Hindawi
Journal of Nanomaterials
Volume 2022, Article ID 1280411, 17 pages
https://doi.org/10.1155/2022/1280411

Review Article

Evolution and Recent Scenario of Nanotechnology in Agriculture and Food Industries

M. D. Vijayakumar,[1] **G. J. Surendhar**,[1] **L. Natrayan**,[2] **Pravin P. Patil**,[3] **P. M. Bupathi Ram**,[1] **and Prabhu Paramasivam**[4]

[1]*Centre for Additive Manufacturing, Chennai Institute of Technology, Chennai 600069, India*
[2]*Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai, Tamil Nadu 602105, India*
[3]*Department of Mechanical Engineering, Graphic Era Deemed to be University, Bell Road, Clement Town, 248002 Dehradun, Uttarakhand, India*
[4]*Department of Mechanical Engineering, College of Engineering and Technology, Mettu University, Ethiopia 318*

Correspondence should be addressed to M. D. Vijayakumar; vijayakumarmd@citchennai.net, L. Natrayan; natrayanl.sse@saveetha.com, and Prabhu Paramasivam; prabhuparamasivam21@gmail.com

Received 1 March 2022; Revised 12 April 2022; Accepted 29 June 2022; Published 11 July 2022

Academic Editor: Lakshmipathy R

Nanotechnology is an emerging technology in the field of food and agriculture; every individual molecule and atom can be modified or controlled by this technology. Everything that exists on the earth is made up of atoms and molecules. Problems in all the fields can easily be overcome by modifying or altering their nanosize. Similarly, nanotechnology could address many issues in the agriculture and food industries. Nanomaterials play a keen role in the place of pesticides, fertilizers, and biosensors. Nutrition enhancement, safe delivery of bioactive components and micronutrients, and food preservations were facilitated by the applications of nanotechnologies. Efforts have to be taken to create awareness among the public in this nanotechnology field. Future research directions were identified in this review to improve the nanoembedded agriculture system. This article reviews the recent development in the agriculture and food industries through nanotechnology, application of nanotechnology in the food and agricultural sectors, and research backlogs in such sectors.

1. Introduction

The population of the world is increasing rapidly. It is expected to reach nearly six billion by the end of 2050 [1]. The productivity of the crops is getting decreased because of specific biotic and abiotic stresses, climatic changes, and water unavailability [2]. They are a roadblock to the development of the agricultural field [3]. For overcoming all such barriers, there is a need for an innovative technology called nanotechnology [4]. Nano is a Greek word that means billionth of something. One billionth of a meter is termed as one nanometer. Nanotechnology is a science that deals with the alteration and generation of materials in the size of one to a hundred nanometers [5]. Nanotechnology can revolutionize the food system and the field of agriculture. The properties of the nanoparticles show better results than the bulk particles like increment in the surface area and physical strength [6]. For instance, zinc nanoparticles are transparent, but their bulk particles are white and opaque [7]. The surface area difference between the nanoparticle and standard particle is shown in Figure 1.

Nanomaterials can be prepared in two methods: the top-down and bottom-up approaches [8]. Various physical and chemical treatments like sonication, milling, and high-pressure homogenization were involved in the top-down approach to nanoparticles [9]. In the bottom-up approach, the building blocks of the nanoparticles are formed first and assembled for producing the final particles [10–13]. Nanomaterials are classified into two, namely, organic nanomaterials and inorganic nanomaterials. Examples of organic

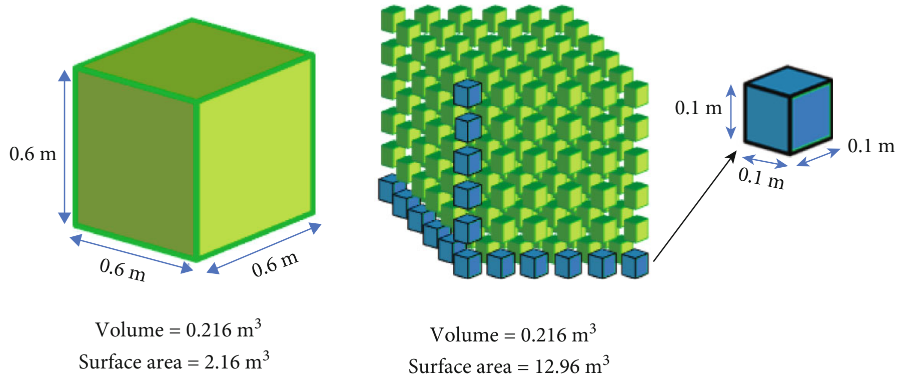

FIGURE 1: Difference in the surface area of bulk and nanoparticles.

and inorganic nanomaterials are carbon nanotubes (CNT) and titanium oxide (TiO_2), respectively [14–16]. Nanotechnology is applied in the agricultural field using nanofertilizers, nanopesticides, and nanobiosensors. Using nanotechnology in agriculture increases the yield and production rate, resources will be efficiently utilized, and waste products will be reduced [17–20]. Nanomaterials can be applied to the agricultural field in three ways, which are pictorially represented in Figure 2.

Nanotechnologies applied in the food sector are increasing with an astonishing number of patents and publications in packaging, quality control, nutraceutical delivery, and the new developments in nanotechnology [21]. Nanotechnology is considered a critical enabling technology for Europe, among other technologies [22]. Investments were increased over the past years in nanotechnology [23]. It is predicted that the nanotechnology incorporated products will contribute nearly one trillion dollars to the global economy [24]. Most importantly, two million people may be employed in such nanotech industries [25]. Nanotechnologies could be applied in the whole process involved in product development. It includes the usage of nanofertilizers, nanosensors for assuring safety and quality, and even nanopackaging [26]. The method, size, and physical properties of various nanomaterials are tabulated in Table 1.

This research mainly focuses on applying nanotechnology and nanomaterials in the agriculture and food industries. This review was conceived to provide the applications, futuristic analysis, challenges, and requirements in the nanotechnology field to uplift agriculture and the food industry. This review offers the current applications of nanomaterials in the food packaging sectors and agricultural sectors. And this review will be a unique reference for the researchers working in different domains in the food and agriculture field.

2. Agricultural Applications of Nanomaterials

Nowadays, nanomaterials have been applied in many fields. The application of nanomaterials in agriculture also helps the farmer by improving the health of the soil, enhancing the production of crops, reducing the needed amount of water, etc. The primary concerns for the production of crops are pesticides and fertilizers [35]. Hence, the developments of nanopesticides and nanofertilizers are illustrated in this review [36]. The possible applications of nanotechnologies in agriculture are pictorially represented in Figure 3.

The impact and possible interactions of nanomaterials and variation of physicochemical properties of soil are tabulated in Table 2.

2.1. Nanofertilizers. In recent decades, the increment in the production of crops has been tremendous. They are pinpointing that the growth of cereals showcased a significant part in the nutritional need of the world. The increased use of chemical fertilizers majorly boosts the yields of the crops. The usage of chemical fertilizers is increased by the varieties of fertilizer responsive crops [47–49]. However, due to the poor efficiency of the chemical fertilizer, its usage is reduced. The cost of crop production increases due to the leaching and volatilization of chemical fertilizers that are contaminated [50]. DeRosa et al. depict that 50 to 70% of the nitrogen is being lost to the surrounding by the chemical fertilizers [51]. Therefore, the research community is concentrating on the development of different generalship. Nanotechnologies have to be implemented in such cases to develop the slow-release fertilizers, reduce the loss of the mobile nutrients, and improve the accessibility of the poorly available nutrients. The surface area of the nanoparticles plays a crucial role in attaining all such advantages [52–54]. Nanofertilizers are of two types: nutrients themselves and the other is added with other nutrients. Nanofertilizer's application on the plants is shown in Figure 4.

Nanofertilizer contributes a crucial part to agricultural sustainability by improving the productivity of the crops and improving the quality with great nutrients, and most importantly, nanofertilizers reduce the production cost of the crops [56]. Singh reviewed the emerging ways which increases the efficiency of the crop production. It is concluded that the production of the crops was improved while applying different nanofertilizers in it. Such nanofertilizers will reduce the production cost and it also minimizes the hazards in the population. It is mentioned that the growth of the crops will be improved in terms of optimum usage of nanofertilizers. If the concentration and the doses of the nanofertilizers exceeds the optimum usage, the crop

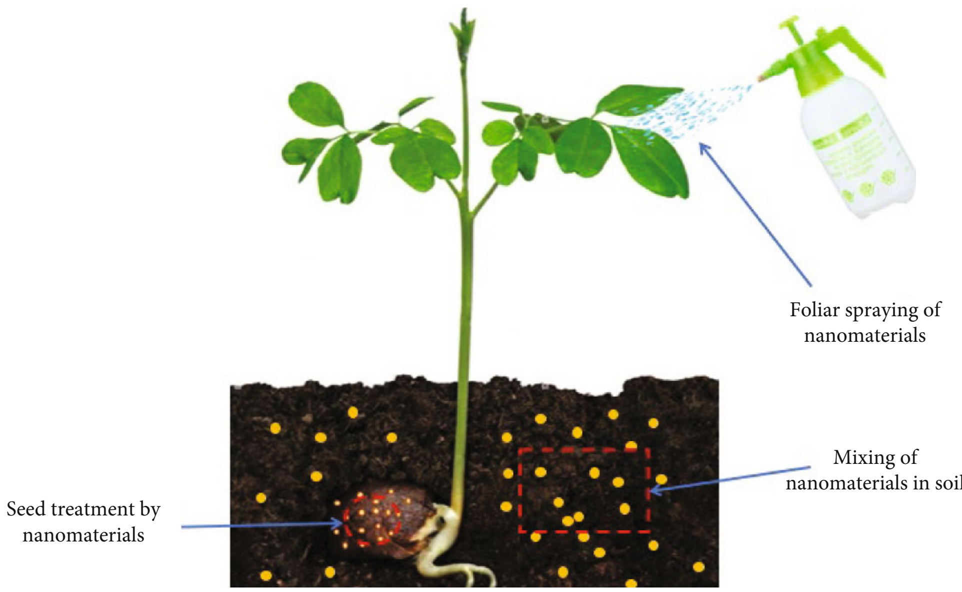

Figure 2: Methods for applying nanomaterials in the agricultural field.

Table 1: Types, size, and characteristics of specific nanomaterials.

