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Review

Harnessing the Known and Unknown Impact of Nanotechnology on Enhancing Food Security and Reducing Postharvest Losses: Constraints and Future Prospects

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Abstract: Due to the deterioration of natural resources, low agricultural production, significant postharvest losses, no value addition, and a rapid increase in population, the enhancement of food security and safety in underdeveloped countries is becoming extremely tough. Efforts to incorporate the latest technology are now emanating from scientists globally in order to boost supply and subsequently reduce differences between the demand and the supply chain for food production. Nanotechnology is a unique technology that might increase agricultural output by developing nanofertilizers, employing active pesticides and herbicides, regulating soil features, managing wastewater and detecting pathogens. It is also suitable for processing food, as it boosts food production with high market value, improves its nutrient content and sensory properties, increases its safety, and improves its protection from pathogens. Nanotechnology can also be beneficial to farmers by assisting them in decreasing postharvest losses through the extension of the shelf life of food crops using nanoparticles. This review presents current data on the impact of nanotechnology in enhancing food security and reducing postharvest losses alongside the constraints confronting its application. More research is needed to resolve this technology's health and safety issues.

Keywords: agriculture; food processing; food safety; nanoformulation; nanosensors

1. Introduction

One of the most challenging concerns of the 21st century is ensuring food security for the world's rapidly growing population. According to projections, the global food demand will increase from 59 to 98% by 2050, with a population of 9 billion [1,2]. Although the world's population is growing, most especially in developing nations, the local and international supply of food is being disrupted by the use of bio-resources for chemical manufacturing, production of energy, low-value addition, high postharvest losses, poor marketing systems, and inefficient distribution and other similar factors [3]. Farmers globally have concentrated most of their efforts on improving the yield of crops via extensive and intensive agriculture by implementing novel technologies and ideas [4,5]. Precision farming in combination with the application of nano-modified stimulants has boosted the current attempts. Agricultural efficiency, secure water usage, food quality, soil improvement and food distribution in outlets are all essential aspects of food security that nanotechnology research can improve [6].

It is critical to develop new technologies that will enhance product output while reducing food waste in order to preserve a nation's sustainable living standards and improve food security. Nanotechnology is notable for providing foods with exceptional physical quality in addition to incrementing nutrient bioavailability. Recently, most research studies have concentrated on expanding the use of nanotechnology in food processing and agricultural production [7,8]. Nutraceutical distribution, packing, food processing, serviceability, and quality control are all areas of nanotechnology research that are experiencing an increase in intellectual property, patents and publications [9].

Nanotechnology is among the most promising alternatives for increasing food availability and developing new products related to water application, food, environment, agriculture, energy, electronics, and medicine. It is a rapidly growing field with novel food research and exclusive agricultural applications [10]. Growth enhancement and decreasing postharvest expenditures through improved outcomes and assistance by advanced scientific studies involving biotechnology and nanotechnology in foodstuffs may be the ideal solution [11]. In agriculture, nanomaterials are being used to discourage the dependency on pesticides in crop production, limit the loss of nutrients in fertilization and boost crop output via nutrient and pest control [12].

Smart nutrition delivery, chemical pollutants, bioseparation of proteins, quick monitoring of biological, nutraceutical nanoencapsulation, solubilization, and distribution are examples of new themes approached by nanotechnology and involved in food security that might be greatly improved [13,14]. The application of nanocarrier techniques to reinforce bioactive components in order to adjust their biological accessibility and resistance against a variety of environmental or chemical variations is referred to as food nanotechnology [15]. It improves food dependability by enhancing sensory features such as color, texture, and taste [16]. It may also increase the capture and biological administration of nutraceuticals and medicine systems [17]. Food companies benefit from nanotechnology as a unique food packaging supply with improved mechanical and antibacterial properties [18,19]. Other advantages of the nanotechniques include the development of nanosensors for trace elements detection, monitoring the state of foodstuffs during storage, transportation and encapsulation of food modifiers or additional components [20]. There is an increased need for nanoparticles in food biotechnology, food processing, functional food creation, food packaging, detection of pathogens in food, food safety and prolonged shelf-life of food driven by nanotechnology-based applications [21]. Nanomaterials are very good in the enhancement of food security and in promoting the growth of the food production industry. Depositing food processing equipment (through biofilm coating), membranes, sieves, nanofabricated filters, catalytic agents, nanosized adsorbents and nanocomposite-based are all research areas that could contribute to the development of food processing [22]. Using nanoparticles in food packaging is reported to reduce the amount of time it takes for items to be packed, as well as the use of valuable raw resources and waste generation [13].

Nanotechnology has a promising potential for developing improved and novel products. Many scientific groups, however, remain skeptical of the public health problems linked with products emanating from nanotechnology, which requires further research [23,24]. The purpose of this review is to discuss the essentials of nanotechnology, as well as its applications in food process technology, postharvest, and packaging. It also explores its role in enhancing food security, as well as the challenges associated with its use in the agricultural and food systems.

2. Approaches to Nanotechnology

Nanomaterials can be synthesized by either a "bottom-up" or a "top-down" approach. On a commercial scale, nanomaterials are mostly produced using the "top-down" strategy, in which bulk precursors are reduced to nano size using nanolithography, precision engineering or milling techniques [13]. The milling process is used to secure flour having small size particles and high water-holding capacity. By reducing the size of green tea, the top-down technique can improve its antioxidant capabilities [25]. A study revealed that green tea powder with a particle size of 1000 nm has a stronger capacity to digest nutrients, resulting in an increased ability of oxygen removal by the enzyme dismutase and, hence, increased antioxidant activity [26]. A similar top-down strategy is homogenization, which is often employed in the dairy industry for the size reduction of globules, laser applications and vaporization linked to chilling [27]. A surface area with superior qualities allows achieving food material with the functions desired for the needed purpose.

The top-down technique is related to nanotechnology-based devices, which are often controlled with external forces to produce the necessary parameters and particle initiation from greater levels with stuffing and fragmenting, to obtain the required size [28]. In the bottom-up approach, atoms are turned into materials of nanoscale dimensions, and this may involve some complicated processes. The matching of attracting and repulsive interactions among paired molecules employed as components for making effective supramolecular assemblies is essential for self-assembly [26]. Self-assembly or clustering of casein micelles, for example, results in the creation of carbohydrate-binding proteins. The arrangement of casein micelles, the structures generated in protein–polysaccharide liposomes, and their aggregates are examples of nanostructures that are self-assembled in food. According to research, the bottom-up strategy allows for the creation of nanostructures with fewer faults and a more uniform chemical arrangement [29].

3. Nanotechnology in Agriculture

Agriculture is important in food production through the cultivation of a variety of crops and the rearing of livestock. Most developing countries regard it as the backbone of their economies, and it plays a major role in their progress and development. As the global population expands, so does the need for more food, and food engineers and scientists are devising innovative ways to boost agricultural productivity [30]. Agricultural nanotechnology has spent the last several years focusing on applications and research to address environmental and agriculture challenges for crop enhancement and increased production. In relation to undernutrition and the need to reduce hunger and child mortality, agricultural nanotechnology appears to be quite promising in underdeveloped nations [31]. Germany, China, the USA, France, Brazil, Korea and India are among the developed and rising nations that have shown a great interest in employing nanomaterials for agricultural purposes, as evidenced by the increased number of related patents and publications [31].

Nanotechnology may be used to refurbish the agricultural sector as a prospective tool; it also helps in studying the biochemical routes of crops by changing conservative approaches for assessing environmental difficulties and its application towards improved production [32]. Nanotechnology, when compared to eco-friendly agricultural biotechnology, demonstrates the potential for a greater and faster influence on all elements of the agro-value chain, resulting in synchronized benefits to the public, moral, legal, and environmental repercussions [33]. The techniques employed for traditional agricultural have been transformed through the use of nanoscale agrochemicals such as nanopesticides, nanofertilizers, nanoformulations, and nanosensors in agriculture (Figure 1).

