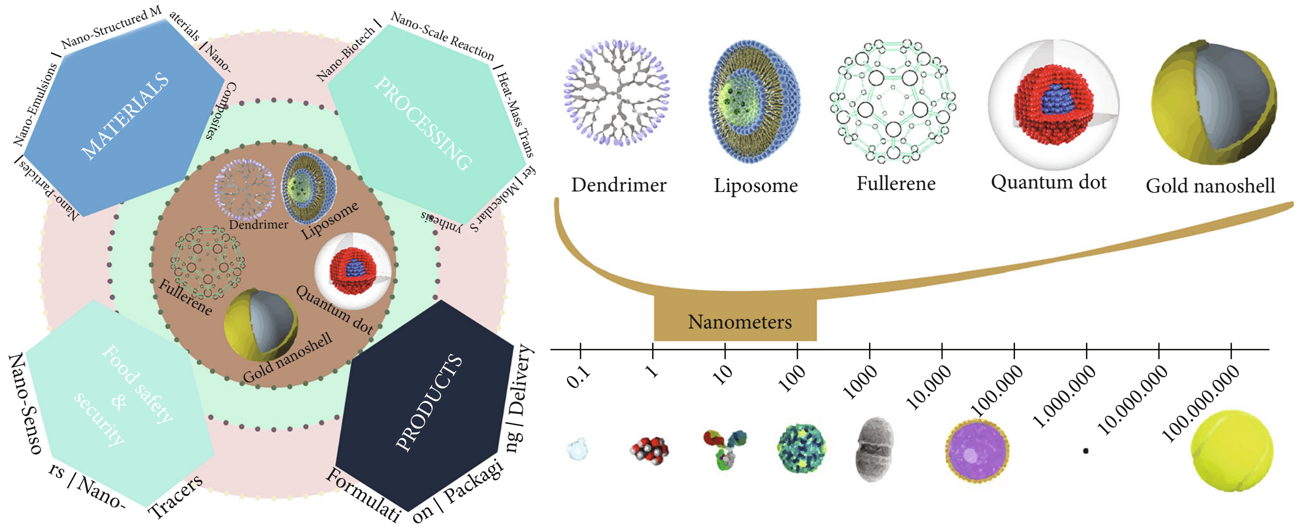

Figure 2: Different nanoparticles based on categories and sizes used for food quality and safety.

arable soil got already degraded to some extent, and this situation is getting worse day by day. It also is anticipated that out of the total food production, 30% of the food is wasted due to improper management [42]. The current nutrient management technology, especially nitrogenous fertilizers, is a highly energy-intensive system and contributes a significant portion to the raising of greenhouse gas emissions [44].

It is expected that NT may show the way of development in technologically advanced agriculture and allied sectors, such as plant protection chemicals, plant nutrients, and water, by utilizing a series of high-tech NMs. With the improvement of agricultural science and technology, the pesticide and fertilizer delivery system gradually became smarter, and scientists are trying to increase the use of efficiencies of the final product at field levels. The development of various novel nanoagrochemicals in the form of "nano-based or nanoencapsulated fertilizers and pesticides" is one of the greatest significant interventions in this arena [45]. Researchers from throughout the world found that nanoagrochemicals showed extraordinary properties like accelerated cation exchange capacity, ion adsorption, and higher surface area than conventional bulky materials [46].

The effects of different NPs on plant growth and phytotoxicity were reported by several works including magnetite (Fe_3O_4) nanoparticles and plant growth [47]; alumina, zinc, and zinc oxide on seed germination and root growth of five higher plant species; radish, rape, lettuce, corn, and cucumber, silver nanoparticles, and seedling growth in wheat [48]; sulfur nanoparticles on tomato [49]; and zinc oxide in mung bean, as well as nanoparticles of AlO, CuO, FeO, MnO, NiO, and ZnO [50]. Silver nanoparticles can stimulate wheat growth and yield. Soil applied with 25 ppm SNPs had highly favorable growth-promoting effects on wheat growth and yield. Ghidan et al. [51] showed synthesized nanoparticles of magnesium oxide (MgO) and tested the effect of different concentrations on the green peach aphid (GPA) under greenhouse conditions [52, 53]. The synthesis of nanomaterials of copper oxide (CuO), zinc oxide (ZnO), magnesium hydroxide (MgOH), and magnesium oxide (MgO) has been carried out successfully by using aqueous extracts of *Punica granatum* peels, *Olea europaea* leaves, and *Chamaemelum nobile* flowers [54]. Nanomaterials such as copper oxide (CuONPs), zinc oxide (ZnONPs), magnesium hydroxide (MgOHNPs), and magnesium oxide (MgONPs) effectively control various pests and diseases [55].

2.2. Engineered Nanomaterials in Food Application. The use of naturally occurring nanomaterials (NONMs) in foodstuffs and allied sectors is increasing day by day [56]. Various NONMs have been utilized in the European God House since early progress [57]. Milk (mainly casein micelle) comprises one of the most useful natural nanomaterials distinguished as nanocapsules with a size of 100–200 nm [58]. Additionally, control of casein micelle through mixed enzymatic reactions can create nanodesigned foods like cheese. Along with the casein micelle, nanofibers (~4 nm in length) composed of β-lactoglobulin are also present in milk. These nanofibers are commonly manipulated during processing via the addition of pressure and heat and/or the modification of pH; and, in the case of yogurt, they aggregate into larger structures forming a supramolecular network capable of forming an elastic gel network [59]. The application of NT is expanded into different orders, including medicinal, automated rationale, horticulture, and food applications.

Security appraisal and affirmation on ENMs is necessary as its scale could be disseminated all through the body framework. Another proviso is the absence of blended NT rules to help food makers in pronouncing the nearness of nanofixing or ENMs in their food items. Because of this, makers confronted challenges in guaranteeing the nearness of ENMs in their items by alluding to the existing laws of food manufacturing and processing [42]. Henceforth, ENMs are frequently utilized in the upstream procedure of the food framework including farming utilization, food packaging and processing ingredients, and the safety of food at home

Table 1: List of nanomaterials used in enhancing the quality and safety of food.