Sl. no.	Type	Method	Size	Characteristics	Ref
1	Carbon-based nanocarriers	Laser ablation, chemical vapor deposition, and arc discharge	0.5–3 nm	Hexagonal and pentagonal geometric cage-like structures of carbon faces are found in fullerenes	[27, 28]
2	Polymeric nanoparticles	Solvent evaporation, dialysis, interfacial polymerization, mini emulsion, and surfactant-free emulsion	20–1,000 nm	Provide complete drug protection, biocompatible, and biodegradable	[28, 29, 30]
3	Silver nanoparticles	Gamma irradiation, electron irradiation, microwave processing, and synthetic biological methods	1–100 nm	Electrical, antimicrobial, and optical properties depend upon shape and size	[31, 32]
4	Liposomes	Reversed-phase evaporation, high-pressure homogenization, depletion of mixed detergent lipid micelles, heat treatment	50–100 nm	Liquid state at room temperature	[28, 33]
5	Iron oxide nanoparticles	Hydrothermal, thermal decomposition, protein-mediated, laser-induced pyrolysis	5–50 nm	Extremely reactive with oxidizing agents, higher surface area, surface-to-volume ratio, and easy separation methodology	[31, 34]

production will be reduced [57]. Kah et al. proved that the gain in the median efficacy is increased by 18-29% while using nanofertilizers over conventional fertilizers [58]. Liu and Lal showed that the growth rate was increased by 32% when the phosphatic nanofertilizers were used over the traditional fertilizers. Nanofertilizers help intake nutrients through nanocuticle pores and improve the metabolism of plants [59]. Nitrogenous fertilizer, conventionally used, has only 30-60% efficiency in fertilizer use. Due to the chemical bonding in the soil, 8-90% of the phosphatic fertilizers are lost [60]. When the fertilizers are used as a nanocomposite of hydroxyapatite and urea, it is observed that the nitrogen release is controlled, volatilization of ammonia is limited, and the phosphorus is sustainably available even after the four weeks of incubation. Most fertilizers are lost to the environment by leaching and volatilization in conventional fertilizer [61]. But, in nanofertilizers, their quantity is reduced by using slow-release products. It can release the nutrients to the plants when and where the nutrient is required [62]. This feature limits the unwanted volatilization of fertilizers to the environment. Such intelligent fertilizers are possible by explaining the signal transmission of soil microbes and plant roots [63]. Syu et al. reported that the internal root signals are modified by applying nanoparticles. It will affect the production of ethylene by Arabidopsis roots [64]. Controlled release of nanofertilizers would be a significant

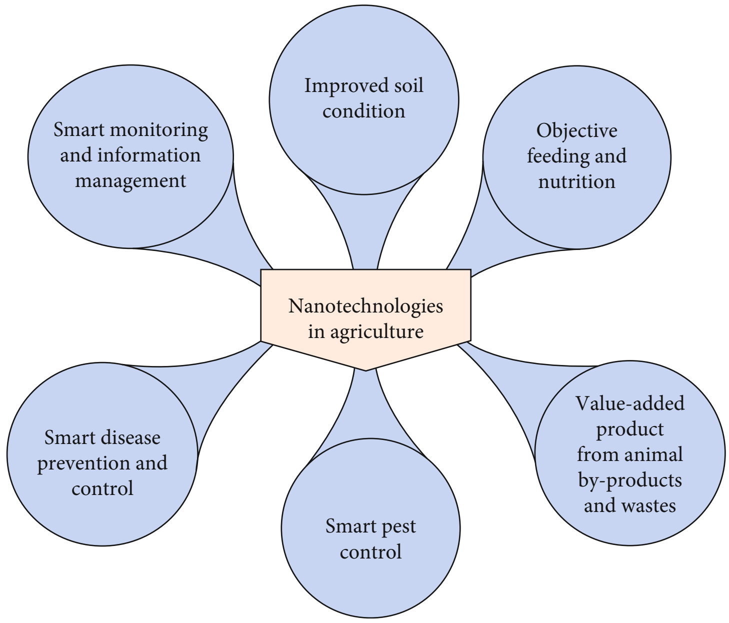

Figure 3: Applications of nanotechnologies in agriculture.

Table 2: Physicochemical properties of nanomaterials and their impact.

Sl. no.	Soil parameters	Nanomaterial	Findings	Ref
	pH			
1	Alkaline	TiO_2	Soil microbial community is reduced significantly	[37, 38]
2	Acidic	AgNPs, ZnO	Toxicity is enhanced toward Eisenia fetida adverse effect on respiration, dehydrogenase, and ammonification activity of soil microbes	[39, 40]
	Organic matter			
3	Low	CuO, Fe3O4	Enhancement in the toxicity of the microbial community	[41]
4	High	AgNPs	Toxicity is reduced toward biofilm-forming communities	[42, 43]
	Soil types			
5	Silty clay	TiO_2	Carbon mineralization was lowered significantly	[37]
6	Sandy loam	CuO, ZnO	The toxic effect on Triticum aestivum	[44]
	Cation exchange capacity			
7	Low	AgNPs	Enhancement in the toxicity of soil microbes	[45]
8	High	ZnO	Nontoxic effect on Lepidium sativum	[46]

breakthrough by the internal stimuli from roots for nutrient release in response to P and N deficiency. It is reported that the nanofertilizers are not having any issues for traditional agencies in an article reviewed by Adisa et al. [65] and Kah et al. [58].

Nanofertilizers are developed by nanostructured materials like chitosan, zeolite, polyacrylic acid, clay minerals, and hydroxyapatite. They may be applied to soil as fertilizer or sprayed on the plants by foliar application [66]. When comparing the conventional fertilizers, nanofertilizer with the composite of modified urea nanoparticles of hydroxyapatite can release nitrogen for sixty days to the plant. This is possible because of the largest available surface area of the hydroxyapatite, and the strong bonding between them leads to the slow liberation of nitrogen from urea [67–69]. A report declares that the potassium is liberated slowly when the polyacrylamide polymer is coated on the potassic fertilizer. Sandy soils need the slow release of potassium to decrease leaching [70]. Compost production and enhancement in the decomposition of organic wastes could be a significant aspect of nanotechnology in the agricultural field. Still, no mentionable results have come to date, but they will certainly rule the world in the future [71]. These are all clearly visible from the information that the nanofertilizers possess high efficiency and reduce the amount of fertilizer needed, and the main thing is nutrient losses in the environments are reduced. At the same time, for attaining profitable and sustainable agriculture, studying the economic feasibility of nanofertilizers is very important [72].

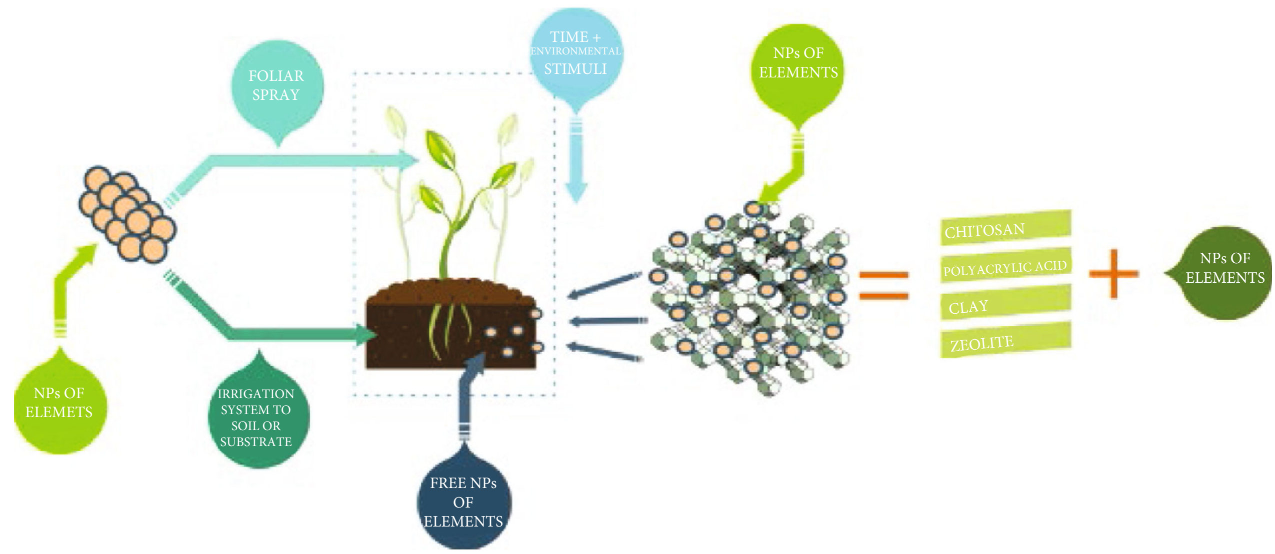

Figure 4: Application of nanofertilizer in plants [55].

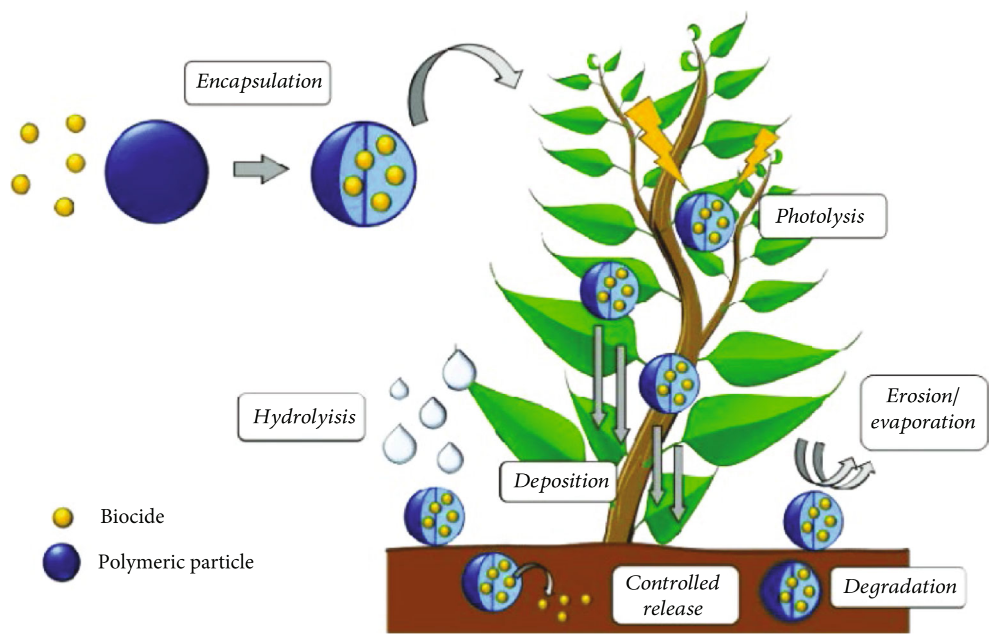

Figure 5: Application of nanotechnology in delivering the pesticides [76].

2.2. Nanopesticide. In agriculture, using a pesticide is a part of their regular practice for getting greater yield. Strange and efficient pesticides are being developed continuously for specific targets. Hence, year-by-year different pesticides are concealed numerously [73]. But relatively significantly less amount (0.1%) of pesticide is reaching the targeted pests. The other remaining 99.99% of the applied pesticides are contaminated. Human health and the food chain are severe consequences of contaminated pesticides in the environment. The ubiquitous presence of pesticides all over the domain results in the pesticide-resistance development in pathogens, weeds, and insects [74]. All these harmful effects can be overcome by using biopesticides over synthetic pesticides. But their progress is slow, and the biopesticides' efficiency over the pest was primarily environment-dependent. The problems can easily be overcome by replacing nanopesticides with synthetic pesticides. The nanopesticides can offer effective pest control for a long duration by releasing the active components slowly and closely controlled [75]. Thus, to minimize the usage of synthetic pesticides and their environmental risks, nanopesticides are essential for sustainably and efficiently managing different pests. Figure 5 shows the pesticide delivery via nanotechnology.