In agriculture, nanotechnology has a variety of uses, which include the treatment of wastewater, quality improvement of contaminated soil, and the increment of crop yield through the use of sensors to detect diseases [22,34]. Nanobiosensors, for instance, are examples of nanotools that support the highly technological development of agricultural farms, while also aligning with the usage of nanotools for farm management accuracy and the control of agricultural inputs [35]. Nanopores carrying zeolite for delayed discharge and better efficiency, nanosensors for the measurement of soil quality, and smooth herbicide delivery mechanisms are some of the beneficial impacts of nanotechnology use in agricultural development [36].

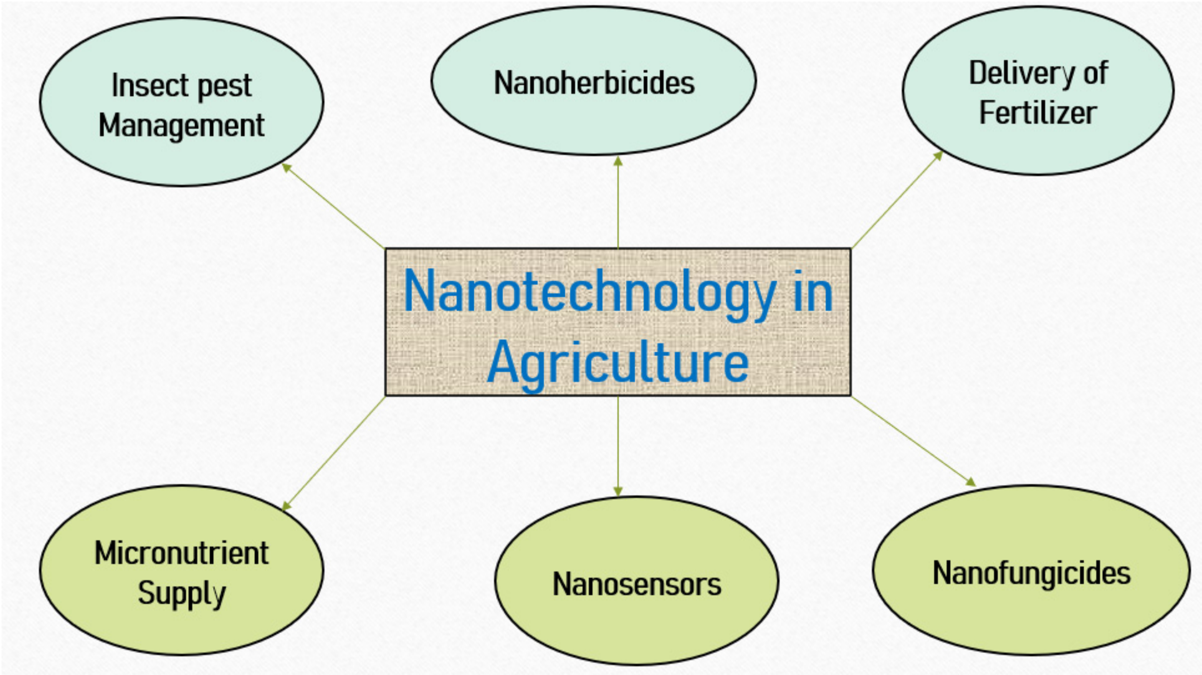

Figure 1. Schematic diagram of the potential applications of nanotechnology in agriculture.

Nano-forms of alumino-silicates, silver, silica, and carbon are examples of nanoparticles used for the monitoring of plant diseases. The application of nanomaterials in agricultural practice has been reported to decrease pesticide usage by ensuring a steady supply of energetic molecules. It enhances nutrient waste reduction during the application of fertilizer sand increases harvests by ensuring a better management of nutrients and water [31]. The responses of different cultivars of rice to engineered nanoparticles have also been studied at various stages of development and under various conditions [37].

Pests and diseases of plants have been reported to cause 20–40% of crop losses each year throughout the world [38]. Pest control in current farming techniques is mainly reliant on the use of pesticides such as herbicides, fungicides and insecticides. It is critical to produce cost-effective and very active insecticides that are eco-friendly. Pesticides may benefit from emerging concepts such as nanotechnology, which can reduce toxicity, improve shelf-life, and increase the solubility of poorly water-soluble pesticides, all of which might have a good impact on the environment [39]. Other studies also reported the importance of nanotechnology in agriculture, which majorly regards disease control and safety [31,33].

Pesticides and herbicides developed through nanotechnology help plants receive steady agricultural chemicals and supply nutrients in regulated proportion [40]. Nanoparticles may potentially be useful in the management of viruses, insects and pests that infect hosts [41]. For the manufacture of nano-insecticides, some polysaccharides such as polyesters, starch, chitosan, and alginates have been investigated [39]. In general, nanoparticles that can be used for plant protection may act in two ways: (a) they directly protect crops and (b) they act as carriers when commonly used pesticides are sprayed [42]. The application of nanoparticles in food production and plant protection, on the other hand, remains mostly unexplored [12].

4. Role of Nanotechnology in Postharvest Loss Reduction

More than 40% of food losses (cereals, fruit, pulses, oil crops, vegetables, fish, roots and tubers, dairy and meat) occur at the distribution and trade stages in developed countries, whereas more than 40% of losses recorded for foodstuffs occur at the processing and postharvest stages in developing countries [43]. Due to microbial attack, most of freshly harvested high-moisture crops are not well preserved, and may soon decay. Nanotechnology is a newer and more improved technology that can assist in reducing postharvest losses by creating an active packing element with a low amount of bioactive compounds, enhanced mechanical and gas capabilities, and a minimized influence on the quality of fruits and vegetables. [44].

Edible coatings are applied on food in the form of a liquid, usually by immersing the agricultural product in a material-providing solution created via a structural medium (protein, lipid, carbohydrate or a mixture). They prevent untreated foods from deteriorating by reducing respiration, preventing dehydration, preserving volatile fragrance molecules, inhibiting microbial development and refining textural qualities [45]. Nano-coatings with edible properties deposited on a variety of foods create a barrier to moisture and gas exchange, while also delivering enzymes, colors, antioxidants, browning-resistant chemicals, and tastes which may extend the shelf life of foods produced synthetically [45]. The method allows for the creation of nanoscale coatings with a thickness of up to 5 (5) nm [46]. Thin films and edible coatings are commonly used on horticulture products. Cost, functional characteristics, availability, mechanical properties (tension and elasticity), photosensitive properties (opacity and brilliance), the fence effect vs. gas flow, the structural barrier to the movement of water, sensory appropriateness, and microbes are all factors that influence their utilization [47].

To manage the postharvest activities of newly harvested items, numerous edible coatings that are within nanoscale dimensions are applied to food crops. Silver nanoparticles have lately generated a lot of interest because of their antibacterial qualities, which are important for the processing of food. The application of PVP-dependent Ag nanoparticles on asparagus significantly slowed down microbial growth and weight loss and reduce changes in the color of the skin [48]. A similar study found that edible gelatin-derived coverings containing nanocrystalline cellulose extended significantly the shelf-life of strawberries [49]. In comparison to other treatments, a chitosan supplement nano-silica coating increased the physiological and physicochemical value of longan fruit at room temperature by effectively generating an exceptional semi-permeable layer [50]. Furthermore, coatings with alginate or a lysozyme-based nanolaminate [51] and chitosan film-based nano-SiO_2 [52] were reported to preserve the value of fresh foods throughout a long storage. In addition, nano-ZnO coating prevented microbial decay and preserved the postharvest quality of selected fruits throughout storage [53].