Nanomaterials	Use in storage, processing, and detection	Mode of actions	References
AuNPs	Storage and processing of meat, dairy, and juice	Integrates DNA or enzymes or antibodies of pathogens with AuNPs	Paul et al. [15]
Nanolaminates	Food-grade film	As carriers, nanolaminates improve the textural properties of foods	Acevedo-Fani et al. [16]
Chitosan nanoparticles	Coating agent for fruit packing	Antimicrobial activity	Xing et al. [17]
Graphene	Detection of contaminants in food materials	Nanoplate-based nanocomposites detect pollutants in the target foods	Sundramoorthy and Gunasekaran [18]
Silica-coated silver shells	Use for controlling *E. coli*	Water purification	Zhu et al. [19]
CdTe QDs	Integration as biomolecules	CdTe QDs generally used in the food industry	Sonawane et al. [20]
Al_2O_3, La, Nano	Water purification and soil cleaning	Oxidation of contaminants	Thangavel and Thiruvengadam [21]
AuNPs	Paraoxon (insecticide)	Glycine buffer	Simonian et al. [22] and Pérez-López and Merkoçi [23]
	Mycobacterium avium subsp. *paratuberculosis*	Milk	Yakes et al. [24]
Silver zeolite	Preservation, disinfection, and decontamination	Antimicrobial agent	Matsumura et al. [25]
CuNPs and AuNPs	Control pathogens	Surface water	Zhang et al. [26]
Fe_3O_4 MNPs	Glucose	Acetate buffer solution	Wei and Wang [27]
Carbon nanotubes	Food inspection and vacuum proof food packaging	Optical, electrical, mechanical, and thermal conductivity	Yadav [28]
Polymeric nanoparticles	Food preservation and packaging	Use as the bactericidal and efficient delivery mechanism	Senapati et al. [29]
Silicon dioxide	Increasing shelf life of food during food storage and wrapping	Act as anticaking, colorant, hygroscopic, and drying agent in food processing and storage	Jones et al. [30]
Magnetic nanoparticles	Pathogen monitoring	Large specific surface area	Augustine et al. [31]
ZnO	Increasing shelf life of food during food storage and wrapping	Decreases the flow of oxygen inside the overflowing containers	Zhao et al. [32]
TiO_2	Increasing shelf life of food during food storage and wrapping	Used as a whitener in dairy products (e.g., milk and cheese)	
Inorganic nanoceramic	Increasing shelf life of food during food storage and wrapping	Use in cooking (frying)	Arshak et al. [33]
Silver nanoparticles	Increasing shelf life of food during food storage and wrapping	Act as antibacterial agents, absorb, and decompose ethylene in fruits and vegetables	Acosta [34]
CdSe@ZnS NPs	Enhance shelf life and reduce disease infection and decontamination during food processing	Antimicrobial agents	Matsumura et al. [25]
Cellulose nanocrystals	Food wrapping	Biocompatible high water uptake	He et al. [35]

and industrial levels [57–59]. At present, the effects and reactions of ENM utilization in the value chain of food are seriously concentrated to guarantee their security for the well-being of human beings.

Several nanomaterials are used as antimicrobial agents in food packing. Nanoparticles currently used are titanium dioxide (TiO_2), zinc oxide (ZnO), silicon oxide (SiO_2), magnesium oxide (MgO), gold, and silver [60]. Among the different inorganic nanoparticle-based antimicrobial agents, silver has been extensively studied by many researchers because of its several advantages over other nanoparticles such as copper, zinc, gold, ZnO, Al_2O_3, and TiO_2 [61].

2.3. Nanomaterials in Food Security. Adoption of the sustainable food production system is always advocated for ensuring eco-friendly and economically viable food production system in the long run [62]. Nanotechnological approaches could limit the unfavorable issues of the existing food fabrication and processing system by enlightening the security and efficiency of food through the successful implementation of nanobased input options and nanodevices in agriculture. Different investigations on the utilization of ENMs in these ventures have been directed, comprising the nanosensor for checking plant development and distinguishing plant maladies [63], the improvement of indicative devices [64], the advancement of nanoplant protection chemicals and nanofertilizers [65, 66], the foundation of moderate discharge fertilizers and pesticides, and the improvement of the useful foodstuff framework and nanoempowered packaging and processing of food [67].

2.4. Nanomaterials as Food Flavors and Food Processing. In food enterprises, methodologies of nanoscience are utilized for food flavors and processing as top-down and bottom-up procedures. The nanobased top-down method includes the decreased molecule size employing physical preparation, for example, handling and homogenization, while the "bottom-up" method includes the self-aggregation procedure of NMs at the nanoscale through parity of differentiating noncovalent interactions. NONMs are instances of "top-down" NMs, while "bottom-up" NMs are nanoemulsions, nanolipid congregations, liposomes, and micelles to increase the quality, flavor, taste, solidity, and constancy of food items. As often as possible, the most utilized food-added substance, titanium dioxide, fills in as shade that upgrades the white pigmentation in different nonwhite food [68, 69].

Intensifying the health hazard related to an inactive way of life accelerates the creation of food items with payback in healthiness. Antioxidants are mostly used in strengthening and improving the usefulness of food items. But they are unstable with low biological ability when included in the dissimilar food microstructure, and as a result, antioxidants could not show their genuine health benefits to the ultimate consumers [70]. The development of nanoparticles prompts the chance of upgrading the biodynamic solidness and usefulness in the fortified food item [42]. Antioxidants are often encapsulated by the nanoparticles to ensure the permanence of the storage duration. Anthocyanin, an antioxidant compound with high water dissolvability, is generally in various organic fruits including blueberry and strawberry to minimize pH neutrality [71].

2.5. Food Contact Nanomaterials in Food Packaging. In the processing, packaging, and storage of food at home and in industries, NMs can be categorized as follows: (a) lead to advancement in food packaging science, (b) avert food deterioration, (c) allow the keeping of food newness and quality, (d) give assurance on food safety, (e) expand food timeframe of realistic usability, (f) lessen food waste, and (g) give ongoing checking of the quality of food (by using nanosensors). NMs, for example, Ag, Au, and ZnO, are recognized for their antimicrobial properties [72]. These NMs help to sustain the hygienic food preparation as well as the storage and anticipation from the contamination of harmful microorganisms [73]. A few nanoforms that have picked up an endorsement for usage in food commerce ingredients are SiO_2, titanium nitride, carbon dark, kaolin, and copolymeric nanoform [74]. Of late, a greener option such as nanoencapsulated common antimicrobial extortion has been incorporated on different surfaces as opposed to utilizing different chemicals/synthetics [75–77]. The eco-friendly packaging technique is an inclining application in clean technological innovation, emerging with public alertness to conserve environmental safety for the future generation [78]. The utilization of nanocomposites for food packaging is a natural well-disposed choice to diminish or supplant the utilization of plastic which is nonbiodegradable [79]. Biodegradability of bundling could be upgraded through the presentation of an inorganic molecule, for example, nanoearth, arranged from regular and adjusted montmorillonite [80].

2.6. Nanoenabled Sensors in Food Application. Recent advancements in food processing industries created an arena of diversified processed food products, and these industries used different types of packaging materials to keep the product fresh as long as possible. But these processed and packaged food materials may be contaminated by the toxins produced by the different microorganisms [81]. Food-contaminating microorganisms can ruin food products by deteriorating taste, flavor, and aroma and may also infect humans. But nowadays, the detection and mitigation of food adulteration vis-à-vis the finding of the authenticity of band products are major challenging issues in food industries [81]. Application of different nanoenabled sensors may be successfully utilized to overcome such challenges of food industries such as the detection of pathogenic bacteria, food-contaminating toxins, and adulterants, as well as taste and smell of foods. The various uses of nanoenabled sensors in food and allied sectors are summarized in Figure 3.