The behavior of nanopesticides is quite different from conventional pesticides [77]. Since the particles are nanosized, they are transported in colloidal and dissolve states. Because of its tiny size, the solubility of the active components will be increased. Hence, the hazardous impact is

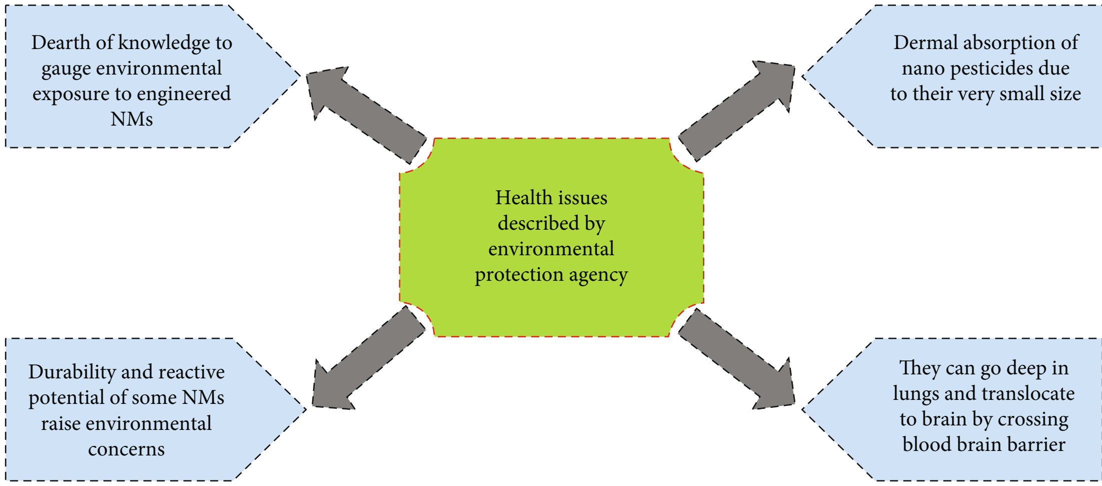

Figure 6: Health issues declared by the environmental production agency.

significantly reduced on the environment by using nanopesticides than conventional pesticides. On the whole, as the nanopesticides are applied in a lesser amount, water and energy are highly conserved by them [78]. Usage of nanopesticides also helps achieve great productivity of crops in less input cost; mainly, it reduces the labour cost and the water usage. As per the declaration of the environmental production agency, nanopesticides may cause specific health issues. All such health issues are listed in Figure 6.

Kumar et al. experienced that the disadvantageous effects of bacteria in soil and plants were reduced while using nanopesticides [79]. Pradhan et al. [80] and Pankaj et al. [81] also experienced similar results while using polyethylene glycol-based nanoformulations of carbofuran and acephate; nanoacephate's toxicity was lowered in the organisms which are not targeted. The increase in efficiency is only because of the slow release of the active components and is not in the rise in the uptake of nanoformulated active components. Song et al. concluded that the insecticidal activity, as opposed to the cotton bollworm, was increased by two times while using nanoparticles of silica-associated chlorfenapyr over the microparticles of silica-associated chlorfenapyr [82]. From all such results, it is clear that the liberation of active components against different crop pests will be an effective tool in the future for managing the pests present in the field. Pathogens of viruses, bacteria, and fungus are well-recognized by the antimicrobial behavior of nanoparticles. Silver (Ag), copper (Cu), and aluminum (al) are specific inorganic nanomaterials which are having pesticidal properties in them [83, 84]. It is observed that the disappearance of pathogens in the infected leaves while spraying silver-silica nanoparticles in them and process just requires three days for its disappearance. Significant antibacterial and antifungal activities are observed in the nanoparticles of copper (Cu) [85].

The primary threat emerging in modern agriculture is the growth of weeds. The efficiency of nanoherbicides mainly relies on biodegradable polymers. For instance, atrazine is encapsulated by a biopolymer to enhance its biocompatibility, bioavailability, and better physiochemical properties [86]. It has been proven that the stability and herbicidal activities have improved, and the mobility in the soil is reduced while using polymer encapsulated atrazine over that of free atrazine [87]. Usually, atrazine contaminates the fields and groundwater sources. Using atrazine in the nanoformulations against the targeted weeds was more effective than conventional atrazine. Foliar interaction of nanoformulation of atrazine with mustard (India) shows that the herbal activity occurs directly through the vascular tissues of leaves [88]. This proves that the nanoformulation of components has the potential to maintain a low concentration of herbal activity. Hairy beggarticks and slender amaranth are effectively handled over by the nanocapsules loaded with atrazine. Thus, nanoherbicides are an efficient way of managing the weed as well [89]. Knowledge about the impact of ecotoxicology by nanopesticides is very little. The ecotoxicological impact reduces earthworms in the agricultural field [90]. Inorganic nanoparticles like Ni, Cu, SiO_2, Ag, ZrO_2, and TiO_2 are responsible for the toxicity of earthworms. It is observed that the reproduction failure in the earthworms when the soil is treated with nanoparticles of silver (Ag) [91]. Even though earthworms can sense and avoid silver nanoparticles, they are affected [92]. Significant reductions in the reproduction of earthworms are observed when they are exposed to Ag nanoparticles or silver nitrate (AgNO3). From the investigations made by Unrine et al., it is clear that the copper nanoparticles have a disadvantageous impact on the earthworms [93].

3. Nanobiosensors for Soil-Plant Systems

Biosensors are used to sense the medium's physical and chemical properties, denoting the transducer-receptor hybrid system. The next era of biosensors is most probably nanobiosensors [94]. They will be linked with the sensitized elements for observing the particular fragment through a physiochemical transducer at ultralow concentration. These sensors are beneficial in early sensing, and thus, rapid decisions were made to enhance the yield of the crops [95]. High sensitivity, rapid

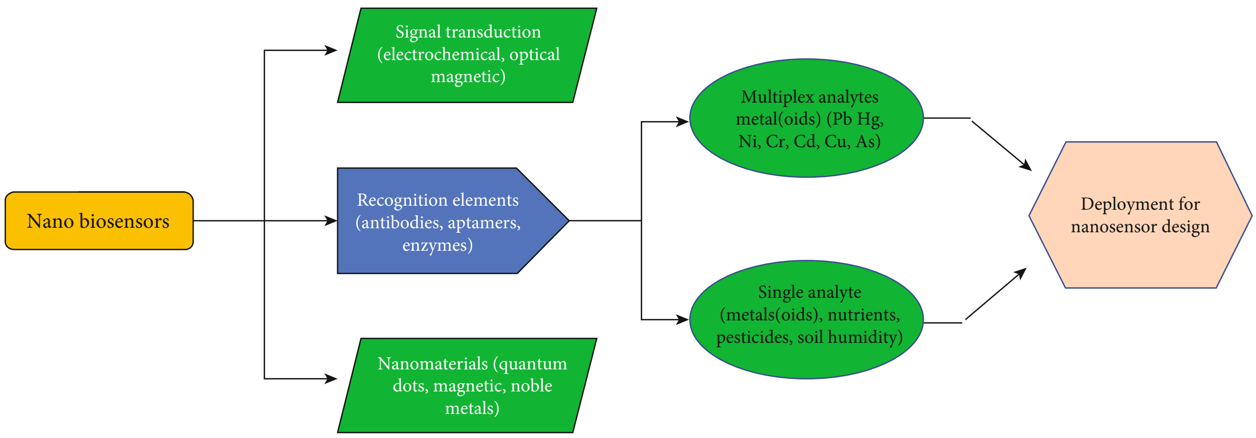

Figure 7: Mechanistic functions of nanoscaled biosensors.

Table 3: Matrix of biosensors and its application.

Sl. no.	Analyte	Sensor matrix	Dye	Application	Integration method	Ref
1	O_2	PS-PVP nanoparticles	Meso-tetra(4-fluorophenyl)tetrabenzoporphyrin, platinum (II)	Microorganism	Inflow	[102]
2	O_2	Polystyrene (PS) nanoparticles	Platinum porphyrin (platinum (II)-5, 10, 15, 20-meso-tetraphenyltetrabenzoporphyrin)	Cell culture	Inflow	[103]
3	pH	PS-PVP nanoparticles	Aza-BODIPY dye	Enzymatic reactions	Inflow	[104]
4	CO_2	Dowex® chloride form	Fluorescein	Fluorescein	Dissolved indicator	[105]

electron-transfer kinetics, long-life stability, and high surface-to-volume ratio are the irreplaceable features in nanobiosensors over the previous generation biosensors [96].

Nanosized particles present in the nanobiosensors act as bioreceptor on a transducer. Recognition elements are provided with the signal to detect a single (or) multiple fragments. Immobilization, miniaturization, and fictionalization are the interesting characteristics that integrate a transduction system's biocomponents into complex architecture to improve nanomaterials' systematic performance [97, 98]. The design and the mechanical function of nanobiosensors are shown in Figure 7.

Table 3 depicts the applications and sensing strategies of nanobiosensors. Nanobiosensors are very helpful in detecting the analytes present in the water bodies and soil. The detrimental effects can easily be prevented. A universal problem with consequential health threats is a stockpile of toxic metal ions in plants and soil above the threshold level. Optical sensors were used for detecting such stockpiles [99]. Optical sensor uses electromagnetic radiation for detection and is chemical in nature [100]. SERS (surface-enhanced Raman scattering) and fluorescent are two optical sensors that are commonly used. These sensors use reduced metal oxides or macromolecules for recognizing the metal ions present in the soil and river [101]. It will be very promising when the paper chip strategy is integrated with nanosystems for obtaining portable nanosensors for industries and commercial applications.

Neonicotinoids, pesticides, atrazine, carbamates, and organophosphates are dominant classes. Because of its homogeneity, their residues persist long in the soil, even at low concentrations too. Interaction of antigen-antibody with a piezoelectric transducer is employed by the nanobiosensors for detecting such pesticides [106]. Based on the limit of detection and its cost in developing antibodies, the efficiency of nanobiosensors will be varied. This hinders the commercial application of nanobiosensors [107]. Hence, its efficiency has to be improved by multisampling and pretreatment processes.

4. Nanomaterial's Fate in Soil

Natural and organic minerals present in the soil may interact with nanomaterials and result in partitioning the aqueous and solid phases of the soil system. Fate and the behavior of nanomaterials in the water system are mainly deduced in research [108], whereas limited data are available in finding the fate and behavior of nanomaterials in soil systems. The stability, reactivity, toxicity, and mobility of the nanomaterials can be controlled by certain processes. Such processes are described in Figure 8.

Nanomaterials will transform chemically, physically, and biologically, depending on the interaction with soil and its nature [109]. When the nanomaterials are introduced into the environmental fields, aggregation of particles will occur spontaneously. Reactivity of the nanomaterials is getting

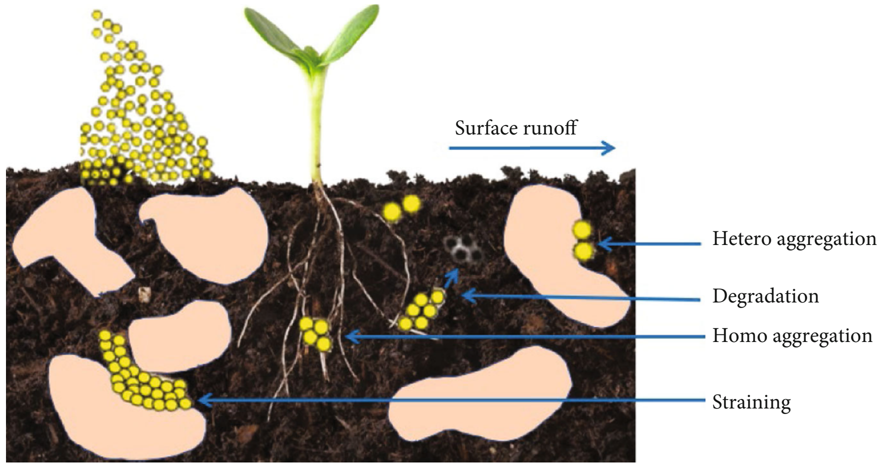

Figure 8: The fate of nanomaterials in soil.