5. Impact of Nanotechnology in Food Processing

The world's largest food industries are looking for new ways to improve food's value, safety and nutritional characteristics. To improve market price, production and quality in the food industry, newer technologies are necessary. Nanotechnology is useable in diverse ways in the food industry, including nanoencapsulation, nanoparticle-based food additives, nanosensors, nano-packing, and nanoparticle-based smart distribution systems [54]. Its uses include encapsulation, biopolymer matrix, emulsions, related colloids and simple solutions, all of which provide effective delivery methods. Nanotechnology is gaining attention in industrial food processing, notably for the encapsulation of flavors or the enhancement of odor, food texture modification or value increase, and as innovative viscosity- or gelatin-enhancing agents [55]. Food nanotechnology focuses on the creation of structures at the nanometer-scale having unique qualities that are often used for various applications, e.g., as delivery systems, food interaction surfaces with distinct superficial properties, food characterization tools, sensor technology, nanocomposite coatings and microfluidic instruments [10]. Figure 2 depicts the multiple applications of food technology.

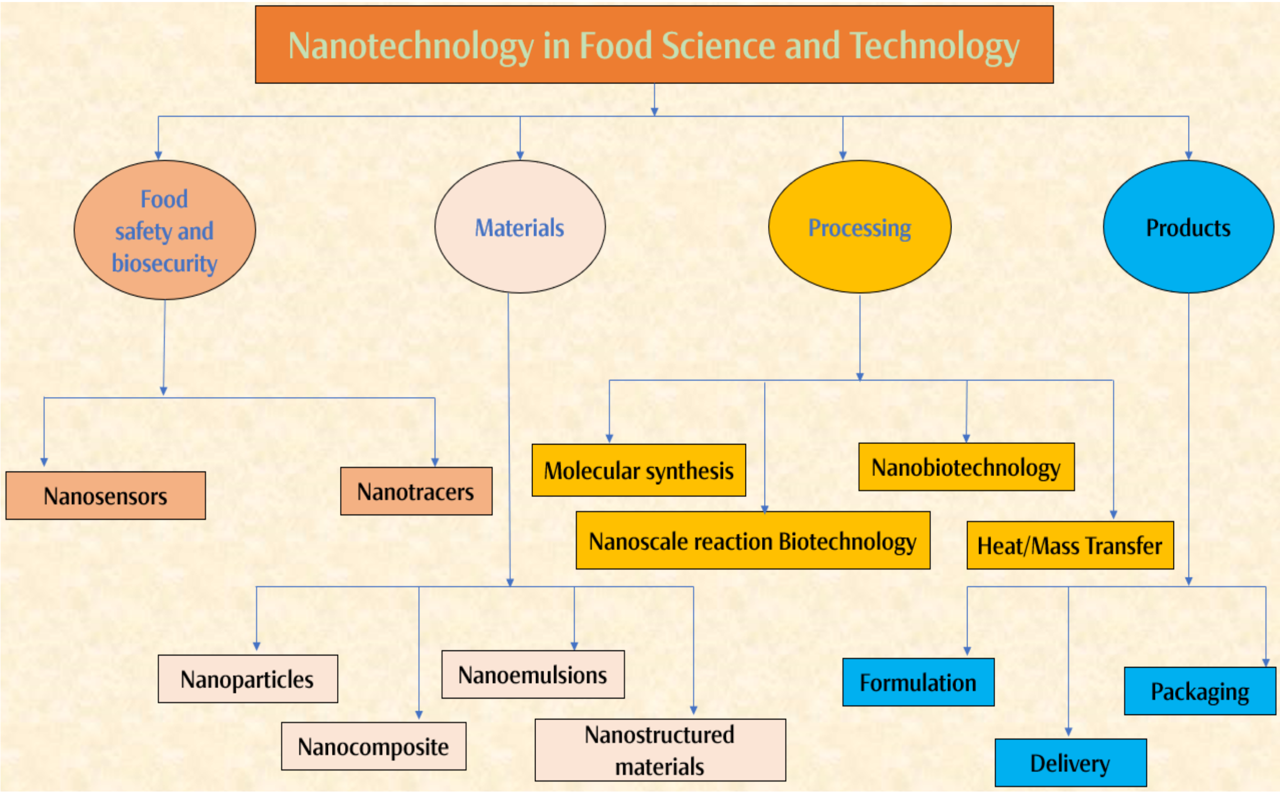

Figure 2. Application of nanotechnology in food science and technology.

At the nanoscale (water/oil system), nanoemulsions are formed by minute emulsion droplets with diameters of less than 100 nm [56]. The generation of scattered phases requires more mechanical energy, such as a high-pressure homogenizing step or the use of a sonication process or microfluidizer. The application of nanoemulsions brings about a reduction in the involvement of stabilizers by protecting the food from splitting and breaking, leading to a considerable reduction in the fat quantity required [9]. Numerous nanoemulsions often appear to be transparent optically and possess numerous technical advantages when the mixing of a liquid is involved [12]. Nanoemulsions' end products often appear creamy, just like other foodstuffs, with no alterations in flavor or taste [9]. They are used to improve drinks, oils taste, sweeteners, salad dressings and other processed foods. Nanomaterials are often involved in the processing of food as anti-caking agents, food additives, antimicrobial agents, transporters for nutrient delivery, filling factors for mechanical power increment and stability of packing material, as well as to improve the assessment of food security and safety through food nanosensing [57]. This is true for dietary additions as seen for nutraceuticals, which are produced with improved stability and bioavailability [55].

Nanoparticles are naturally present in a wide range of food items. Several meals include proteins that have globular structures with a size ranging from 10 to 100 nm, while others possess polymers that are linear, with a thickness of 1 nm, and mostly consist of lipids and carbohydrates. Casein, a nanoscale protein, is found in milk, while meat contains protein filaments that are classified as nanomaterials [12]. A number of food firms have been focusing on increasing food safety, production efficiency and nutritional characteristics in the beverage and food industry, which is a high-finance industry across the world [27]. Increased bioavailability and antibacterial capabilities, improved sensory qualities and guided distribution of substances with superior bioactivity are outstanding advantages of using nanoparticles in meatpacking and processing [58]. Nanotechnology is used to create motivating nano-protocols, fabricate ecologically friendly procedures and smart nano-packaging, manufacture goods with the best texture and flavor and produce lowcalorie drinks and food items to improve the health of humans [59]. It can use instruments such as atomic force microscopy (AFM) for faster diagnosis of component shortfalls and enhance the development of nanosensors that can be used to identify infections in food [54]. Atomic force microscopy is a powerful tool for studying food assemblages and chemical interactions that occur at the nanoscale level [59]. It is also a very useful tool for studying fine food assemblages and chemical interactions at the nanoscale level [45,59].

Food science, like other scientific fields, uses modern nanotechnologies to improve consumers' quality of life through updated food formulations and packaging, innovative ingredient synthesis and process monitoring to produce healthier, safer, precise food systems, with high quality and long shelf lives [27]. Food security, functionality, processing and economic issues regarding distribution and efficiency are developing key links between nanotechnologies and food systems [54]. Nanofiltration, modification and absorption of nanoencapsulation, nanoscale enzyme-based reactors, mass and heat transfer and nanofabrication are multipurpose uses of nanotechnology in food processing. In the pharmaceutical industry, nanofiltration is very effective in purifying medications and as a necessary step in removing certain solutes. It is equally employed for the treatment of water and dairy products in a bid to improve the quality of products by eliminating salt from lactose [9]. Nanofabrication through mass and heat transfer improves package heat resistance. Nanoscale enzyme reactors are used to change food systems so to improve flavor and nutritional value and provide a variety of health benefits. As a result of their assistance in scattering food due to large surface-to-volume relationships, nanomaterials result in greater enzyme-mediated systems (to enhance economy, activity and shelf life) in comparison with macroscale amended goods [60]. The action of lipase in nanotubes was reported to be 70% greater when compared with that of conventional lipases. For instance, nano-SiO_2 particles considerably hydrolyzed olive oil, leading to increased reusability, adaptability and stability at extreme temperatures (65 °C) [61].