The different nanoenabled sensors are effectively applied to detect the occurrence of pollutants in foodstuffs [54], trace plants from sources to intake, and identify features responsible for food decomposition [81]. Gold nanoparticle- (AuNP-) based nanosensors nowadays are presently extensively applied for the recognition of aflatoxin contamination in milk [81]. Advanced nanosensors also can be used to distinguish the existence of multiple pathogens or food toxins [54]. In the agriculture and food sectors, carbon nanotubes and silver nanoparticles (AgNPs) are frequently applied for the recognition of toxins such as melamine, pesticides, and toxins in food items [82, 83]. The involvement of nanoenabled sensors in various aspects of food industries not only helps the uses for speedy and highly subtle applications for the exposure of the contaminants but also reduces the involvement of money and manpower as compared to the conventional detection methods.

3. Impact of Nanomaterials in Securing Food Safety and Quality

NMs are considered to be one of the emerging products for the benefit of humans. The use of NMs is predicted to increase remarkably in different areas, including agriculture, food technology, and medical sciences. The application of NMs in the field of drug delivery systems, farming, cosmetics, food industry, and personal healthcare systems invites contamination of natural resources in the long run. Eventually, there is a potential chance of getting the residues

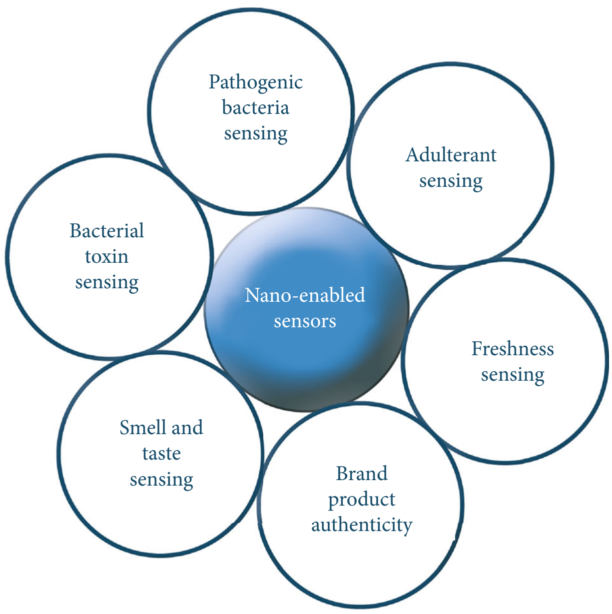

Figure 3: Different nanoempowered sensors in food application.

of NMs into the human food chain. Successful utilization of NMs for different purposes would readily accelerate the global economy simultaneously. In the application of these NTs in every sector, one should measure the positive and negative consequences. Before approving any nanomaterial for practical use in the food industry, a rigorous study on its toxicity is needed to ensure its safety to human health and the environment.

3.1. Characterization Techniques of Nanomaterials in Food Matrices. The emergence of NT has provided support to the application of different NMs not only in the field of food industry but also in the field of biomedicine [84], optics, proteomics, sensing [85], energy, and electronics [86]. The certain conventional method of characterization of NMs includes size, morphology, zeta potential, and polydispersity indices. These characterization technologies help in the basic understanding of the shape, size, dimension, charge, porosity, surface area, and structure of the nanocomposites that can be understood by chemical characterization. However, understanding the physicochemical features of the nanocomposites requires enhancement in the technology of characterization and resolution ranges.

Various spectroscopic and electron microscopic methods are useful for food matrix estimation. Usually, biomaterials are present in the form of polymers that enhance the resolution capability of the material. Some of the major spectroscopy techniques used in the characterization of biomaterials and NMs are X-ray absorbance spectroscopy, X-ray fluorescence, nuclear magnetic resonance spectroscopy, Fourier transform infrared spectroscopy, and UV-visible spectroscopy. However, advanced microscopic characterization techniques are also used for understanding the morphology, size, and interaction of the NMs. Skimming investigation microscopy, nuclear power microscopy, scanning and transmission electron microscopy, confocal laser perusing microscopy, and field radiation skimming electron microscopy are useful for a detailed description of NMs.

X-ray absorbance spectroscopy can provide information regarding the elemental map and electronic structure of a given compound [87]. Nuclear magnetic resonance spectroscopy is used to understand the molecular structure, quality control, and purity of the samples. Fourier transform infrared spectroscopy helps in understanding the structure and the chemical bonds formed in the formation of the sample [88]. UV-visible spectroscopy is utilized in the measurement of preoccupation and diffusion of specified NMs in the form of resolution. Microscopic techniques like electron microscopy and atomic force microscopy help in understanding biological interaction and visualization. All these techniques help in the characterization of different food matrices to analyze different prospects of the biomolecules for enhancing the understanding of the biomolecules used in human consumption.

3.2. Nanomaterials in Food Processing. Nanotechnology has been successfully applied in various aspects of food production [89]. It has brought a vital impression on the field of the food sector and is aimed at providing better quality and preservation [90]. The growth of the global economy depends upon the successful implementation of NT [91]. The food industry is one of the sectors that could get a lot of benefit from NT with great prospects for quality, safety, and preservation of food materials [92]. Recently, several nanostructured-based food ingredients are developed which claim to offer improved taste, consistency, and texture along with increased shelf life [92, 93]. Advancement in NT has also reduced the wastage of food due to microbial contamination [93]. Several nanocarriers, with different particle sizes, are developed for carrying the food additives in the food product without any disturbance in their morphology [94].

3.3. Nanomaterials in Food Packaging. Plastic is measured as the furthermost extensively essential polymer for packing materials in our daily life [95]. It is estimated that more than 350 million tons of plastics are utilized in our daily life across the globe [95, 96]. However, most of the plastics are disposable items and these are not environmentally friendly. Based on the burning issue, significant investigations have already been done for the proper utilization of biopolymers as a substitute for partial alteration of plastics [97]. Recently, several nanomaterials have been established as an auspicious approach for improving the efficient utilization of food packaging ingredients [98]. Among them, nanomaterials such as reinforcement agents in different biopolymers including alginate [99], chitosan [100], gelatin [101], pullulan [102], polyvinyl alcohol (PVA) [103], chitosan/PVA blend [104], starch/PVA blend [105], and cellulose nanostructures (cellulose nanocrystals (CNC) and cellulose nanofibers (CNF)) have been widely studied as thin-layer coatings [106] for food packing. Several useful NMs as a material for packaging that can be used for the improvement of food packaging are shown in Figure 4.