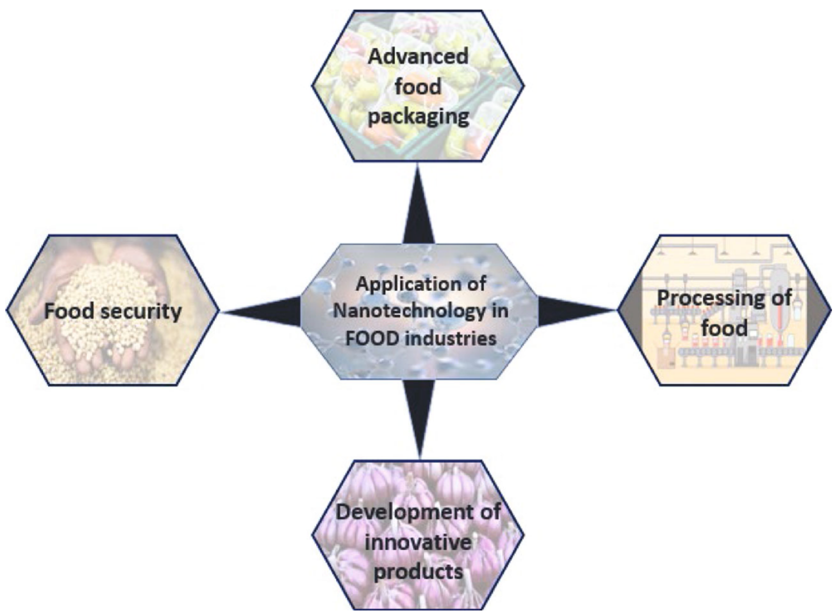

Figure 9: Application of nanotechnologies in the food sector.

affected by the reduction of surface area due to aggregation [110]. Aggregation may happen in two ways; they are homo-aggregation and hetero-aggregation. Homo-aggregation occurs between the nanomaterials, and hetero-aggregation occurs between the nanomaterial and another particle in the environment [111].

5. Nanotechnologies and Its Application in Food Industries

Nanotechnology is the science of tiny materials having a great impact in the food industry field [112]. Nanotechnology has significant potential in verifying the modifications of nutritional values, flavour, and colour, monitoring the integrity of foods through barcodes, and increasing the shelf life of food [113]. Nanotechnology is an emerging technology with a great potential for generating absolute new products and certain processes in the food sector. Nanotechnology can be applied in the food industry through food additives (inside nanomaterials) and food packaging (outside nanomaterial) [114]. Applications of nanotechnology in the food sector are shown in Figure 9.

Significant advances were brought up in the field of food processing by nanotechnologies. As the food products are required the high-quality standard, and the demands for emerging products like low-calorie and low-fat foods are increasing for dietary requirements, the separation method has to be improved by nanomaterials in food industries [115]. Nanofiltration is one of the most relevant methods based on nanotechnology, which has substantial potential in processing foods. Nanoporous membranes are used for softening, for instance, and water purification. Hence, the divalent ions can be removed by the nanofillers [116, 117]. Several applications are available for this nanotechnology

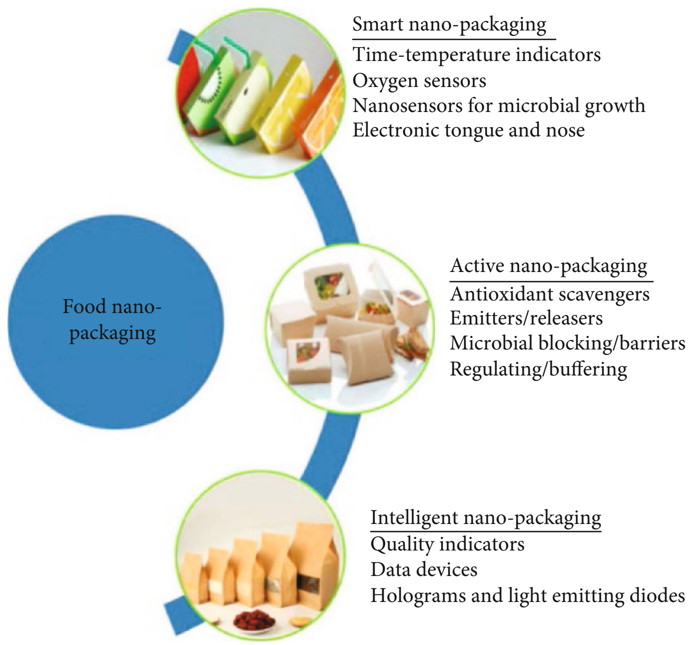

Figure 10: Classifications of nanofood packaging [129].

in the dairy industry. Nanotechnologies are applied in the dairy industries to standardize milk, fractionate the proteins available in the milk, and enhance the microbial quality [118, 119]. This method has various advantages over the normal filtration process. Some of such advantages are lesser processing steps, lower energy consumption, improved quality of the final product, and greater separation efficiency.

This nanotechnology led significant advances in the food safety field. The food contamination processes have highly required a technique with fast, robust, and sensitive detection [120]. In such cases, the most efficient approach for the specific recognition of food contaminants will be the biosensing techniques, which rely on the transducing system coupled with a specific bioreceptor. The bioreceptor, coupled with the transducing system, has to be strong and selective binding biomolecules for certain target compounds, which produce biological or chemical signals [121, 122]. The transducer further measures the produced signal by converting it into a measurable form. Aptamers are peptide molecules or single-standard nucleic acids with a high affinity for their target ligands. Detection of nanobioluminescence in the spray from Agromicron company is a commercial example of biosensing in food contaminant detection. The process is simply based on a luminescent protein that reacts with the pathogenic microorganisms present on the surface, such as Escherichia coli or Salmonella, and emits a visible glow [123].

In the food processing industries, the quality of the food and the safety are the two important aspects being focussed on. Instrumentation and analytical procedures are equipped sufficiently for determining the quality of the food and its hazards with great at very low concentration in the complex food materials [124]. Since the service and these instruments are very expensive, skilled/trained human resources are required, and it consumes little long for obtaining such high accuracy results. Therefore, developing an affordable, field applicable, and simple sensor with sufficient analytical performance has to be focussed on the food nanomaterial's evaluation for the food-based application [125].

6. Food Packaging Nanotechnologies

Among food nanoscience research, nanocomposites are one of the most active areas within the food packaging sector. Figure 10 shows the classification in the nanopackaging of food. For minimizing the impacts of petroleum-based plastics on the environment, biodegradable plastic and its resources are noticed as a powerful strategy [126]. However, no biobased materials can perform as best as petroleum-based materials. The physical properties of biobased packing materials like thermal stability, barrier, and mechanical properties have to be improved [127]. It has been proved that the nanoreinforcement of bioplastics through the incorporation of nano- and microfibre of cellulose, nanoclays, and carbon nanotubes is an effective and efficient way to enhance such properties [128].

Several advantages are available while using nanofiller over the microfillers. Improvement in the relevant physical structure with less loading percentage (<10%) is obtained without compromising the toughness and transparency [130]. Improvement in the adhesion behavior of nanomaterials with the matrix is observed when nanofillers are used; an increment in the surface area of the filler is the reason behind this observation [131]. Active food packaging systems with the applied antimicrobial nanoparticles are tabulated in Table 4.

Society demands in the food packaging industries are responded to by the new emerging technologies [139]. Therefore, bioactive packaging has a significant role in enhancing the impact of food on the consumer's health via

Table 4: Nanomaterials along with their embedding polymer.

Sl. no.	Nanomaterials	Sample	Embedding polymers	Ref
1	Titanium oxide nanoparticles (TiO_2)	Pork	Polylactic acid (PLA)	[132]
2	Sulfur nanoparticles (SNP)	Glycerol and acetic acid	Chitosan	[133]
3	Zinc oxide (ZnO)	Nutrient agar	Chitosan	[134]
4	Silver nanoparticles	—	Wild mushroom	[135]
5	Nisin	Deionized water and NaOH	Pectin	[136]
6	TiO_2 (titanium oxide) nanoparticles	Fresh lettuce	Oriented polypropylene (OPP)	[137]
7	AgNPs (silver nanoparticles)	Carrots and pears	Sodium alginate film	[138]

healthier packaged foods [140, 141]. In the production of functional foods, this would be considered an innovative strategy. These packages can effectively be packed using nanotechnologies, and many nanoparticles have been developed to increase their stability, bioavailability, and functionality [142]. The incorporation of nanoparticles in the structure of the package with bioactive substances would permit a controlled release of such additives [143].

7. Status of Toxicological Assessment and Characterization of Nanomaterials in Food

To understand the challenges in risk assessment of nanotechnologies and its proper characterization, it is important to highlight that the nanoparticles can either be in the food naturally or may be added or even formed in the food processing [144]. It may be added in two ways: intentionally and nonintentionally (through environmental contamination or via migration). Milk is a clear example of natural food containing nanoparticles, where whey proteins with the size of 30 nm coexisted with 100 nm casein micelles [145, 146]. Various food proteins exist in the nanoscale by nature, and simple triglyceride lipids are just 2 nm long. Nanoparticles can also be identified in traditionally processed foods like mayonnaise [147]. Most notably, the foods are broken down in nanoscales during digestion before assimilation. It is still confused whether the nanoscale processing of food results in a different structure from those natural foods or not [148]. A fair and clear has to be carried out for distinguishing the engineered or inorganic nanoparticles (nanofibers, CNT, and nanometals) and nanoparticles produced from food [149].

Some of the intrinsic factors that depend on the type of NMs, such as composition, size, charge, shape and biodegradability, aggregation, and biodistributions, are included when the nanoparticles are coated [150, 151]. These intrinsic properties are the important factors to be taken into account. Several international agencies, especially the International Standard Organization (ISO) or the French N, have elaborated guidelines or protocols for the risk evaluation in nanotechnology [152–154]. Characterization and identification of nanomaterials in food applications were included in the guidelines for the risk analysis of food products by the European Food Safety Authority. Research about the toxicological assays of nanoparticles has been observed to be increased over the recent years. Experts in this field found that much of the research is carried out by nonexperienced researchers, kept incomplete, or leads to wrong conclusions.