To extend the shelf life of food items, nanoencapsulation is also very important. This technique is commonly used to improve flavor, preserve food and provide cooking balance. Nanoceramic derived from nanocapsules in a pot-like form may be used for absorption modification to reduce the time used for cooking and that spent on oil. It further reduces trans fatty acids by using plant oil instead of hydrogenated oil and, finally, leads to safer nanofood production through nanocapsules used for the distribution of nutrients in food for enhanced absorption. Nanoencapsulation can hide taste and odors, manage food interactions with effective ingredients, regulate the release of dynamic agents, ensure accessibility at a specific time intervals and protect them from biological, heat, moisture, or chemical interferences. Its action displays similarities with those of other ingredients present in the system [21,62]. Metallic oxides such as titanium dioxide (TiO_2) and silica (SiO_2) are often used in food preparation as coloring additives. Wasted food nanoparticles based on SiO_2 nanomaterials are used to transfer odors or fragrances to foodstuffs [63].

6. Impact of Nanotechnology on Food Packaging

One of the important roles of nanotechnology is the protection of food from physical injury and quality deterioration. Food packaging should be passive, safe, low-cost, readily reusable or disposable, stable in transportation and storage and resistant to physical abuse. The content and kind of packing materials have an impact on food quality. Packaging materials with lightweight, heat resistance and strength, among other qualities, could be obtained using nanomaterials. Food packaging obtained through nanotechnology has been widely reported [64,65]. The global nano-based packaging beverage and food industry was predicted to reach USD 4.13 billion in 2008, rising to USD 7.3 billion by 2014, with an 11.65% estimated annual growth rate [55].

Active packing applications are used on a variety of metal and metal oxide nanoparticles. In food packaging, TiO_2 and silver (Ag) are extremely valuable [66]. Metal and metal oxide nanoparticles, as well as nanocomposites for food packaging, are used as antimicrobials in active packaging [29]. Due to its semiconducting qualities and improved electrical, photosensitive and optical properties, TiO_2 is commonly used as a stain, catalytic substrate and adsorbent material [67]. Rice storage at 70% relative humidity and a temperature of 37 °C enhanced food characteristics by combining dispersed and antibacterial Ag/TiO_2 nanoparticles with polyethene used as a packing agent [68]. Antimicrobial potential, oxygen transfer, enzyme mobilization and information on the level of vulnerability to degradation-related factors are advantages linked to nanoparticles used in food packaging [69]. When compared to traditional packing materials, material for nano-packaging generated a superior sensory quality [70]. A nano-polymer including zinc oxide and polylactic acid nanoparticles was used to produce a highly functional material for food packaging [45]. A coating with zinc oxide-treated semolina protein was evaluated for the packaging of food and produces a significant reduction in oxygen absorption as well as increased resistance to heat [71].

In food packaging, nanoclay, hydrated alumina–silicate and silicates have been used as layers [62]. The blending of clay with silicate and polymers is a promising nanocomposite contender for food packaging with excellent qualities [70]. Organoclay nanoparticles employed as antibacterial material have also been studied for their usefulness in food packaging [72]. As a result of the large surface area of nanoparticles and their increased activity, cellulose is considered a supporting material in a variety of nanomaterials and is being used in a variety of applications [70]. As a natural polymer, it is extremely strong, ecofriendly, easily recyclable and affordable [73]. Food packaging using nano-composite films modified with nano-cellulose and nano-chitosan-added films has shown an improvement in clearance, elongation to breaking, food protection features and tensile strength [45]. In comparison to chitosan alone, nano-bio-composited films made with polylactides–chitosan were proven to be acceptable for food packaging, with significant and long-term antioxidant prospects [74]. Packaging and paper coatings made of nanocomposites of copper and cellulose have also been reported to have antimicrobial activities [75].

Due to their intrinsic antibacterial properties, nanometer-thick chitosan films have been widely used [76]. Ionic binding is used to make chitosan nanoparticles via the electrostatic interaction of the positive amino sides of chitosan with polyanions as cross-linkers [70]. A chitosan/gelatin-based nanocomposite containing Ag nanoparticles is utilized in the packaging of food and appears to be a very effective protective packaging material for prolonging the lifespan of red grapes up to 14 days [77]. Gold–chitosan and silver–chitosan nanocomposite coatings are used as effective antibacterial agents against Gram-negative bacteria (*P. aeruginosa*), yeast (*C. albicans*), Gram-positive bacteria (*S. aureus*), and fungi (*A. niger*) in food packaging [78].

7. Nanosensors in Food Security

Carbon nanotubes are hollow carbonaceous materials composed of atomic groups arranged in a hexagonal pattern [79]. Nanotubes are used in alumina, medical instruments, food processing equipment and sports equipment. This is due to their ability to tolerate high temperatures and to their flexible and sturdy nature [54]. Inorganics, bio-microtubules, carbon, viral proteins, porins, amyloid proteins, carbohydrates, synthetic polymers, lactalbumin, lipids, DNA28 and other organics are often used to create nanotubular textures [45].

Carbon nanotubes increase food packaging's mechanical qualities [80]. Some polymers have had their tensile strength increased by using polyamides and carbon nanotubes [81]. Because of their lower cost, easy methodology, and acute detection property, carbon nanotube-based biosensors have been used to detect microorganisms, hazardous substances and other metabolites in food and drinks [82]. Carbon nanotubes made of TiO_2 have been shown to have increased disinfecting ability against *B. cereus* spores [83]. TiO_2 nanoparticles doped with silver showed improved their bactericidal effects against *E. coli* [81].

Carbon nanotubes' potent antibacterial properties often lead to the mass destruction of pathogens [80]. Partial hydrolysis of α-lactalbumin (milk proteins) resulted in the formation of nanotubes [13]. According to several studies, α-lactalbumin nanotubes have improved viscosity and hardness and therefore can be used as a thickening agent [84]. According to this study, α-lactalbumin nanotubes can be used as gelation agents, regulating viscosity, encapsulating agents with steady taste and drug delivery agents in pharmaceuticals and foods [85]. Nanotubes have also been studied in contemporary agriculture. Various nanoparticles have been reported to infiltrate the cell walls of plants. Carbon nanotubes have been reported to infiltrate tomato seeds and alter their growth and sprouting [86]. This is because of the greater water intake promoted by carbon nanotubes, which improves the plant's performance. The cell wall was also penetrated by gold-derived mesoporous silica nanoparticles, which aided DNA penetration [87].

8. Nanosensors in Agriculture and Food

The utilization of biosensors in conjunction with better microfluidics technology, nanomaterials, and molecular biology has huge implications for crop yield. They may also be used to track microbes' activities in the soil and anticipate the occurrence of soil diseases. The primary premise behind using a biosensor to examine soil is to determine how the action of negative and positive bacteria in soil is influenced by variations in oxygen consumption during respiration. They also provide several alternatives for detecting pollutants and their obstructive effects by utilizing novel nanomaterial characteristics [30].

For azelaic acid and methyl salicylate, biosensors for detecting nitrate concentrations in plants alongside markers for the identification of infected plants have been reported [88]. Biosensors were used to monitor infections emanating from *P. digitatum* in citrus [89]. Nanosensors and smart delivery systems are used in precision farming to aid in the efficient use of natural agricultural resources such as water, chemicals and nutrients. Applications include geographic systems, remote detection and satellite monitoring tools that can aid the detection of pests' activities in crops or of signs of stress, such as drought [90]. The use of separate sensors linked to real-time GPS tracking is anticipated to be crucial in nanotechnology-assisted instruments [91]. Nanosensors may be strategically placed across a field to monitor crop development and soil factors.