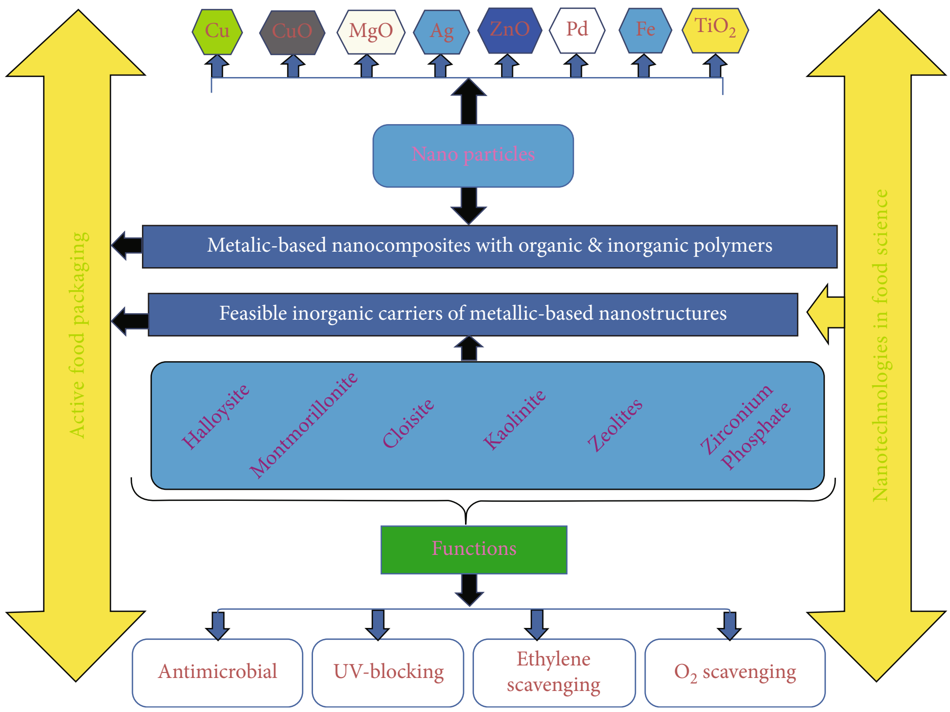

Figure 4: Potential for the development of metallic-based nanocomposites in active food packaging.

NM-based packaging products have several advantages over their conventional counterparts [107]. They provide mechanical strength, antimicrobial films, and the detection of pathogens via nanosensing, tipping off the customers about the freshness of food. Several organic compounds such as essential oil and organic acid are used as polymetric matrices [108]. Inorganic nanoparticles can provide a strong antimicrobial activity and stability in extreme environmental conditions [6]. NM-based packaging is an energetic wrapping material that physically interrelates with the food items and inhibits microbial growth. NMs not only are used for antimicrobial food packaging but also provide a barrier from mechanical shock and extreme thermal shock to extend their shelf life [109]. Usage of inert nanoscale fillers like chitosan and silica nanoparticles [110] renders their properties such as fire resistance, as well as lighter, stronger, and better thermal properties.

4. Nanobased Sensors for the Recognition of Food Quality and Storage Diseases

4.1. Nanomaterial-Based Sensors for Food Quality. Food engineering is continuously confronted by the incidences of foodborne ailments. Foodborne disease is demarcated as some illness typically either communicable or lethal in nature, initiated by mediators that go in the body via the digestion of food [111]. The contributing organisms may be bacteria, protozoa and viruses, fungal or bacterial toxins, pesticides, and metal ions. Some pathogens associated with major foodborne diseases are *Bacillus cereus*, *Brucella*, *Campylobacter jejuni*, *Clostridium botulinum*, *Clostridium perfringens*, *Escherichia coli*, *Listeria monocytogenes*, *Salmonella typhi*, *S. paratyphi*, *Shigella* spp., *Staphylococcus aureus*, *Vibrio cholerae*, and *V. parahaemolyticus* [112]. To manage foodborne disease incidences, it is essential to evolve the cost-effective and easy methods for instant identification of pathogen contamination or existence of toxic substances which can substitute the orthodox testing methods [113]. The PCR-constructed approaches and immunoassay-based procedures are conventional approaches and routinely followed. There is no doubt that these methods are scientific, but there is a need for costly instruments and chemical components, skilled human resources, sizable sample preparation, and lengthy processes involved in these molecular techniques, thus suspending preventive management in patients [114, 115]. There is an urgent need for the development of unique techniques which will be easy to use, rapid, low cost, and delicate for site-specific recognition and steady and movable sensing kits. NT was capable of covering some techniques in this regard in the preceding period (Figure 5).

The adaptability of NMs has provided ample opportunity for the usage of operative nanosensors in the food manufacturing plant for the supervision of food quality [116]. Recent developments in the use of sensors based on nanoparticles used in the food industry are briefly discussed below.

4.1.1. Gold Nanoparticle- (AuNP-) Based Sensors. Escherichia coli is one of the pernicious bacteria affecting human health. Among different strains of the bacterium, *E. coli* O157:H7 is the serotype strain causing foodborne diseases. For the detection of this strain, a mingling movement piezoelectric biosensor (PEB) has been established. The PEB is composed of the *E. coli* O157:H7 *eaeA* gene precise AuNP-conjugated (AuNPC) thiolate investigation which detects the presence of it [117]. Moreover, the AuNPC with *E. coli* O157:H7