8. Technical Constraints and Challenges

Many hurdles are there in the field of nanotechnology. Even though it has a significant potential to create innovative products and food processing [155], making an edible delivery system with effective formulation for safety and human consumption in an economic process is a major challenge here. To ensure the wholesomeness of foods, the leaching and migration of nanoparticles into the food products from the packaging material has to be greatly concerned [156]. For instance, the disadvantages of solid lipid nanoparticles are shown in Figure 11. Sometimes, the nanoparticles may be added directly or indirectly from other sources or even isolated because of their migration. The behavior of material will be entirely different from the bulk materials [157]. Therefore, understanding the toxicity and functionalities of nanoparticles is very important.

Su and Li reported that the nanoparticles enter the cells and organs by crossing the biological barrier [158]. Different chemical methods are used for synthesizing the nanoparticles, which creates hazardous by-products and causes severe environmental pollution [159]. Therefore, besides the public demand and popularity, an exclusive regulatory policy, general concerns, biosafety, and a comprehensive risk assessment program must be considered while packaging and processing nanooriented food products [160]. Studies concentrating on the interaction of nanoparticles with living beings have to be approached to improve their commercial application and generate eco-friendly antibacterial nanoparticles [161].

9. Safety Issues, Regulatory Aspects, and Health Risks

Nanopackaged foods may possess a health risk and an exposure route due to the transfer of nanoparticles into the food from the substandard packages. This effect depends on the nature of the packaging matrix, toxicity, ingestion rate of the particular food, and degree of migration of the nanomaterial used [162]. Nanoparticle-related health risk evidence is increasing every day. Safety hazards and health-associated risks are detrimentally affected by the enhanced activity,

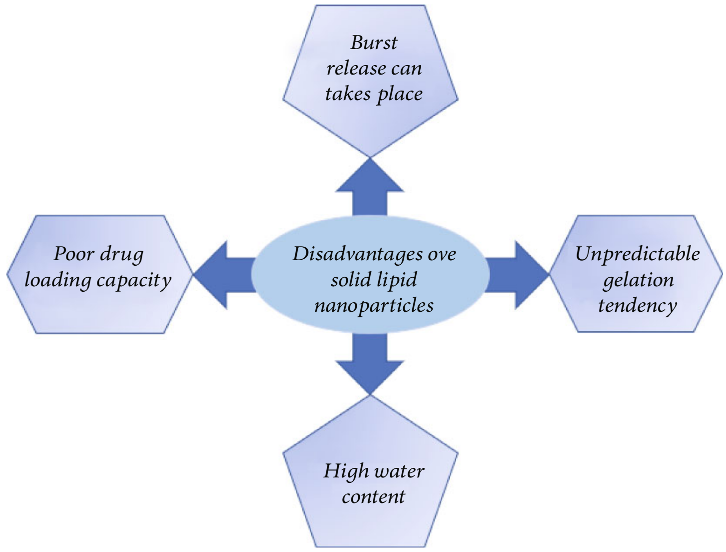

Figure 11: Disadvantages of solid lipid nanoparticles.

overconsumption, and bioaccumulation of nanobased products [163]. Echegoyen and Nerín found that the nanoparticles of silver present in the packaging material may migrate into the food and be taken in by humans. However, the knowledge about the toxicity of such nanomaterials is limited. But such migrated nanoparticles may accumulate in various organs like the stomach, liver, kidney, and small intestine [164]. A single oral dose of zinc oxide (ZnO) nanoparticles may result in hepatic injury, kidney damage, and lung damage. Human health and the environment will be affected by the application of titanium oxide and its end disposal. Nanotechnologies' application gathered significant attention from international agencies, conscious customers, policymakers, and other stakeholders [165, 166]. The nano-eco-bio interactions are complicated by understanding monitoring and the traceability of nanoscale materials' chemical, physical, and functional properties. Sequential case studies and scientific research have to be carried out to pass legislation or draft any regulation [167]. Understanding the behavior of nanomaterials is not at all an easy task. Because every nanomaterial will behave uniquely in every individual product under different specific conditions [168, 169], the academicians, consumers, researchers, and food processors demand a global knowledge platform for discussing and addressing all the aspects of consumption, application, long-term effects, and disposal. This will significantly enhance the application and research in such an emerging field.

10. Futuristic Scopes of Agriculture in Nanotechnology

Optimistic applications would not be available in all areas of nanotechnologies. The negative perceptions about the interventions of nanotechnologies in the agricultural sector must have to be taken seriously for its betterment. So, extensive efforts have to be made based on the knowledge gaps to improve and forward the futuristic research. Futuristic research must be improved in finding ways to avoid the risk factors associated with the usage of nanoparticles. Based on the realistic approaches, the scientific community also has to work together with the research community to improve nanotechnologies in agriculture. Exploring and clarifying the dose of nanoparticles within the safety limits needs to be validated. To achieve this, a concentration-dependent study in the natural soil system has to be attempted better to understand nontoxic and accurate active doses of nanoparticles. The physicochemical characteristics in agriculture have to be overviewed, which will help reduce the risk of soil and plant biota. The soil environment has to be altered to modify the nanoparticles' transport, bioavailability, and fate for reducing their subsequent toxicity. This will obtain beneficial and safe applications for nanotechnology in agriculture. For instance, soil conditions can be improved by advanced soil management practice in bioavailability, reducing transport and further toxicity of nanoparticles with a significant impact on the agricultural ecosystem.

11. Futuristic Scopes of the Food Industry in Nanotechnology

Remarkable advances were brought up in applying food science and research through nanotechnology. The maintenance of the food quality could be assured by nanotechnology by detecting the pathogens, pesticides, and toxins and monitoring them. But these nanotechnologies require high-end equipment and skilled labour. Some nanoparticles are developed as potent nanocomponents, or still, those are at their infancy stage. Researches in the following areas have to be carried out more extensively for broader application of nanotechnology.

Most importantly, the challenges and safety aspects have to be considered simultaneously. Innovative packaging developing an amalgamation of nanoparticles and antigen-specific biomarkers for preparing nanocomposite polymeric films is a novel idea that is slowly being realized. To expand the industrial applications of such novel ideas, extensive research has to be carried out in the future. In future years, the production and formulation of functional foods are likely to be extended by nanotechnology-derived foods. Nanotechnology would rule the whole food processing domain in the future if the rules and regulations to this technology were led down to overcome particular safety challenges. It is predicted that nanotechnology will be an advanced technology with a tremendous growth rate by 2050 to untangle most societal and industrial problems due to its ability to find better solutions at both macro- and microlevels.

12. Conclusion

Nanotechnologies have found many applications in agriculture and food industries, such as nanopesticides, nanobiosensors, nanofertilizers, and nanoembedded food packing. The production of the crops will be increased during the optimum usage of nanofertilizers. At the same time, the productivity of the crops will be decreased in terms of improper nanofertilizer usage. Therefore, the fate of nanomaterials and their impact on the environment has to be understood clearly.

(i) Addressing the environmental issues, potential risk, toxicity, and consequences of nanoparticles is very much essential

(ii) Collaborative studies had to be carried out among various institutions for developing multifunctional, efficient, cost-effective, environment-friendly, and stable nanomaterials

(iii) Bioremediation of nanoparticles should be explored for developing an integrated remediation strategy. Specific difficulties while incorporating nanotechnologies in food have to be concerned more with the betterment of farmers and society

(iv) This article overviewed the recent trends and application of nanomaterials in the agriculture and food industries. Effective research must be carried out collaboratively in different disciplines to overcome specifically mentioned difficulties

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

We thank and acknowledge the management of the Chennai Institute of Technology, Chennai, for their support to carry out this research work. The authors appreciate the supports from the Saveetha School of Engineering, SIMATS, Chennai, and Mettu University, Ethiopia.

References

[1] N. Baig, I. Kammakakam, and W. Falath, "Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges," *Materials Advances*, vol. 2, no. 6, pp. 1821–1871, 2021.

[2] X. Wang, X. Zhong, J. Li, Z. Liu, and L. Cheng, "Inorganic nanomaterials with rapid clearance for biomedical applications," *Chemical Society Reviews*, vol. 50, no. 15, pp. 8669–8742, 2021.

[3] N. Sun, Y. Hailong, W. Hao, X. Shen, and C. Deng, "Advanced nanomaterials as sample technique for bio-analysis," *TrAC Trends in Analytical Chemistry*, vol. 135, p. 116168, 2021.

[4] S. Yogeshwaran, L. Natrayan, S. Rajaraman, S. Parthasarathi, and S. Nestro, "Experimental investigation on mechanical properties of epoxy/graphene/fish scale and fermented spinach hybrid bio composite by hand lay-up technique," *Materials Today: Proceedings*, vol. 37, pp. 1578–1583, 2021.

[5] T. A. Saleh, "Nanomaterials: classification, properties, and environmental toxicities," *Environmental Technology & Innovation*, vol. 20, p. 101067, 2020.

[6] P. Kumar, P. Mahajan, R. Kaur, and S. Gautam, "Nanotechnology and its challenges in the food sector: a review," *Materials Today Chemistry*, vol. 17, p. 100332, 2020.

[7] R. Gupta, H. Chauhan, V. K. Garg, and N. Kataria, "Chemical and physical properties of nanoparticles and hybrid materials," in *Sustainable Nanotechnology for Environmental Remediation*, pp. 199–220, Elsevier, 2022.

[8] A. Acharya and P. K. Pal, "Agriculture nanotechnology: translating research outcome to field applications by influencing environmental sustainability," *NanoImpact*, vol. 19, p. 100232, 2020.

[9] L. Natrayan, V. Sivaprakash, and M. S. Santhosh, "Mechanical, microstructure and wear behavior of the material AA6061 reinforced SiC with different leaf ashes using advanced stir casting method," *International Journal of Engineering and Advanced Technology*, vol. 8, pp. 366–371, 2018.

[10] B. I. Kharisov and O. V. Kharissova, *Carbon allotropes: metal-complex chemistry, properties and applications*, Springer, 2019.

[11] Y. Wang, L. Dong, F. Wang et al., "A new strategy to prepare carbon nanotube thin film by the combination of top-down and bottom-up approaches," *Carbon*, vol. 161, pp. 563–569, 2020.

[12] S. Chakraborty, B. W. Jo, and Y.-S. Yoon, "Development of nano cement concrete by top-down and bottom-up nanotechnology concept," in *Smart Nanoconcretes and Cement-Based Materials*, pp. 183–213, Elsevier, 2020.

[13] A. C. Anselmo and S. Mitragotri, "Nanoparticles in the clinic: an update," *Bioengineering & Translational Medicine*, vol. 4, no. 3, article e10143, 2019.

[14] R. Kumar, K. R. Aadil, S. Ranjan, and V. B. Kumar, "Advances in nanotechnology and nanomaterials based strategies for neural tissue engineering," *Journal of Drug Delivery Science and Technology*, vol. 57, p. 101617, 2020.

[15] F. Lu and D. Astruc, "Nanocatalysts and other nanomaterials for water remediation from organic pollutants," *Coordination Chemistry Reviews*, vol. 408, p. 213180, 2020.

[16] S. Nikazar, M. Barani, A. Rahdar, M. Zoghi, and G. Z. Kyzas, "Photo- and magnetothermally responsive nanomaterials for therapy, controlled drug delivery and imaging applications," *ChemistrySelect*, vol. 5, no. 40, pp. 12590–12609, 2020.