Nanosensors are gaining global attention due to their increasingly important impact in the food sector due to their rapid response capabilities in detecting microorganisms, harmful compounds and gases in packaged foods. Nanobiosensors have been proven to detect infections in processing facilities, so to inform clients and suppliers about food safety [92]. They have also been used to check for impurities, mycotoxins, pollutants and microorganisms in foodstuffs [93]. There have been reports on allergens detected by using nanoparticles and biosensor tools, near commercialization [94]. These technologies can also help in the detection of temperature, expiration date and time history.

9. Challenges and Future Prospects of Nanotechnology in Food Security

Nanotechnology is widely used in agriculture, industry and food production, as previously stated. Nanomaterials are associated with a host of safety problems linked to the fact that they might penetrate cells and remain in the system due to their tiny sizes [70,95]. Increased application of nanotechnology in agricultural operations and production of food is of significant concern to a broad portion of the society due to several antagonistic effects of different nanoparticles [30]. Despite the protection properties and quality of bulk substances being obvious, nanoscale complements consistently show different features when compared to macroscale complements [69]. Nanotechnology poses a concern owing to the use of tiny nanoparticle with big surface areas that are readily dispersed, may penetrate the cells and reach far-flung places of the body, posing a risk of toxicity [9]. Nanomaterials have the potential to react with biological specimens due to their size resemblance to DNA [30].

Environmental conditions can result in the degradation of nanocomposites, leading to the release of incorporated nanoparticles from polymeric materials into the environment [73]. For example, the food packaging material low-density polyethylene loses strength after exposure to environmental factors such as ozone or UV light under humid circumstances [64]. Low-density polyethylene samples oxidized under UV radiation or ozone undergo significant thermal, physical and structural changes [64]. Nanofertilizers and pesticides are used in agriculture and often spread into the soil, water and environment, leading to serious health-endangering consequences for farmers [27]. The development and yield of the plants might be affected by the build-up of nanoparticles in the soil, which may later accumulate in human tissues when plants are consumed [95].

When nanoparticles are discharged into the agro-environment, they quickly undergo a series of changes. One of the main concerns regards the unpredicted effects of nanoparticles on the human body. Nanoparticles can produce oxidative damage and unwanted responses; wasted nanoparticles may be hazardous [64,96]. Nanotoxicity is primarily mediated by the massive creation of free radicals, which cause oxidative stress in the cells, rendering them incapable of performing normal redox-regulated biological functions [29]. In humans, the breakdown of nano-clay found in low-density polyethylene clumps can result in alveolar basal epithelial cell cancer [77]. The antibacterial mechanism of Ag has been the subject of several investigations. However, being a notable heavy metal, it may cause toxicity in the body by denaturing enzymes and proteins when present in large concentrations; its danger should be calculated [66]. Research on TiO_2 and Ag nanoparticles, as well as on carbon nanotubes, revealed that they could penetrate the bloodstream and accumulate in organs due to their insoluble nature [70]. When TiO_2 is consumed as a food additive, it can induce oxidative stress, which causes inflammation, and genotoxicity, which causes chromosomal instability [97].

Inhalation, cutaneous contact and ingestion are different ways through which nanoparticles enter the body. The use of a large number of nanoparticles in food packaging might be a source of worry, as their leakage could lead to contamination of the environment and food materials [64]. However, there is a shortage of data regarding nanoparticles' migration from packaging materials into food, as well as their long-term toxicological effects [29].

The selection of green nanofillers in studies involving nanocomposites is critical for animal, human and environmental safety. Furthermore, concentration, particle size, molecular weight, diffusivity and certain compounds' stability in polymer blends, pH value, temperature, viscosity and polymeric structure, contact duration, food composition and mechanical pressure are critical factors to be considered [45,70]. It is, therefore, important that studies should be channeled towards determining the precise number of nanoparticles discharged into the environment, their buildup in plants and their influence on human health [95].

Generally, for the safe application of nanoparticles in the food industry, comprehensive guidelines, rules and regulatory systems are essential. For instance, in the USA, the Food and Drug Administration (FDA) monitors food packaging and nanofoods, whereas, in Europe, the European Union regulates nanotechnology-based food additives [98]. However, most nations that produce nanomaterials lack adequate and specific nanotechnology regulations [45]. For a legal nanotechnological application, comprehensive government legislation and guidelines, as well as a thorough procedure for impact and toxicological screening are required [98].

10. Conclusions

Nanotechnology is a relatively young but rapidly developing technology that has applications in a wide range of areas including food, agriculture, medicine, various industries and human activities across the world. It is a remarkable phenomenon that nanostructures and nanoparticles improve different qualities of the systems in which they are used because of their high surface area, reduced size and impressive properties such as high catalytic nature. Nanotechnology plays a major role in improving food security, especially in agriculture. This technology has the potential of improving crop yield through the provision of an effective insect, pest, microbial and weed management that has high economic value, safety and security. It further helps in ensuring food safety, monitoring food processing, stability, food modification and shelf life, sensing, extension, and food loss reduction. With improved safety, packaging materials, and stability, nanotechnology also reduces postharvest losses. Metallic and metal oxide nanoparticles such as Au, Zn, Ag, TiO_2, MgO, ZnO and SiO_2, which are often employed in food processing, might cause health problems due to their ease of penetration into the cells, causing undesirable responses in many animals and human organs, as well as plant parts. Future studies should focus on reducing the hazards posed by nanocomposite and nanoparticles attacks by employing greener synthesis and looking for simple and less expensive techniques for removing and degrading existing nanomaterials from the sites where they were deposited.