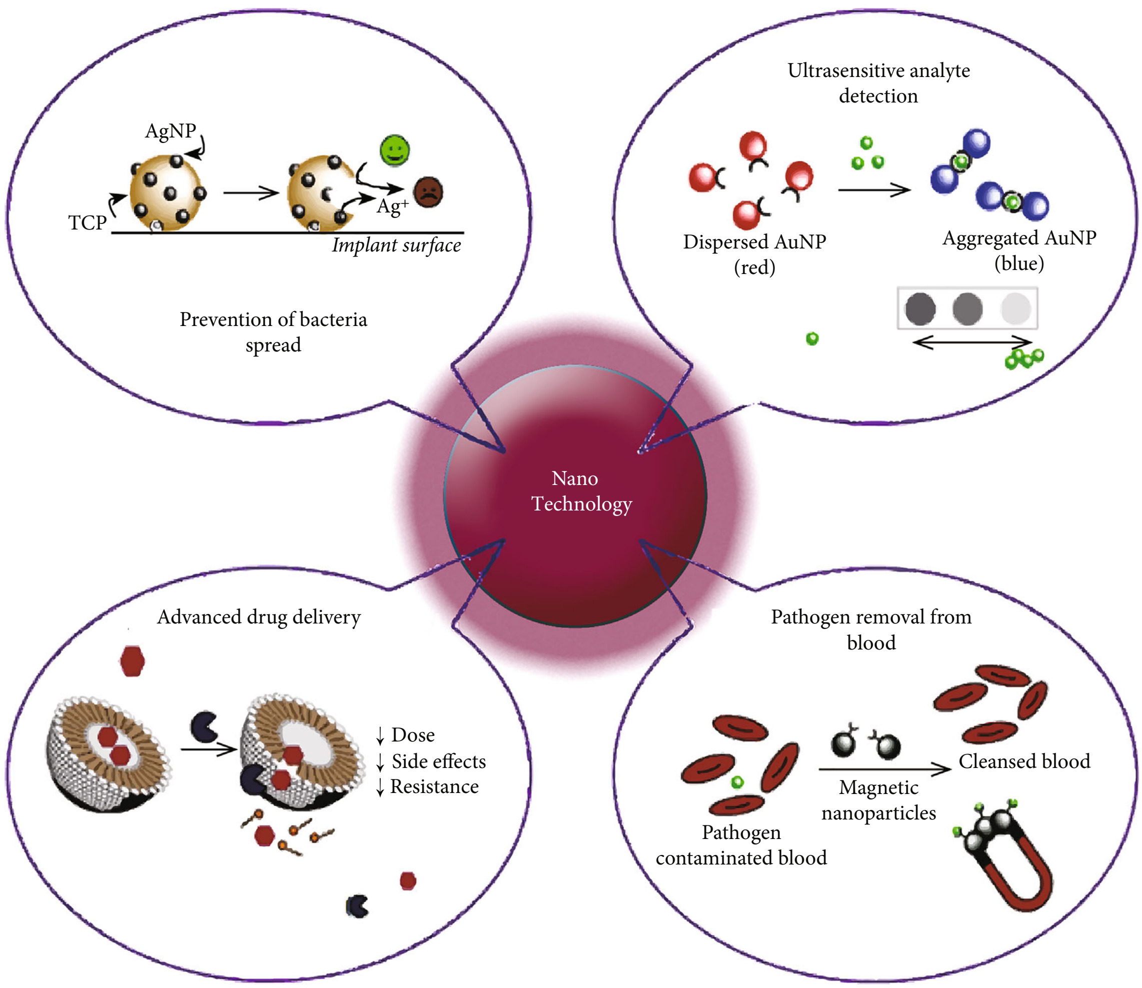

Figure 5: Detection and prevention of microbial infections through nanotechnology.

antibodies was also made to detect the presence of the bacterial strain in milk. The screen-printed carbon electrode (SPCE) technology is composed of 13 nm AuNP which can detect *E. coli* O157:H7 precise antibodies. H_2O_2 and ferrocene dicarboxylic acid (FeDC) play the role of substrates in the detection process. The AuNP and FeDC boost the recognition limit to $1 \times 10^2 - 10^7$ CFU/mL [23]. The AuNPC-based electrochemical immunoassay not only detects the existence of *E. coli* O157:H7 but also is used for noticing *Salmonella typhimurium* [118]. In the occurrence of Cu-enhancer solution and ascorbic acid, the bacteria bind to the AuNPC polyclonal antibodies. And the Cu helps in the recognition of *S. typhimurium* by anodic disrobing voltammetry [119]. The AuNP-based sensors can detect mycotoxins present in food. The AuNP aptasensor has been made for the detection of aflatoxin B1 [120]. Similarly, aflatoxin B2 can also be detected by the AuNP aptasensor constructed on the colorimetric technique [121].

4.1.2. Magnetic Nanoparticle- (MNP-) Based Sensors. Magnetic NM-derived sensors are used for sensing and eliminating food contaminants [122]. The incubation of the MNPs with fluorescently labeled concanavalin resulted in the visualization of the bacterial cells [123]. Moreover, the presence of *Salmonella* in milk can also be detected by MNPs. The immobilized antibodies responsible for the detection of the presence of bacteria in foods are eliminated by the application of the magnetic field. The TiO_2 nanocrystals play a great part in the discovery of germs in the foodstuff by using the UV-noticeable spectrophotometer with a recognition limit of 100 CFU mL^{-1} for milk [124]. The Gram-positive and Gram-negative bacteria from food and water can rapidly be detected by amine-functionalized MNPs. The MNPs are also used for the detection of *Bacillus cereus*, *B. subtilis*, *E. coli*, *Sarcina lutea*, *S. aureus*, *Salmonella*, *Proteus vulgaris*, and *P. aeruginosa*. In the fast detection process, the quantity of amine-functionalized MNPs and the ionic strength played a crucial role [125].

4.1.3. Quantum Dot- (QD-) Based Sensors. The fluorometric-based sensors can be made by semiconductor QDs as these can exhibit electronic and size-dependent properties [126], and the CdSe quantum dots are used frequently for this purpose [127]. The QD-based biosensors are suitable for the detection of *S. typhimurium* in the chicken carcass wash water. The principle of the response of biotin to the streptavidin-coated QDs was used for the detection of germs. Actually, the fluorescence intensity is measured as the cell number and the limit considered is about 1×10^3 CFU/mL [128]. Generally, for the recognition of *Cholera*, *Shiga* toxin, and *Staphylococcal* enterotoxin A, the CdSe QD-derived sensors are used.

5. Regulation of Nanotechnology (NT) in the Food Industry

Nanotechnology (NT) has been developing seriously in numerous businesses in recent decades. Several recently created solicitations for this innovation in the food and horticulture industry have started a renewal in food handling, bundling, and supplement conveyance. A changing trend in physicochemical properties of inbuilt nanomaterials was mostly followed in this sector. Such NT-helped structures have significantly propelled the innovations utilized to improve food quality, increment rack capacity life, and eventually aid the sanitation and quality of the observation framework. As of October 2017, the NT Consumer Products Inventory started by Woodrow Wilson International Center for Scholars and the Project on Emerging NT recorded 118 food and refreshment items out of an aggregate of 1944 items from 715 organizations around the world, comprising an assortment of NMs [129]. Alongside the most recent accomplishments in food, NT comes with an expanded open concern over the security of the new innovation. Guidelines and enactments fall behind the quick turns of events in the NT business. Thus, the security context and real-life welfare of humanity are sustained through NT-based food products and agribusiness items.

Although numerous nations have either begun or given the direction for sanitation evaluation on NT, impressive difficulties stay for most creating nations. Eminently, financial development and improvement are higher needs for the creating nations, leaving such well-being concerns as NT to be tended to at the universal level with the collective endeavors in food, water, and farming [130]. With the likely effects of food and agribusiness, NTs on human and ecological well-being are as yet not completely comprehended, and plentiful insurance with respect to all partners is important to make sure of the sheltered use of novel NT in the food and farming segments for quite a while (Figure 6). In this survey, the most recent advances in the comprehension of nanotoxicology, hazard appraisal, and administrative guidelines on the utilization of NT in food and horticulture items are quickly surveyed and talked about [131].

5.1. Definition of Nanomaterials in Some Countries. Different countries like the USA, Japan, and European countries have found different ways to define NMs which are briefly discussed in Figure 7.

5.2. Regulations for Food Assessment. Different explorations identified with the use of NT in the food division continue expanding and drive the extension of the likely utilization of NT in the food industry. Consequently, the chance of human interaction with these NMs likewise expanded essentially either deliberately or unexpectedly. In any case, just a couple of studies have concentrated on the expected poisonousness of the nearness of nanomaterials in nourishments, by investigating food tests utilized in food-added substances/fixings and food bundling [132]. NMs that are utilized as food-added substances will have direct contact with inner human organs. The degrees of the introduction of nanomaterials on the human subject on their fixation in food and the amount of the food devoured are studied. Expanding employments of NMs in nourishments have pulled in significant consideration of open and government areas. Nanocapsules could enter the human body through oral admission. For instance, lipid NMs were created by utilizing polyethylene glycol (PEG) with different chain lengths as emulsifiers to control their processing destiny in the gastrointestinal lot. In any case, the well-being of nanoencapsulation remains not researched and calls for additional hazard evaluation, especially for long haul poisonousness [133].