[17] S. Majumdar and A. A. Keller, "Omics to address the opportunities and challenges of nanotechnology in agriculture," *Critical Reviews in Environmental Science and Technology*, vol. 51, no. 22, pp. 2595–2636, 2021.

[18] A. Kumar, K. Gupta, S. Dixit, K. Mishra, and S. Srivastava, "A review on positive and negative impacts of nanotechnology in agriculture," *International journal of Environmental Science and Technology*, vol. 16, no. 4, pp. 2175–2184, 2019.

[19] G. A. Achari and M. Kowshik, "Recent developments on nanotechnology in agriculture: plant mineral nutrition, health, and interactions with soil microflora," *Journal of Agricultural and Food Chemistry*, vol. 66, no. 33, pp. 8647–8661, 2018.

[20] K. Hemalatha, C. James, L. Natrayan, and V. Swamynadh, "Analysis of RCC T-beam and prestressed concrete box girder bridges super structure under different span conditions," *Materials Today: Proceedings*, vol. 37, pp. 1507–1516, 2021.

[21] D. Thangadurai, J. Sangeetha, and R. Prasad, Eds., *Nanotechnology for Food, Agriculture, and Environment*, Springer, 2020.

[22] H. Yu, J.-Y. Park, C. W. Kwon, S.-C. Hong, K.-M. Park, and P.-S. Chang, "An overview of nanotechnology in food science: preparative methods, practical applications, and safety," *Journal of Chemistry*, vol. 2018, Article ID 5427978, 10 pages, 2018.

[23] V. K. Bajpai, M. Kamle, S. Shukla et al., "Prospects of using nanotechnology for food preservation, safety, and security," *Journal of Food and Drug Analysis*, vol. 26, no. 4, pp. 1201–1214, 2018.

[24] L. Natrayan and A. Merneedi, "Experimental investigation on wear behaviour of bio-waste reinforced fusion fiber composite laminate under various conditions," *Materials Today: Proceedings*, vol. 37, pp. 1486–1490, 2021.

[25] M. A. Cerqueira, A. A. Vicente, and L. M. Pastrana, "Nanotechnology in food packaging: opportunities and challenges," in *Nanomaterials for Food Packaging*, pp. 1–11, Elsevier, 2018.

[26] M. Thiruvengadam, G. Rajakumar, and I.-M. Chung, "Nanotechnology: current uses and future applications in the food industry," *Biotech*, vol. 8, no. 1, pp. 1–13, 2018.

[27] O. Zaytseva and G. Neumann, "Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications," *Chemical and Biological Technologies in Agriculture*, vol. 3, no. 1, pp. 1–26, 2016.

[28] M. Tamilmagan, D. Easu, V. A. Baskarlal, and V. Andal, "Synthesis, characterisation, design and study of magnetorheological property of nano fe_2O_3," *International Journal of ChemTech Research*, vol. 8, no. 5, pp. 65–69, 2015.

[29] L. Natrayan, P. S. S. Sundaram, and J. Elumalai, "Analyzing the uterine physiological with MMG signals using SVM," *International Journal of Pharmaceutical Research*, vol. 11, no. 2, pp. 165–170, 2019.

[30] J. Rao and K. E. Geckeler, "Polymer nanoparticles: preparation techniques and size-control parameters," *Progress in Polymer Science*, vol. 36, no. 7, pp. 887–913, 2011.

[31] D. J. McClements and H. Xiao, "Is nano safe in foods? Establishing the factors impacting the gastrointestinal fate and toxicity of organic and inorganic food-grade nanoparticles," *Npj Science of Food*, vol. 1, no. 1, pp. 1–13, 2017.

[32] S. Iravani, H. Korbekandi, S. V. Mirmohammadi, and B. Zolfaghari, "Synthesis of silver nanoparticles: chemical, physical and biological methods," *Research in Pharmaceutical Sciences*, vol. 9, no. 6, pp. 385–406, 2014.

[33] M. Fathi, M. R. Mozafari, and M. Mohebbi, "Nanoencapsulation of food ingredients using lipid based delivery systems," *Trends in Food Science & Technology*, vol. 23, no. 1, pp. 13–27, 2012.

[34] P. Asha, L. Natrayan, B. T. Geetha et al., "IoT enabled environmental toxicology for air pollution monitoring using AI techniques," *Environmental Research*, vol. 205, p. 112574, 2022.

[35] S. Dwivedi, Q. Saquib, A. A. Al-Khedhairy, and J. Musarrat, "Understanding the role of nanomaterials in agriculture," in *Microbial Inoculants in Sustainable Agricultural Productivity*, pp. 271–288, Springer, New Delhi, 2016.

[36] A. Husen and M. Jawaid, Eds., *Nanomaterials for Agriculture and Forestry Applications*, Elsevier, 2020.

[37] M. Simonin and A. Richaume, "Impact of engineered nanoparticles on the activity, abundance, and diversity of soil microbial communities: a review," *Environmental Science and Pollution Research*, vol. 22, no. 18, pp. 13710–13723, 2015.

[38] K. Schlich and K. Hund-Rinke, "Influence of soil properties on the effect of silver nanomaterials on microbial activity in five soils," *Environmental Pollution*, vol. 196, pp. 321–330, 2015.

[39] Y. Liang, W. Sun, Y.-G. Zhu, and P. Christie, "Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: a review," *Environmental Pollution*, vol. 147, no. 2, pp. 422–428, 2007.

[40] Z. Shen, Z. Chen, Z. Hou, T. Li, and L. Xiaoxia, "Ecotoxicological effect of zinc oxide nanoparticles on soil microorganisms," *Frontiers of Environmental Science & Engineering*, vol. 9, no. 5, pp. 912–918, 2015.

[41] V. Paranthaman, K. Shanmuga Sundaram, and L. Natrayan, "Influence of SiC particles on mechanical and microstructural properties of modified interlock friction stir weld lap joint for automotive grade aluminium alloy," *Silicon*, vol. 14, no. 4, pp. 1617–1627, 2022.

[42] Z. Sheng and Y. Liu, "Effects of silver nanoparticles on wastewater biofilms," *Water Research*, vol. 45, no. 18, pp. 6039–6050, 2011.

[43] Y. Inomata, M. Kajino, K. Sato et al., "Emission and atmospheric transport of particulate PAHs in Northeast Asia," *Environmental Science & Technology*, vol. 46, no. 9, pp. 4941–4949, 2012.

[44] C. O. Dimkpa, D. E. Latta, J. E. McLean, D. W. Britt, M. I. Boyanov, and A. J. Anderson, "Fate of CuO and ZnO nano- and microparticles in the plant environment," *Environmental Science & Technology*, vol. 47, no. 9, pp. 4734–4742, 2013.

[45] A. J. Calder, C. O. Dimkpa, J. E. McLean, D. W. Britt, W. Johnson, and A. J. Anderson, "Soil components mitigate the antimicrobial effects of silver nanoparticles towards a beneficial soil bacterium, Pseudomonas chlororaphis O6," *Science of the Total Environment*, vol. 429, pp. 215–222, 2012.

[46] I. Jośko and P. Oleszczuk, "Influence of soil type and environmental conditions on ZnO, TiO2 and Ni nanoparticles phytotoxicity," *Chemosphere*, vol. 92, no. 1, pp. 91–99, 2013.

[47] F. FAO, "The future of food and agriculture–trends and challenges," *Annual Report*, vol. 296, pp. 1–180, 2017.

[48] H. Chhipa, "Nanofertilizers and nanopesticides for agriculture," *Environmental Chemistry Letters*, vol. 15, no. 1, pp. 15–22, 2017.

[49] B. Z. Butt and I. Naseer, “Nanofertilizers,” in *Nanoagronomy*, pp. 125–152, Springer, Cham, 2020.

[50] K. S. Subramanian, A. Manikandan, M. Thirunavukkarasu, and C. S. Rahale, “Nano-fertilizers for balanced crop nutrition,” in *Nanotechnologies in Food and Agriculture*, pp. 69–80, Springer, Cham, 2015.

[51] M. C. DeRosa, C. Monreal, M. Schnitzer, R. Walsh, and Y. Sultan, “Nanotechnology in fertilizers,” *Nature Nanotechnology*, vol. 5, no. 2, pp. 91–91, 2010.

[52] F. Zulfiqar, M. Navarro, M. Ashraf, N. A. Akram, and S. Munné-Bosch, “Nanofertilizer use for sustainable agriculture: advantages and limitations,” *Plant Science*, vol. 289, p. 110270, 2019.

[53] G. N. Rameshaiah, J. Pallavi, and S. Shabnam, “Nano fertilizers and nano sensors–an attempt for developing smart agriculture,” *International Journal of Engineering Research and General Science*, vol. 3, no. 1, pp. 314–320, 2015.

[54] M. T. El-Saadony, A. S. ALmoshadak, M. E. Shafi et al., “Vital roles of sustainable nano-fertilizers in improving plant quality and quantity-an updated review,” *Saudi Journal of Biological Sciences*, vol. 28, no. 12, pp. 7349–7359, 2021.

[55] A. B. Morales-Díaz, H. Ortega-Ortíz, A. Juárez-Maldonado, G. Cadenas-Pliego, S. González-Morales, and A. Benavides-Mendoza, “Application of nanoelements in plant nutrition and its impact in ecosystems,” *Advances in Natural Sciences: Nanoscience and Nanotechnology*, vol. 8, no. 1, p. 013001, 2017.

[56] M. A. Iqbal, “Nano-fertilizers for sustainable crop production under changing climate: a global perspective,” *Sustainable Crop Production*, vol. 8, pp. 1–13, 2019.

[57] M. D. Singh, “Nano-fertilizers is a new way to increase nutrients use efficiency in crop production,” *International Journal of Agriculture Sciences, ISSN*, vol. 9, no. 7, pp. 0975–3710, 2017.

[58] M. Kah, R. S. Kookana, A. Gogos, and T. D. Bucheli, “A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues,” *Nature Nanotechnology*, vol. 13, no. 8, pp. 677–684, 2018.

[59] R. Liu and R. Lal, “Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (Glycine max),” *Scientific Reports*, vol. 4, no. 1, pp. 1–6, 2015.

[60] E. S. Hamed, “Effect of nitrogenous fertilization and spraying with nano-fertilizer on Origanum syriacum L. var. syriacum plants under North Sinai conditions,” *Journal of Pharmacognosy and Phytochemistry*, vol. 7, no. 4, pp. 2902–2907, 2018.

[61] J. H. Mejías, “Nanofertilizers: a cutting-edge approach to increase nitrogen use efficiency in Grasslands,” *Science*, vol. 9, p. 52, 2021.

[62] T. Thirugnanasambandan, “Advances of engineered nanofertilizers for modern agriculture,” in *Plant-Microbes-Engineered Nano-Particles (PM-ENPs) Nexus in Agro-Ecosystems*, pp. 131–152, Springer, Cham, 2021.

[63] A. Y. Ghidan, A.-M. S. Kahlel, and T. M. Al-Antary, “Effect of nanotechnology liquid fertilizers on yield and nitrogenous compounds of broad bean (Vicia faba l.),” *Fresenius Environmental Bulletin*, vol. 29, no. 6, p. 41244128, 2020.