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References

1. Elemike, E.E.; Uzoh, I.M.; Onwudiwe, D.C.; Babalola, O.O. The role of nanotechnology in the fortification of plant nutrients and improvement of crop production. *Appl. Sci.* **2019**, *9*, 499. [CrossRef]
2. Duro, J.A.; Lauk, C.; Kastner, T.; Erb, K.-H.; Haberl, H. Global inequalities in food consumption, cropland demand and land-use efficiency: A decomposition analysis. *Glob. Environ. Change* **2020**, *64*, 102124. [CrossRef]
3. Barrett, C.B. Overcoming global food security challenges through science and solidarity. *Am. J. Agric. Econ.* **2021**, *103*, 422–447. [CrossRef]
4. Ajilogba, C.F.; Babalola, O.O.; Nikoro, D.O. Nanotechnology as Vehicle for Biocontrol of Plant Diseases in Crop Production. In *Food Security and Safety: Africa's Perspective*; Babalola, O.O., Ed.; Springer: Cham, Switzerland, 2021; pp. 709–724. [CrossRef]
5. Fadiji, A.E.; Babalola, O.O. Elucidating mechanisms of endophytes used in plant protection and other bioactivities with multifunctional prospects. *Front. Bioeng. Biotechnol.* **2020**, *8*, 467. [CrossRef]
6. Ashraf, S.A.; Siddiqui, A.J.; Abd Elmoneim, O.E.; Khan, M.I.; Patel, M.; Alreshidi, M.; Moin, A.; Singh, R.; Snoussi, M.; Adnan, M. Innovations in nanoscience for the sustainable development of food and agriculture with implications on health and environment. *Sci. Total Environ.* **2021**, *768*, 144990. [CrossRef]
7. Peters, R.J.; Bouwmeester, H.; Gottardo, S.; Amenta, V.; Arena, M.; Brandhoff, P.; Marvin, H.J.; Mech, A.; Moniz, F.B.; Pesudo, L.Q. Nanomaterials for products and application in agriculture, feed and food. *Trends Food Sci. Technol.* **2016**, *54*, 155–164. [CrossRef]
8. Abobatta, W.F. Nanotechnology application in agriculture. *Acta Sci. Agric.* **2018**, *2*, 99–102.
9. Dasgupta, N.; Ranjan, S.; Mundekkad, D.; Ramalingam, C.; Shanker, R.; Kumar, A. Nanotechnology in agro-food: From field to plate. *Food Res. Int.* **2015**, *69*, 381–400. [CrossRef]
10. Sadeghi, R.; Rodriguez, R.J.; Yao, Y.; Kokini, J.L. Advances in nanotechnology as they pertain to food and agriculture: Benefits and risks. *Annu. Rev. Food Sci. Technol.* **2017**, *8*, 467–492. [CrossRef]
11. Yadollahi, A.; Arzani, K.; Khoshghalb, H. The role of nanotechnology in horticultural crops postharvest management. In Proceedings of the Southeast Asia Symposium on Quality and Safety of Fresh and Fresh-Cut Produce, Bangkok, Thailand, 3–5 August 2009; Volume 875, pp. 49–56.
12. Prasad, R.; Bhattacharyya, A.; Nguyen, Q.D. Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Front. Microbiol.* **2017**, *8*, 1014. [CrossRef]
13. Sozer, N.; Kokini, J.L. Nanotechnology and its applications in the food sector. *Trends Biotechnol.* **2009**, *27*, 82–89. [CrossRef] [PubMed]
14. Ravichandran, R. Nanotechnology applications in food and food processing: Innovative green approaches, opportunities and uncertainties for global market. *Int. J. Green Nanotechnol. Phys. Chem.* **2010**, *1*, P72–P96. [CrossRef]
15. Reza Mozafari, M.; Johnson, C.; Hatziantoniou, S.; Demetzos, C. Nanoliposomes and their applications in food nanotechnology. *J. Liposome Res.* **2008**, *18*, 309–327. [CrossRef]
16. Kalita, D.; Baruah, S. The impact of nanotechnology on food. In *Nanomaterials Applications for Environmental Matrices*; Ronaldo, F.N., Odair, P.F., Vicente, O.S.N., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 369–379.
17. Jafari, S.M.; McClements, D.J. Nanotechnology approaches for increasing nutrient bioavailability. *Adv. Food Nutr. Res.* **2017**, *81*, 1–30.
18. Rossi, M.; Passeri, D.; Sinibaldi, A.; Angjellari, M.; Tamburri, E.; Sorbo, A.; Carata, E.; Dini, L. Nanotechnology for food packaging and food quality assessment. *Adv. Food Nutr. Res.* **2017**, *82*, 149–204.

19. Mustafa, F.; Andreescu, S. Nanotechnology-based approaches for food sensing and packaging applications. *RSC Adv.* **2020**, *10*, 19309–19336. [CrossRef]
20. Chaudhry, Q.; Scotter, M.; Blackburn, J.; Ross, B.; Boxall, A.; Castle, L.; Aitken, R.; Watkins, R. Applications and implications of nanotechnologies for the food sector. *Food Addit. Contam.* **2008**, *25*, 241–258. [CrossRef]
21. Singh, T.; Shukla, S.; Kumar, P.; Wahla, V.; Bajpai, V.K.; Rather, I.A. Application of nanotechnology in food science: Perception and overview. *Front. Microbiol.* **2017**, *8*, 1501. [CrossRef]
22. Bartolucci, C. Nanotechnologies for agriculture and foods: Past and future. In *Nanotechnology in Agriculture and Food Science*; Axelos, M.A., Van De Voorde, M., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 2017; pp. 1–14.
23. Díaz-Soler, B.M.; Martínez-Aires, M.D.; López-Alonso, M. Potential risks posed by the use of nano-enabled construction products: A perspective from coordinators for safety and health matters. *J. Clean. Prod.* **2019**, *220*, 33–44. [CrossRef]
24. Kamarulzaman, N.A.; Lee, K.E.; Siow, K.S.; Mokhtar, M. Public benefit and risk perceptions of nanotechnology development: Psychological and sociological aspects. *Technol. Soc.* **2020**, *62*, 101329. [CrossRef]
25. Shibata, T. Method for Producing Green Tea in Microfine Powder. U.S. Patent 6,416,803, 9 July 2002.
26. Sanguansri, P.; Augustin, M.A. Nanoscale materials development—A food industry perspective. *Trends Food Sci. Technol.* **2006**, *17*, 547–556. [CrossRef]
27. Roohinejad, S.; Greiner, R. Nanoscience: Relevance for agriculture and the food sector. In *Nanotechnology in Agriculture and Food Science*; Axelos, M.A., Van De Voorde, M., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 2017; pp. 347–362.
28. Sangeetha, J.; Thangadurai, D.; Hospet, R.; Purushotham, P.; Karekalammanavar, G.; Mundaragi, A.C.; David, M.; Shinge, M.R.; Thimmappa, S.C.; Prasad, R. Agricultural Nanotechnology: Concepts, Benefits, and Risks. In *Nanotechnology*; Springer: Singapore, 2017; pp. 1–17.
29. Pathakoti, K.; Manubolu, M.; Hwang, H.-M. Nanostructures: Current uses and future applications in food science. *J. Food Drug Anal.* **2017**, *25*, 245–253. [CrossRef] [PubMed]
30. Baruah, S.; Dutta, J. Nanotechnology applications in pollution sensing and degradation in agriculture: A review. *Environ. Chem. Lett.* **2009**, *7*, 191–204. [CrossRef]
31. Gogos, A.; Knauer, K.; Bucheli, T.D. Nanomaterials in plant protection and fertilization: Current state, foreseen applications, and research priorities. *J. Agric. Food Chem.* **2012**, *60*, 9781–9792. [CrossRef]
32. Prasad, R.; Kumar, M.; Kumar, V. *Nanotechnology: An Agricultural Paradigm*; Springer Nature: Singapore, 2017; p. 371.
33. Sastry, K.; Rashmi, H.; Rao, N. Nanotechnology patents as R&D indicators for disease management strategies in agriculture. *J. Intellect. Prop. Rights* **2010**, *15*, 197–205.
34. Singh, H.; Sharma, A.; Bhardwaj, S.K.; Arya, S.K.; Bhardwaj, N.; Khatri, M. Recent advances in the applications of nano-agrochemicals for sustainable agricultural development. *Environ. Sci. Processes Impacts* **2021**, *23*, 213–239. [CrossRef] [PubMed]
35. Sivarethinamohan, R.; Sujatha, S. Unlocking the potentials of using nanotechnology to stabilize agriculture and food production. *AIP Conf. Proc.* **2021**, *2327*, 20022.
36. Chinnamuthu, C.; Boopathi, P.M. Nanotechnology and agroecosystem. *Madras Agric. J.* **2009**, *96*, 17–31.
37. Wang, Y.; Deng, C.; Rawat, S.; Cota-Ruiz, K.; Medina-Velo, I.; Gardea-Torresdey, J.L. Evaluation of the effects of nanomaterials on rice (*Oryza sativa* L.) responses: Underlining the benefits of nanotechnology for agricultural applications. *ACS Agric. Sci. Technol.* **2021**, *1*, 44–54. [CrossRef]
38. Flood, J. The importance of plant health to food security. *Food Secur.* **2010**, *2*, 215–231. [CrossRef]
39. Mali, S.C.; Raj, S.; Trivedi, R. Nanotechnology a novel approach to enhance crop productivity. *Biochem. Biophys. Rep.* **2020**, *24*, 100821.
40. Duhan, J.S.; Kumar, R.; Kumar, N.; Kaur, P.; Nehra, K.; Duhan, S. Nanotechnology: The new perspective in precision agriculture. *Biotechnol. Rep.* **2017**, *15*, 11–23. [CrossRef] [PubMed]
41. Khot, L.R.; Sankaran, S.; Maja, J.M.; Ehsani, R.; Schuster, E.W. Applications of nanomaterials in agricultural production and crop protection: A review. *Crop Prot.* **2012**, *35*, 64–70. [CrossRef]
42. Worrall, E.A.; Hamid, A.; Mody, K.T.; Mitter, N.; Pappu, H.R. Nanotechnology for plant disease management. *Agronomy* **2018**, *8*, 285. [CrossRef]
43. FAO. *The State of Food and Agriculture. Moving Forward on Food Loss and Waste Reduction*; FAO: Rome, Italy, 2019.
44. Flores-López, M.L.; Cerqueira, M.A.; de Rodríguez, D.J.; Vicente, A.A. Perspectives on utilization of edible coatings and nano-laminate coatings for extension of postharvest storage of fruits and vegetables. *Food Eng. Rev.* **2016**, *8*, 292–305. [CrossRef]
45. Neme, K.; Nafady, A.; Uddin, S.; Tola, Y.B. Application of nanotechnology in agriculture, postharvest loss reduction and food processing: Food security implication and challenges. *Heliyon* **2021**, *7*, e08539. [CrossRef]
46. Sekhon, B. Food nanotechnology—An overview. *Nanotechnol. Sci. Appl.* **2010**, *3*, 1–15.
47. Falguera, V.; Quintero, J.P.; Jiménez, A.; Muñoz, J.A.; Ibarz, A. Edible films and coatings: Structures, active functions and trends in their use. *Trends Food Sci. Technol.* **2011**, *22*, 292–303. [CrossRef]
48. An, J.; Zhang, M.; Wang, S.; Tang, J. Physical, chemical and microbiological changes in stored green asparagus spears as affected by coating of silver nanoparticles-PVP. *LWT-Food Sci. Technol. Soc.* **2008**, *41*, 1100–1107. [CrossRef]
49. Fakhouri, F.; Casari, A.; Mariano, M.; Yamashita, F.; Mei, L.I.; Soldi, V.; Martelli, S. Effect of a gelatin-based edible coating containing cellulose nanocrystals (CNC) on the quality and nutrient retention of fresh strawberries during storage. *IOP Conf. Ser. Mater. Sci. Eng.* **2014**, *64*, 012024. [CrossRef]