5.3. Regulations for Food Contact Material Risk Assessment. NT is one of the emerging technologies which can redefine different dimensions of our lives. In recent years, enormous development in using nanotechnologies is noted including food sectors [14, 39]. The food sector is one of the various sectors which witnessed an application of engineered nanomaterials with anticipated benefits starting from production to packaging. But several materials are being used in foods for different purposes, of which some are found to be carcinogenic and reasons for many diseases. These materials are presented in Figure 8.

5.4. Regulations for Labeling Nanomaterials. The application of NT in the food and farming enterprises is a recently evolved theme, which was first inclined by the US Branch of Agriculture by means of documentation given in September 2003. Later, the EU, Japan, China, Canada, India, Iran, Thailand, and numerous different nations overall additionally put endeavors into creating security direction or enactment. Much exertion has been committed to advancing the sheltered use of NMs and NT in the food and rural segments. Examination gatherings and meetings to talk about the turn of events, application, well-being, and guideline of NMs and NT have been held consistently; a few models are as follows:

(i) Nano Forum (http://www.nanoforum2017.com/)

(ii) Asia Nano Forum (https://www.asia-anf.org/)

(iii) International Conference on Advanced NT (http://NT.alliedacademies.com/)

(iv) World Nano Conference (https://nano.conferenceseries.com/)

In any case, in all actuality, there are a lot more nations that have not drafted any guidelines and direction for the creation and utilization of nanoempowered items [138, 139]. Based on the available literature, the regulation provided by various countries and organizations are listed below (Table 2).

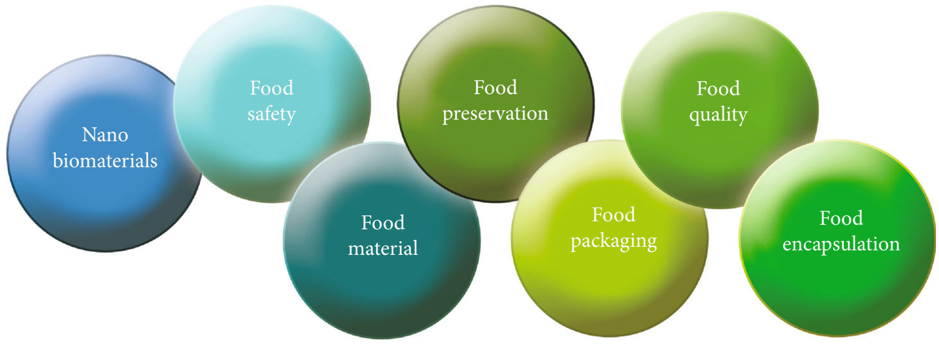

Figure 6: Nanomaterials and their relationship with food industries.

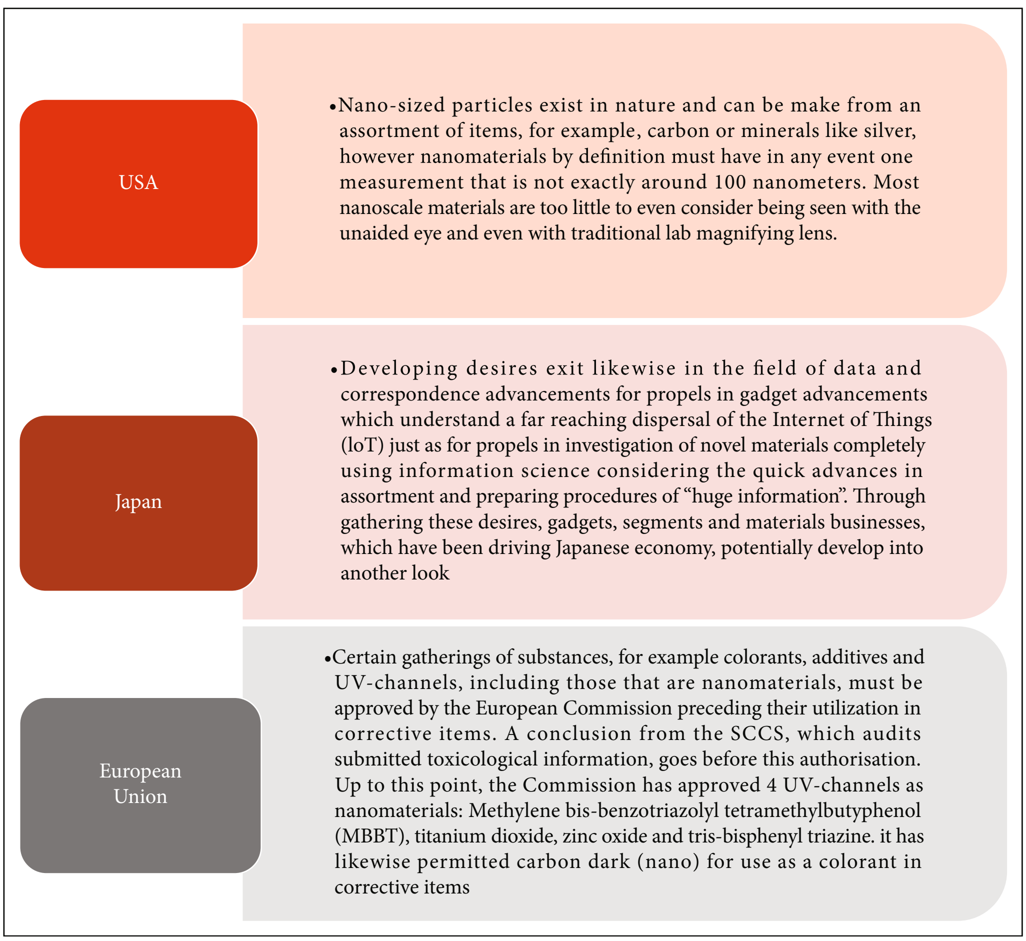

Figure 7: Definition of nanomaterials as revealed by different countries. Sources: https://ec.europa.eu/jrc/sites/default/files/jrc_reference_report_201007_nanomaterials.pdf; https://www.epa.gov/chemical-research/research-nanomaterials;https://www.nano.gov/search/node?keys=Nanomaterials; and https://ec.europa.eu/environment/chemicals/nanotech/faq/definition_en.htm.

5.5. Toxicological Aspects of NMs. Although ENMs have many benefits particularly for food quality and safety, the imbalance and uncareful use of NMs have observed nanotoxicity crisis effects in the human body [140]. NMs are shaped through molecular-level engineering (for example, a small scale (<100 nm)) to attain exclusive features [141]. Conversely, these modified properties have shown new encounters for accepting, expecting, handling, and thinking for food and environmental safety since the use of NMs has been found to be a potential health hazard recently [142, 143].