[64] Y.-Y. Syu, J.-H. Hung, J.-C. Chen, and H.-w. Chuang, “Impacts of size and shape of silver nanoparticles on Arabidopsis plant growth and gene expression,” *Plant Physiology and Biochemistry*, vol. 83, pp. 57–64, 2014.

[65] I. O. Adisa, V. L. Reddy, J. R. Pullagurala et al., “Recent advances in nano-enabled fertilizers and pesticides: a critical review of mechanisms of action,” *Nano*, vol. 6, no. 7, pp. 2002–2030, 2019.

[66] M. Iqbal, S. Umar, and Mahmooduzzafar, “Nano-fertilization to enhance nutrient use efficiency and productivity of crop plants,” in *Nanomaterials and Plant Potential*, pp. 473–505, Springer, Cham, 2019.

[67] E. Broda, A. Gładysz-Płaska, E. Skwarek, and V. V. Payentko, “Structural properties and adsorption of uranyl ions on the nanocomposite hydroxyapatite/white clay,” *Applied Nanoscience*, vol. 12, no. 4, pp. 1101–1111, 2022.

[68] M. Karami, M. A. Akhavan Bahabadi, S. Delfani, and A. Ghozatloo, “A new application of carbon nanotubes nanofluid as working fluid of low-temperature direct absorption solar collector,” *Solar Energy Materials and Solar Cells*, vol. 121, pp. 114–118, 2014.

[69] C. Tarafder, M. Daizy, M. M. Alam et al., “Formulation of a hybrid nanofertilizer for slow and sustainable release of micronutrients,” *ACS Omega*, vol. 5, no. 37, pp. 23960–23966, 2020.

[70] D. H. H. Sim, I. A. W. Tan, L. L. P. Lim, and B. H. Hameed, “Encapsulated biochar-based sustained release fertilizer for precision agriculture: a review,” *Journal of Cleaner Production*, vol. 303, p. 127018, 2021.

[71] M. Usman, J. M. Byrne, A. Chaudhary et al., “Magnetite and green rust: synthesis, properties, and environmental applications of mixed-valent iron minerals,” *Chemical Reviews*, vol. 118, no. 7, pp. 3251–3304, 2018.

[72] M. M. Abd El-Azeim, M. A. Sherif, M. S. Hussien, I. A. A. Tantawy, and S. O. Bashandy, “Impacts of nano- and non-nanofertilizers on potato quality and productivity,” *Acta Ecologica Sinica*, vol. 40, no. 5, pp. 388–397, 2020.

[73] L. Natrayan, S. Yogeshwaran, L. Yuvaraj, and M. Senthil Kumar, “Effect of graphene reinforcement on mechanical and microstructure behavior of AA8030/graphene composites fabricated by stir casting technique,” *AIP Conference Proceedings*, vol. 2166, no. 1, article 020012, 2019.

[74] Z. M. M. Gamal, “Nano-particles: a recent approach for controlling stored grain insect pests,” *Academia Journal of Agricultural Research*, vol. 6, no. 5, pp. 88–94, 2018.

[75] A. S. Hashem, S. S. Awadalla, G. M. Zayed, F. Maggi, and G. Benelli, “Pimpinella anisum essential oil nanoemulsions against Tribolium castaneum—insecticidal activity and mode of action,” *Environmental Science and Pollution Research*, vol. 25, no. 19, pp. 18802–18812, 2018.

[76] M. Álvarez-Paino, A. Muñoz-Bonilla, and M. Fernández-García, “Antimicrobial polymers in the nano-world,” *Nanomaterials*, vol. 7, no. 2, p. 48, 2017.

[77] K. Seeniappan, B. Venkatesan, N. N. Krishnan et al., “A comparative assessment of performance and emission characteristics of a DI diesel engine fuelled with ternary blends of two higher alcohols with lemongrass oil biodiesel and diesel fuel,” *Energy & Environment*, 2021.

[78] A. Dubey and D. R. Mailapalli, “Nanofertilisers, nanopesticides, nanosensors of pest and nanotoxicity in agriculture,” in *Sustainable Agriculture Reviews*, pp. 307–330, Springer, Cham, 2016.

[79] R. S. Suresh Kumar, P. J. Shiny, C. H. Anjali et al., “Distinctive effects of nano-sized permethrin in the environment,” *Environmental Science and Pollution Research*, vol. 20, no. 4, pp. 2593–2602, 2013.

[80] S. Pradhan, I. Roy, G. Lodh et al., “Entomotoxicity and biosafety assessment of PEGylated acephate nanoparticles: a

biologically safe alternative to neurotoxic pesticides," *Journal of Environmental Science and Health, Part B*, vol. 48, no. 7, pp. 559–569, 2013.

[81] N. A. Pankaj, J. K. Shakil, M. K. Singh, and K. Singh, "Bioefficacy evaluation of controlled release formulations based on amphiphilic nano-polymer of carbofuran against Meloidogyne incognita infecting tomato," *Journal of Environmental Science and Health, Part B*, vol. 47, no. 6, pp. 520–528, 2012.

[82] M.-R. Song, S.-M. Cui, Y.-R. Fei Gao, C.-L. F. Liu, T.-Q. Lei, and D.-C. Liu, "Dispersible silica nanoparticles as carrier for enhanced bioactivity of chlorfenapyr," *Journal of Pesticide Science*, vol. 37, no. 3, pp. 258–260, 2012.

[83] P. Shukla, P. Chaurasia, K. Younis, O. S. Qadri, S. A. Faridi, and G. Srivastava, "Nanotechnology in sustainable agriculture: studies from seed priming to post-harvest management," *Nanotechnology for Environmental Engineering*, vol. 4, no. 1, pp. 1–15, 2019.

[84] A. A. A. Aljabali and M. A. Obeid, "Inorganic-organic nanomaterials for therapeutics and molecular imaging applications," *Nanoscience & Nanotechnology-Asia*, vol. 10, no. 6, pp. 748–765, 2020.

[85] K. Khalid, X. Tan, H. F. M. Zaid et al., "Advanced in developmental organic and inorganic nanomaterial: A review," *Bioengineered*, vol. 11, no. 1, pp. 328–355, 2020.

[86] T. Hofmann, G. V. Lowry, S. Ghoshal et al., "Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture," *Nature Food*, vol. 1, no. 7, pp. 416–425, 2020.

[87] P. Zhang, Z. Guo, S. Ullah, G. Melagraki, A. Afantitis, and I. Lynch, "Nanotechnology and artificial intelligence to enable sustainable and precision agriculture," *Nature Plants*, vol. 7, no. 7, pp. 864–876, 2021.

[88] S. Ahmar, T. Mahmood, S. Fiaz et al., "Advantage of nanotechnology-based genome editing system and its application in crop improvement," *Frontiers in Plant Science*, vol. 12, 2021.

[89] N. Mitter and K. Hussey, "Moving policy and regulation forward for nanotechnology applications in agriculture," *Nature Nanotechnology*, vol. 14, no. 6, pp. 508–510, 2019.

[90] R. Grillo, L. F. Fraceto, M. J. B. Amorim, J. J. Scott-Fordsmand, R. Schoonjans, and Q. Chaudhry, "Ecotoxicological and regulatory aspects of environmental sustainability of nanopesticides," *Journal of Hazardous Materials*, vol. 404, p. 124148, 2021.

[91] M. R. Assalin, L. D. L. dos Santos, D. R. C. de Souza et al., "Nanoformulation as a tool for improvement of thiamethoxam encapsulation and evaluation of ecotoxicological impacts," *Energy, Ecology and Environment*, vol. 4, no. 6, pp. 310–317, 2019.

[92] C. O. Adetunji, "Environmental impact and ecotoxicological influence of biofabricated and inorganic nanoparticle on soil activity," in *Nanotechnology for Agriculture*, pp. 221–239, Springer, Singapore, 2019.

[93] J. M. Unrine, O. V. Tsyusko, S. E. Hunyadi, J. D. Judy, and P. M. Bertsch, "Effects of particle size on chemical speciation and bioavailability of copper to earthworms (Eisenia fetida) exposed to copper nanoparticles," *Journal of Environmental Quality*, vol. 39, no. 6, pp. 1942–1953, 2010.

[94] F. Arduini, S. Cinti, V. Scognamiglio, and D. Moscone, "Nanomaterials in electrochemical biosensors for pesticide detection: advances and challenges in food analysis," *Microchimica Acta*, vol. 183, no. 7, pp. 2063–2083, 2016.

[95] P. Gruber, M. P. C. Marques, N. Szita, and T. Mayr, "Integration and application of optical chemical sensors in microbioreactors," *Lab on a Chip*, vol. 17, no. 16, pp. 2693–2712, 2017.

[96] N. Ullah, M. Mansha, I. Khan, and A. Qurashi, "Nanomaterial-based optical chemical sensors for the detection of heavy metals in water: recent advances and challenges," *TrAC Trends in Analytical Chemistry*, vol. 100, pp. 155–166, 2018.

[97] N. Shahcheraghi, H. Golchin, Z. Sadri, Y. Tabari, F. Borhanifar, and S. Makani, "Nano-biotechnology, an applicable approach for sustainable future," *3 Biotech*, vol. 12, no. 3, pp. 1–24, 2022.

[98] U. Chaurasia, A. Kumar, D. K. Maurya, S. K. Yadav, T. Hussain, and V. K. Maurya, Eds., "Role of nano-biotechnology in agriculture and allied sciences," in *Nanotechnology in Sustainable Agriculture*, pp. 69–96, CRC Press, 2021.

[99] F. C. Christopher, P. S. Kumar, F. J. Christopher, G. J. Joshiba, and P. Madhesh, "Recent advancements in rapid analysis of pesticides using nano biosensors: a present and future perspective," *Journal of Cleaner Production*, vol. 269, p. 122356, 2020.

[100] A. El-Ghany, M. Nesreen, A. El-Aziz, E. Shadia, and S. S. Marei, "A review: application of remote sensing as a promising strategy for insect pests and diseases management," *Environmental Science and Pollution Research*, vol. 27, no. 27, pp. 33503–33515, 2020.

[101] M. Karthick and K. Yoganandam, "Investigation of mechanical properties and corrosion performance of CNT coated on EN8 mild steel," *Materials Today: Proceedings*, vol. 46, pp. 4224–4227, 2021.

[102] M. Horka, S. Sun, A. Ruszczak, P. Garstecki, and T. Mayr, "Lifetime of phosphorescence from nanoparticles yields accurate measurement of concentration of oxygen in microdroplets, allowing one to monitor the metabolism of bacteria," *Analytical Chemistry*, vol. 88, no. 24, pp. 12006–12012, 2016.

[103] J. Cao, S. Nagl, E. Kothe, and J. Michael Köhler, "Oxygen sensor nanoparticles for monitoring bacterial growth and characterization of dose–response functions in microfluidic screenings," *Microchimica Acta*, vol. 182, no. 1-2, pp. 385–394, 2015.

[104] J. Ehgartner, M. Strobl, J. M. Bolivar et al., "Simultaneous determination of oxygen and pH inside microfluidic devices using core–shell nanosensors," *Analytical Chemistry*, vol. 88, no. 19, pp. 9796–9804, 2016.

[105] Y. Zilberman, S. K. Ameri, and S. R. Sonkusale, "Microfluidic optoelectronic sensor based on a composite halochromic material for dissolved carbon dioxide detection," *Sensors and Actuators B: Chemical*, vol. 194, pp. 404–409, 2014.