50. Shi, S.; Wang, W.; Liu, L.; Wu, S.; Wei, Y.; Li, W. Effect of chitosan/nano-silica coating on the physicochemical characteristics of longan fruit under ambient temperature. *J. Food Eng.* **2013**, *118*, 125–131. [CrossRef]
51. Medeiros, B.G.; Souza, M.P.; Pinheiro, A.C.; Bourbon, A.I.; Cerqueira, M.A.; Vicente, A.A.; Carneiro-da-Cunha, M.G. Physical characterisation of an alginate/lysozyme nano-laminate coating and its evaluation on 'Coalho'cheese shelf life. *Food Bioprocess Technol.* **2014**, *7*, 1088–1098. [CrossRef]
52. Yu, Y.; Zhang, S.; Ren, Y.; Li, H.; Zhang, X.; Di, J. Jujube preservation using chitosan film with nano-silicon dioxide. *J. Food Eng.* **2012**, *113*, 408–414. [CrossRef]
53. Sogvar, O.B.; Saba, M.K.; Emamifar, A.; Hallaj, R. Influence of nano-ZnO on microbial growth, bioactive content and postharvest quality of strawberries during storage. *Innov. Food Sci. Emerg. Technol.* **2016**, *35*, 168–176. [CrossRef]
54. Rashidi, L.; Khosravi-Darani, K. The applications of nanotechnology in food industry. *Crit. Rev. Food Sci. Nutr.* **2011**, *51*, 723–730. [CrossRef]
55. Duncan, T.V. Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. *J. Colloid Interface Sci.* **2011**, *363*, 1–24. [CrossRef]
56. Anton, N.; Vandamme, T.F. Nano-emulsions and micro-emulsions: Clarifications of the critical differences. *Pharm. Res.* **2011**, *28*, 978–985. [CrossRef]
57. Ezhilarasi, P.; Karthik, P.; Chhanwal, N.; Anandharamakrishnan, C. Nanoencapsulation techniques for food bioactive components: A review. *Food Bioprocess Technol.* **2013**, *6*, 628–647. [CrossRef]
58. Ramachandraiah, K.; Han, S.G.; Chin, K.B. Nanotechnology in meat processing and packaging: Potential applications—A review. *Asian-Australas. J. Anim. Sci.* **2015**, *28*, 290. [CrossRef]
59. Katouzian, I.; Jafari, S.M. Nano-encapsulation as a promising approach for targeted delivery and controlled release of vitamins. *Trends Food Sci. Technol.* **2016**, *53*, 34–48. [CrossRef]
60. Yu, L.; Banerjee, I.A.; Gao, X.; Nuraje, N.; Matsui, H. Fabrication and application of enzyme-incorporated peptide nanotubes. *Bioconjugate Chem.* **2005**, *16*, 1484–1487. [CrossRef] [PubMed]
61. Bai, Y.-X.; Li, Y.-F.; Yang, Y.; Yi, L.-X. Covalent immobilization of triacylglycerol lipase onto functionalized nanoscale SiO_2 spheres. *Process Biochem.* **2006**, *41*, 770–777. [CrossRef]
62. Weiss, J.; Takhistov, P.; McClements, D.J. Functional materials in food nanotechnology. *J. Food Sci.* **2006**, *71*, R107–R116. [CrossRef]
63. Dekkers, S.; Krystek, P.; Peters, R.J.; Lankveld, D.P.; Bokkers, B.G.; van Hoeven-Arentzen, P.H.; Bouwmeester, H.; Oomen, A.G. Presence and risks of nanosilica in food products. *Nanotoxicology* **2011**, *5*, 393–405. [CrossRef]
64. Han, C.; Zhao, A.; Varughese, E.; Sahle-Demessie, E.J.N. Evaluating weathering of food packaging polyethylene-nano-clay composites: Release of nanoparticles and their impacts. *NanoImpact* **2018**, *9*, 61–71. [CrossRef] [PubMed]
65. Noorbakhsh-Soltani, S.; Zerafat, M.; Sabbaghi, S. A comparative study of gelatin and starch-based nano-composite films modified by nano-cellulose and chitosan for food packaging applications. *Carbohydr. Polym.* **2018**, *189*, 48–55. [CrossRef]
66. Li, L.; Zhao, C.; Zhang, Y.; Yao, J.; Yang, W.; Hu, Q.; Wang, C.; Cao, C. Effect of stable antimicrobial nano-silver packaging on inhibiting mildew and in storage of rice. *Food Chem.* **2017**, *215*, 477–482. [CrossRef]
67. Prakash, J.; Sun, S.; Swart, H.C.; Gupta, R.K. Noble metals-TiO2 nanocomposites: From fundamental mechanisms to photocatalysis, surface enhanced Raman scattering and antibacterial applications. *Appl. Mater. Today* **2018**, *11*, 82–135. [CrossRef]
68. Zhao, L.; Li, F.; Chen, G.; Fang, Y.; An, X.; Zheng, Y.; Xin, Z.; Zhang, M.; Yang, Y.; Hu, Q. Effect of nanocomposite-based packaging on preservation quality of green tea. *Int. J. Food Sci. Technol.* **2012**, *47*, 572–578. [CrossRef]
69. De Azeredo, H.M. Nanocomposites for food packaging applications. *Food Res. Int.* **2009**, *42*, 1240–1253. [CrossRef]
70. Sharma, C.; Dhiman, R.; Rokana, N.; Panwar, H. Nanotechnology: An untapped resource for food packaging. *Front. Microbiol.* **2017**, *8*, 1735. [CrossRef] [PubMed]
71. Jafarzadeh, S.; Alias, A.; Ariffin, F.; Mahmud, S. Characterization of semolina protein film with incorporated zinc oxide nano rod intended for food packaging. *Pol. J. Food Nutr. Sci.* **2017**, *67*, 183–190. [CrossRef]
72. Fasihnia, S.H.; Peighambardoust, S.H.; Peighambardoust, S.J. Nanocomposite films containing organoclay nanoparticles as an antimicrobial (active) packaging for potential food application. *J. Food Processing Preserv.* **2018**, *42*, e13488. [CrossRef]
73. Moustafa, H.; Youssef, A.M.; Darwish, N.A.; Abou-Kandil, A.I. Eco-friendly polymer composites for green packaging: Future vision and challenges. *Compos. Part B Eng.* **2019**, *172*, 16–25. [CrossRef]
74. Basu, A.; Kundu, S.; Sana, S.; Halder, A.; Abdullah, M.F.; Datta, S.; Mukherjee, A. Edible nano-bio-composite film cargo device for food packaging applications. *Food Packag. Shelf Life* **2017**, *11*, 98–105. [CrossRef]
75. Pinto, R.J.; Daina, S.; Sadocco, P.; Neto, C.P.; Trindade, T. Antibacterial activity of nanocomposites of copper and cellulose. *BioMed Res. Int.* **2013**, *2013*, 280512. [CrossRef]
76. Rieger, K.A.; Eagan, N.M.; Schiffman, J.D. Encapsulation of cinnamaldehyde into nanostructured chitosan films. *J. Appl. Polym. Sci.* **2015**, *132*, 41739. [CrossRef]
77. Kumar, S.; Shukla, A.; Baul, P.P.; Mitra, A.; Halder, D. Biodegradable hybrid nanocomposites of chitosan/gelatin and silver nanoparticles for active food packaging applications. *Food Packag. Shelf Life* **2018**, *16*, 178–184. [CrossRef]
78. Youssef, A.M.; Abdel-Aziz, M.S.; El-Sayed, S.M. Chitosan nanocomposite films based on Ag-NP and Au-NP biosynthesis by Bacillus subtilis as packaging materials. *Int. J. Biol. Macromol.* **2014**, *69*, 185–191. [CrossRef]
79. Scott, N. Nanotechnology and animal health. *Rev. Sci. Et Tech.* **2005**, *24*, 425. [CrossRef]