For example, nonbiodegradable materials (such as plastics), degradable materials, biodegradables [144], and smart packaging (containing sensors and nanocomposites) or even edible packaging (using lipids, proteins, polysaccharides, etc.) have been widely used in food packaging [145].

Graphene

- For example, plants can be antagonistically affected by the introduction of graphene and its subordinates, including graphite oxide and graphene oxides, found that graphite oxide nanomaterials could extraordinarily intensify the phytotoxicity of arsenic (As), which is a broad contaminant in wheat and other farming plants. The utilization of graphite oxide could diminish wheat biomass and root numbers and prompt oxidative pressure. Graphite oxide along with arsenic restricted straches digestion, hampered fattyacid digestion, and blocked the area cycle however expanded amino corresive and auxiliary digestion. Furthermore, graphite oxite additionally initiated cell structure harm and electrolyte spillage, with expanded cell take-up of arsenic.

Metal oxides

- In spite of the upside of having metal/metal oxide nanomaterials fused into nanocomposite food bundling materials, the relocation of nanomaterials to food substance has been the principle subject of concern with respect to medical problems. It is being accounted for that announced that Ti relocated from nano-TiO2-polyethylene composite bundling material into food simulants through halfway disintegration at the surface and cut edges of the strong film. It has likewise been discovered that silver could move from polyvinyl chloride (PVC) nanocomposite bundling.

Chitosan

- One ongoing investigation has demonstrated that eatable cellulose films fusing chitosan nanoparticles could essentially improve the mechanical properties and warm dependability of movies. Be that as it may, in another examination, chitosan-consolidated poly (methacrylic corrosive) nanoparticles utilized in food bundling films showed possible poisonous impact to cells. Studies have likewise demonstraed the utilization of different nanocomposites in palatable movies, including bacterial cellulose nanocrystal films, hydroxypropyl methylcellulose films containing chitosan nanoparticle, and alginate/lysozyme nanolaminate coatings. Concerns in this way ascend alongside the yet-to a great extent predetermined number of tests on the potential dangers related with eatable nanocoatings

Figure 8: Effect of different nanomaterials. Source: graphene [134, 135], metal oxides [136], and chitosan [137].

Biodegradable and edible packaging materials have observed major problems due to poor mechanical properties, low degradation temperatures, humidity, and gas permeability that prevent expansion [144].

The size of nanoparticles is an important factor in observed dermal cell cytotoxicity in vitro [146]. Absorbed nanoparticles in different absorption routes such as digestion, inhalation, or skin absorption could trigger an immune system response [147]. After absorption, nanoparticles may enter the bloodstream and settle in different tissues such as the brain or trigger immune responses [148]. The small size of these particles allows them to pass through different biological barriers and settle in tissues like the central nervous system [149]. Therefore, the size of the nanoparticles in different routes of exposure should be considered in assessing the safety of nanomaterials that are to be used in food and food-related industries [150].

During the production of nanoparticles, many reagents that are used could be toxic [140]. For instance, some observed toxic effects of carbon nanotubes and semiconductor nanoparticles are related to residual reagents during synthesis. The remaining reagents and impurities may hinder our understanding of the possible side effects of carbon nanotubes. Iron ions and impurities can accelerate oxidative stress in human cells [151]. Crystallinity is another important aspect of chemical composition. Titanium oxide has three different levels of crystallinity that each has different cytotoxic effects [152].

Surface chemistry is one of the most important factors affecting the interaction of nanoparticles and biological systems [153]. There are many factors such as hydrophobicity, charge, roughness, and, most importantly, surface chemistry in the surfaces of nanostructures that could affect their cytotoxicity [154]. Evidence indicates that positively charged nanoparticles are more toxic than negative or neutral nanoparticles [155]. Solubility is also important in the toxicity of nanoparticles [140]. For instance, soluble (hydrophilic) titanium oxide nanoparticles are more toxic than insoluble titanium oxide nanoparticles [156]. Some soluble nickel compounds are recognized as carcinogenic agents [157].

A report by the British Royal Society revealed that to avoid environmental and health risks from nanotechnology,

Table 2: Regulations to the use of nanomaterials across the globe.

Sl. no.	Country	Regulation on nanomaterials
1	EU	Guideline (EU) No. 10/2011 with changes and rectifications indicated in Regulation (EC) 2016/1416 is a structured guideline that conceals all resources and training planned to originate into contact with food (Commission Regulation (EU) 2016/1416, 2016). In this specific guideline, just a single proviso explicitly specifies nanoforms measurable to be utilized as added substances in all plastics. It expresses that substances in the nanoform will possibly be utilized if the nanoform is unequivocally approved and referenced in the details of Annex I of the guideline. In EU 10/2011, titanium nitride is named as an NM for use as an added substance or polymer creation with the help of Annex 1; however, "covered and uncoated ZnO for use in the unplasticized polymer" has been included in the change. What is more, carbon dark and nebulous SiO_2 are recorded without being explicitly named as "nanoparticle" but with sizes reached determined, which are underneath or around 100 nm, while, in the corrected variant, another material which is silanated silicon dioxide with essential particles of 1–100 nm is permitted when the particles are accumulated to a size of 0.1–1 μm and shape agglomerates inside the size circulation of 0.3 μm. The changes mirror the openness of new data on the security of NMs, and in this way, further revisions or adjustments will be expected as more specialized and well-being appraisal on NMs is accomplished.
2	FDA	Multiple governmental agencies, including the Environmental Protection Agency (EPA), the FDA, the Occupational Safety and Health Administration (OSHA), and the Consumer Product Safety Commission (CPSC), in the United States, have been part of the decentralized approach toward the regulation of NT to provide the regulatory oversight responsibility for NT regulation. Basic regulations regarding the evaluation of the safe use of nanomaterials remain effective, whereas the proposed guidance has been amended several times later. For example, guidance proposed by the EFSA was first issued in 2006, then modified in 2009 and 2011, and we have the up-to-date version, known as "NT applications in the agricultural, feed and food sector."
3	Japan	In Japan, several governmental agencies including the several ministries (MEXT, METI, MHLW, and MOE) make regulatory decisions cooperatively. However, regulations on the safety issues of nanomaterials or NT remain mostly unclear. As recently as January 2016, the MHLW issued new safety standards for agriculture and food in the 190th Conference for the Promotion of Food Import Facilitation report. Nevertheless, the report did not include any specifications on NT or nanomaterials.
4	Australia and New Zealand	Currently, the utilization for new food substances manufactured with NMs or by means of NT is evaluated under existing Australian and New Zealand laws and standards. Food Standards Australia New Zealand (FSANZ) is an independent standard developing agency of the Australian government, established by the FSANZ Act, for developing food regulatory measures. A variety of approaches have been adopted by FSANZ to assess and manage hazardous risks associated with food nanoingredients or packaging nanomaterials. Working together with other Australian regulatory agencies, the *Application Handbook*, which provides practical guidance for application to FSANZ, was amended in 2008 to incorporate the application information for the use and approval of food NT, considering thorough risk assessment as a required component. Through such legislation advancement, the food NT industry has to observe new regulations and ensure public health and safety with the production and use of novel nanomaterials. In addition, a Scientific NT Advisory Group (SNAG), with experts from NT, nanotoxicology, and nanosafety, was also established by FSANZ to advise the safe application of food nanomaterials.
5	India	Food safety laws in India are currently under the existing Food Safety and Standards Act, established by the Food Safety and Standards Authority of India (FSSAI). The launch of the Nano Mission, a Mission Mode Program within the Department of Science and Technology (DST), steered by a Nano Mission Council (NMC), stimulated concerns over the potential health and environmental risks associated with NT. Regulatory efforts regarding novel nanomaterials in the food industry have been advocated to offer scientific support and legal guidance for the public concerns about the regulation status on NT. In 2015, the Insecticides (Amendment) Bill in the Lok Sabha was aimed at limiting the registration to nanoinsecticides, with a mandatory requirement for assessing and reporting the potential risks of the nanoinsecticides on humans and the environment. With a comprehensive review on reports from regulatory agencies such as the ISO, the OECD, the US National Institute for Occupational Safety and Health (NIOSH), and the OSHA, the DST issued a guidance document in 2016 to provide information for the safe use and disposal of manufactured nanomaterials in research and industries.
6	China	In China, the National Center for Nanoscience and Technology (NCNST), founded in March 2003, has the responsibility for establishing national NT standards. Protocols for characterization of nanomaterials and safety requirements for manufacturing then started to develop. In 2005, the Commission on NT Normalisation, connected with the NCNST, was founded and began to regulate nanomaterial engineering and production and safety assessment. However, the current code is still based on the China national standard at that time, and there is no clear legislation regarding a specific nanomaterial or any NT associated with the food and agricultural sectors.

Sources: https://ec.europa.eu/jrc/sites/default/files/jrc_reference_report_201007_nanomaterials.pdf; https://www.epa.gov/chemical-research/research-nanomaterials; https://www.nano.gov/search/node?keys=Nanomaterials; and https://ec.europa.eu/environment/chemicals/nanotech/faq/definition_en.htm [129–139].

a comprehensive understanding should be necessary before their utilization [158]. The knowledge from the overview in the earlier findings revealed that nanotechnology is a challenging technology for use in food industries due to the distinctive physicochemical features of NMs to enlighten and manufacture foodstuffs. Therefore, the toxicity of NMs in food and the environment has become a great concern to the researcher for the safe use of the emerging tool in food industries for improving quality by ensuring packing and processing and extending shelf life [159]. Therefore, to minimize the health and environmental risks, it is essential to understand the illumination associations between the toxicity-constructed, toxicodynamic, and toxicokinetic features of NMs [160–162]. The information on the nanotoxicological exploration, including the connections of NMs with other toxic substances, by improving or sinking the hostile health hazard as well as environmental pollution, will be helpful to alleviate the adverse effect of NMs [163, 164].

6. Challenges toward the Safe Use of Nanomaterials for the Quality and Safety of Foodstuffs

The incorporation of NMs in the food sector is one of the emergent and pioneering novel approaches for safer and quality foods [46, 60, 61, 63]. But, the use of NMs in foodstuffs, particularly the insoluble and biopersistent nanoparticles, must be safe for consumer health and the environment [45]. Although NMs offer a lot of potential welfare, the anxiety is that NMs with huge volatile exteriors may irritate biological processes to reach those parts of the body. Therefore, for the safe use of NMs, clear fit-for-purpose definitions of NMs and NT are needed. The authenticated approaches for the recognition and categorization of NMs in complex food matrices are currently unavailable [63].

Though there are several advantages of using these NMs, in reality, the use of these materials by farmers is still not encouraging. Numerous studies revealed that less availability and high price as compared to conventional products are considered the major cause. On the other side, a fallacy regarding its use, related to the safety and security of ENM use in the agricultural production system, has played a synergistic role in its less acceptance, while the manufacturers are also in doubt and still wavering on the large-scale production cost of nanomaterials in agriculture [66]. Therefore, an exceeding collaboration between industries, regulatory organizations, and research institutes as well as interdisciplinary research is required to investigate the promising possibility of ENMs in agricultural sectors.

Most of the developed countries have regulatory control acts for the safe usage of NMs. Since the application of NT in developing countries is at the initial level, the safe use of the NMs should be emphasized at the home and industrial levels [56–59]. A hardheaded regulatory oversight in some countries, mostly underdeveloped countries, sometimes hinders the wide use of NT and also creates limitations to safeguard a case-by-case premarket protection evaluation of NT-derived foodstuffs. Besides these, the knowledge gaps regarding the thoughtfulness of the possessions, actions, and belongings of NMs also limit the broader applications of NT in the food sector both at the home and industrial levels.

7. Conclusion

Nanotechnology is emerging as a potential tool for ensuring the quality and safety of agrifood. The present study highlights the updates of NT to confirm the superiority and safety of foodstuffs at home and also in industrial corridors. However, several benefits of NT in food sectors propose huge prospects for the upliftment of public nourishment and health in developing countries, while the toxicity of NMs in the food industry is a great concern of researchers for their greater application. Therefore, the use of NMs in foodstuffs, particularly the insoluble and biopersistent nanoparticles, must be evaluated before utilization for ensuring consumer health and environmental safety. However, most of the developed countries have regulatory control acts for the safe use of NMs, but most of the developing countries do not yet have supervisory agenda for the production and commercialization of NMs in food and other industries. Therefore, the safe usage of NT in food sectors in developing countries should carefully be emphasized at the home and industrial levels. However, a hardheaded regulatory misunderstanding and also knowledge gaps regarding the thoughtfulness of the belongings, activities, and properties of NMs also sometimes limit the broader applications of NT in the sector of food both at the home and manufacturing levels. Thus, a globally concerted effort is needed to develop protocols for effective NM use for the quality and safety of foodstuffs.

Data Availability

Data used in the article are available in the form of tables and figures.

Consent

Consent is not applicable.

Conflicts of Interest

The authors declare that they have no competing interests.

Authors' Contributions

The contributions of the authors involved in this study are as follows: conceptualization: A.H., R.G.K., Sa.M., and Su.S.; methodology: A.H.; software: A.H., M.S., and M.B.; writing—original draft preparation: A.H., R.G.K., Su.M., Sa.M., Su.S., P.B., and M.T.I; writing—review and editing: A.H., M.S., M.B., M.P., A.G., V.H., P.V., and T.I.; and funding acquisition: M.B., A.G., and M.S. All authors have read and agreed to the published version of the article.

Supplementary Materials

Graphical abstract. *(Supplementary Materials)*

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