80. Abdelmonem, A.M. Application of carbon-based nanomaterials in food preservation area. In *Carbon Nanomaterials for Agri-Food and EnvironmentalApplications*; Abd-Elsalam, K.A., Ed.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 583–593.
81. Kim, J.Y.; Han, S.I.; Hong, S. Effect of modified carbon nanotube on the properties of aromatic polyester nanocomposites. *Polymer* **2008**, *49*, 3335–3345. [CrossRef]
82. Singh, T.; Jyoti, K.; Patnaik, A.; Singh, A.; Chauhan, R.; Chandel, S. Biosynthesis, characterization and antibacterial activity of silver nanoparticles using an endophytic fungal supernatant of *Raphanus sativus*. *J. Genet. Eng.* **2017**, *15*, 31–39. [CrossRef] [PubMed]
83. Krishna, V.; Pumprueg, S.; Lee, S.-H.; Zhao, J.; Sigmund, W.; Koopman, B.; Moudgil, B. Photocatalytic disinfection with titanium dioxide coated multi-wall carbon nanotubes. *Process Saf. Environ. Prot.* **2005**, *83*, 393–397. [CrossRef]
84. Graveland-Bikker, J.; De Kruif, C. Unique milk protein based nanotubes: Food and nanotechnology meet. *Trends Food Sci. Technol.* **2006**, *17*, 196–203. [CrossRef]
85. Ipsen, R.; Otte, J. Self-assembly of partially hydrolysed α-lactalbumin. *Biotechnol. Adv.* **2007**, *25*, 602–605. [CrossRef]
86. Khodakovskaya, M.; Dervishi, E.; Mahmood, M.; Xu, Y.; Li, Z.; Watanabe, F.; Biris, A.S. Carbon nanotubes are able to penetrate plant seed coat and dramatically affect seed germination and plant growth. *ACS Nano* **2009**, *3*, 3221–3227. [CrossRef]
87. Torney, F.; Trewyn, B.G.; Lin, V.S.-Y.; Wang, K. Mesoporous silica nanoparticles deliver DNA and chemicals into plants. *Nat. Nanotechnol.* **2007**, *2*, 295–300. [CrossRef] [PubMed]
88. Griesche, C.; Baeumner, A.J. Biosensors to support sustainable agriculture and food safety. *Trends Anal. Chem.* **2020**, *128*, 115906. [CrossRef]
89. Chalupowicz, D.; Veltman, B.; Droby, S.; Eltzov, E. Evaluating the use of biosensors for monitoring of *Penicillium digitatum* infection in citrus fruit. *Sens. Actuators B Chem.* **2020**, *311*, 127896. [CrossRef]
90. Sekhon, B.S. Nanotechnology in agri-food production: An overview. *Nanotechnol. Sci. Appl.* **2014**, *7*, 31. [CrossRef]
91. Davari, M.; Bayat Kazazi, S.; Akbarzadeh Pivehzhani, O. Nanomaterials: Implications on agroecosystem. Nanotechnology. In *Nanotechnology*; Prasad, R., Kumar, M., Kumar, V., Eds.; Springer: Singapore, 2017; pp. 59–71.
92. Cheng, M.M.-C.; Cuda, G.; Bunimovich, Y.L.; Gaspari, M.; Heath, J.R.; Hill, H.D.; Mirkin, C.A.; Nijdam, A.J.; Terracciano, R.; Thundat, T. Nanotechnologies for biomolecular detection and medical diagnostics. *Curr. Opin. Chem. Biol.* **2006**, *10*, 11–19. [CrossRef] [PubMed]
93. Bratovčić, A.; Odobašić, A.; Ćatić, S.; Šestan, I. Application of polymer nanocomposite materials in food packaging. *Croat. J. Food Sci. Technol.* **2015**, *7*, 86–94. [CrossRef]
94. Warriner, K.; Reddy, S.M.; Namvar, A.; Neethirajan, S. Developments in nanoparticles for use in biosensors to assess food safety and quality. *Trends Food Sci. Technol.* **2014**, *40*, 183–199. [CrossRef]
95. Rajput, V.; Minkina, T.; Mazarji, M.; Shende, S.; Sushkova, S.; Mandzhieva, S.; Burachevskaya, M.; Chaplygin, V.; Singh, A.; Jatav, H. Accumulation of nanoparticles in the soil-plant systems and their effects on human health. *Ann. Agric. Sci.* **2020**, *65*, 137–143. [CrossRef]
96. Narei, H.; Ghasempour, R.; Akhavan, O. Toxicity and safety issues of carbon nanotubes. In *Carbon Nanotube-Reinforced Polymers: From Nanoscale to Macroscale*; Rafiee, R., Ed.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 145–171.
97. Oleszczuk, B.-W.E.S.D. Effects of titanium dioxide nanoparticles exposure on human health—A review. *Biol. Trace Elem. Res.* **2020**, *193*, 118–129.
98. Nile, S.H.; Baskar, V.; Selvaraj, D.; Nile, A.; Xiao, J.; Kai, G. Nanotechnologies in food science: Applications, recent trends, and future perspectives. *Nano-Micro Lett.* **2020**, *12*, 1–34. [CrossRef]