[106] K. Tsougeni, G. Kaprou, C. M. Loukas et al., "Lab-on-chip platform and protocol for rapid foodborne pathogen detection comprising on-chip cell capture, lysis, DNA amplification and surface-acoustic-wave detection," *Sensors and Actuators B: Chemical*, vol. 320, p. 128345, 2020.

[107] E. Gavi, D. Kubicki, G. A. Padron, and N. Gül Özcan-Taşkın, "Breakup of nanoparticle clusters using microfluidizer M110-P," *Chemical Engineering Research and Design*, vol. 132, pp. 902–912, 2018.

[108] N. Xu, Z. Li, X. Huangfu et al., "Facilitated transport of $nTiO_2$-kaolin aggregates by bacteria and phosphate in

water-saturated quartz sand," *Science of the Total Environment*, vol. 713, p. 136589, 2020.

[109] M. Murali, H. G. Gowtham, S. B. Singh et al., "Fate, bioaccumulation and toxicity of engineered nanomaterials in plants: current challenges and future prospects," vol. 811, pp. 152249–Science of The Total Environment, 2022.

[110] S. T. Khan, S. F. Adil, M. R. Shaik, H. Z. Alkhathlan, M. Khan, and M. Khan, "Engineered Nanomaterials in Soil: Their Impact on Soil Microbiome and Plant Health," *Plants*, vol. 11, no. 1, p. 109, 2022.

[111] J. Wu, *Fate, Accumulation and Impact of Metallic Nanomaterials in the Terrestrial Environment*, Diss Leiden University, 2021.

[112] S. Das, S. H. Panda, M. Bolem, N. Pal, B. R. Samantaray, and H. Thatoi, "Facets of nanotechnology in Food processing, packaging and safety: an emerald insight," in *Bio-Nano Interface*, pp. 75–92, Springer, Singapore, 2022.

[113] S. M. Amini, M. Gilaki, and M. Karchani, "Safety of nanotechnology in food industries," *Electronic Physician*, vol. 6, no. 4, pp. 962–968, 2014.

[114] L. Jaiswal, S. Shankar, and J.-W. Rhim, "Applications of nanotechnology in food microbiology," in *Methods in Microbiology*, vol. 46, pp. 43–60, Academic Press, 2019.

[115] T. Ramesh, A. P. Sathiyagnanam, M. V. De Poures, and P. Murugan, "A Comprehensive Study on the Effect of Dimethyl Carbonate Oxygenate and EGR on Emission Reduction, Combustion Analysis, and Performance Enhancement of a CRDI Diesel Engine Using a Blend of Diesel and Prosopis juliflora Biodiesel," *International Journal of Chemical Engineering*, vol. 2022, Article ID 5717362, 12 pages, 2022.

[116] M. Karthick, M. Meikandan, S. Kaliappan et al., "Experimental Investigation on Mechanical Properties of Glass Fiber Hybridized Natural Fiber Reinforced Penta-Layered Hybrid Polymer Composite," *International Journal of Chemical Engineering*, vol. 2022, Article ID 1864446, 9 pages, 2022.

[117] M. Vijayaragavan, B. Subramanian, S. Sudhakar, and L. Natrayan, "Effect of induction on exhaust gas recirculation and hydrogen gas in compression ignition engine with simarouba oil in dual fuel mode," *International Journal of Hydrogen Energy*, vol. 47, pp. 1–13, 2021.

[118] Y. Lugani, S. Oberoi, and G. Rattu, "Nanotechnology in food industry–applications and future perspectives," in *Sustainable Agriculture Reviews 55*, pp. 71–92, Springer, Cham, 2021.

[119] P. Jagtap, H. Nath, P. B. Kumari et al., "Mycogenic Fabrication of Nanoparticles and Their Applications in Modern Agricultural Practices & Food Industries," *Fungi Bio-Prospects in Sustainable Agriculture, Environment and Nano-Technology*, vol. 3, pp. 475–488, 2021.

[120] P. J. Babu, "Nanotechnology mediated intelligent and improved food packaging," *International Nano Letters*, vol. 12, no. 1, pp. 1–14, 2022.

[121] A. R. Singh, P. K. Desu, R. K. Nakkala et al., "Nanotechnology-based approaches applied to nutraceuticals," *Drug Delivery and Translational Research*, vol. 12, no. 3, pp. 485–499, 2022.

[122] M. Thakur, B. Wang, and M. L. Verma, "Development and applications of nanobiosensors for sustainable agricultural and food industries: recent developments, challenges and perspectives," *Environmental Technology & Innovation*, vol. 26, p. 102371, 2022.

[123] R. Ningthoujam, B. Jena, S. Pattanayak, S. Dash, M. K. Panda, R. K. Behera, N. K. Dhal, and Y. D. Singh, Eds., "Nanotechnology in food science," in *Bio-Nano Interface*, pp. 59–73, Springer, Singapore, 2022.

[124] S. S. H. Rizvi, C. I. Moraru, H. Bouwmeester, F. W. H. Kampers, and Y. Cheng, "Nanotechnology and food safety," in *Ensuring Global Food Safety*, pp. 325–340, Academic Press, 2022.

[125] P. J. Babu and J. M. R. Tingirikari, "A review on polymeric nanomaterials intervention in food industry," *Polymer Bulletin*, vol. 79, pp. 1–28, 2022.

[126] D. Enescu, M. A. Cerqueira, P. Fucinos, and L. M. Pastrana, "Recent advances and challenges on applications of nanotechnology in food packaging. A literature review," *Food and Chemical Toxicology*, vol. 134, p. 110814, 2019.

[127] M. Primožič, Ž. Knez, and M. Leitgeb, "(Bio) nanotechnology in food science—food packaging," *Nanomaterials*, vol. 11, no. 2, p. 292, 2021.

[128] L. Mei and Q. Wang, "Advances in using nanotechnology structuring approaches for improving food packaging," *Annual Review of Food Science and Technology*, vol. 11, no. 1, pp. 339–364, 2020.

[129] D. Veeman, M. S. Sai, P. Sureshkumar et al., "Additive manufacturing of biopolymers for tissue engineering and regenerative medicine: an overview, potential applications, advancements, and trends," *International Journal of Polymer Science*, vol. 2021, Article ID 4907027, 20 pages, 2021.

[130] F. Mustafa and S. Andreescu, "Nanotechnology-based approaches for food sensing and packaging applications," *RSC Advances*, vol. 10, no. 33, pp. 19309–19336, 2020.

[131] S. Sahani and Y. C. Sharma, "Advancements in applications of nanotechnology in global food industry," *Food Chemistry*, vol. 342, p. 128318, 2021.

[132] S. Li, G. Chen, S. Qiang, Z. Yin, Z. Zhang, and Y. Chen, "Synthesis and evaluation of highly dispersible and efficient photocatalytic TiO2/poly lactic acid nanocomposite films via sol-gel and casting processes," *International Journal of Food Microbiology*, vol. 331, p. 108763, 2020.

[133] S. Shankar and J.-W. Rhim, "Preparation of sulfur nanoparticle-incorporated antimicrobial chitosan films," *Food Hydrocolloids*, vol. 82, pp. 116–123, 2018.

[134] Z. L. Wang and W. Wenzhuo, "Nanotechnology-enabled energy harvesting for self-powered micro-/nanosystems," *Angewandte Chemie International Edition*, vol. 51, no. 47, pp. 11700–11721, 2012.

[135] Y. K. Mohanta, D. Nayak, K. Biswas et al., "Silver nanoparticles synthesized using wild mushroom show potential antimicrobial activities against food borne pathogens," *Molecules*, vol. 23, no. 3, p. 655, 2018.

[136] T. Krivorotova, A. Cirkovas, S. Maciulyte et al., "Nisin-loaded pectin nanoparticles for food preservation," *Food Hydrocolloids*, vol. 54, pp. 49–56, 2016.

[137] C. Chawengkijwanich and Y. Hayata, "Development of TiO_2 powder-coated food packaging film and its ability to inactivate Escherichia coli in vitro and in actual tests," *International Journal of Food Microbiology*, vol. 123, no. 3, pp. 288–292, 2008.

[138] A. Mohammed Fayaz, K. Balaji, M. Girilal, P. T. Kalaichelvan, and R. Venkatesan, "Mycobased synthesis of silver nanoparticles and their incorporation into sodium alginate films for vegetable and fruit preservation," *Journal of Agricultural and Food Chemistry*, vol. 57, no. 14, pp. 6246–6252, 2009.

[139] A. Ashfaq, N. Khursheed, S. Fatima, Z. Anjum, and K. Younis, "Application of nanotechnology in food packaging: pros and cons," *Journal of Agriculture and Food Research*, vol. 7, p. 100270, 2022.

[140] R. Suryanarayanan, V. G. Sridhar, L. Natrayan et al., "Improvement on mechanical properties of submerged friction stir joining of dissimilar tailor welded aluminum blanks," *Advances in Materials Science and Engineering*, vol. 2021, Article ID 3355692, 6 pages, 2021.

[141] M. Rastogi, C. V. Bhavana, and R.-K. Kadeppagari, "Nanotechnology: a revolutionary approach toward food packaging," in *Handbook of Consumer Nanoproducts*, pp. 1–13, Springer Singapore, Singapore, 2022.

[142] R. Sharma, "Nanotechnology: pros and cons in food quality," *Nano Life*, vol. 12, no. 1, p. 2230001, 2022.

[143] N. Chausali, J. Saxena, and R. Prasad, "Recent trends in nanotechnology applications of bio-based packaging," *Journal of Agriculture and Food Research*, vol. 7, p. 100257, 2022.

[144] M. Ahamed, M. J. Akhtar, H. A. Alhadlaq, and S. A. Alrokayan, "Assessment of the lung toxicity of copper oxide nanoparticles: current status," *Nanomedicine*, vol. 10, no. 15, pp. 2365–2377, 2015.

[145] M. Sajid, M. Ilyas, C. Basheer et al., "Impact of nanoparticles on human and environment: review of toxicity factors, exposures, control strategies, and future prospects," *Environmental Science and Pollution Research*, vol. 22, no. 6, pp. 4122–4143, 2015.

[146] S. L. Chia and D. T. Leong, "Reducing ZnO nanoparticles toxicity through silica coating," *Heliyon*, vol. 2, no. 10, article e00177, 2016.

[147] W. N. Missaoui, R. D. Arnold, and B. S. Cummings, "Toxicological status of nanoparticles: what we know and what we don't know," *Chemico-Biological Interactions*, vol. 295, pp. 1–12, 2018.

[148] T. A. Wani, F. A. Masoodi, S. M. Jafari, and D. J. McClements, "Safety of nanoemulsions and their regulatory status," in *Nanoemulsions*, pp. 613–628, Academic Press, 2018.

[149] Y. Yang, G. I. N. Waterhouse, Y. Chen, D. Sun-Waterhouse, and D. Li, "Microbial-enabled green biosynthesis of nanomaterials: current status and future prospects," *Biotechnology Advances*, vol. 55, p. 107914, 2022.

[150] A. Mansuri, R. Chaudhari, S. Nasra, N. Meghani, S. Ranjan, and A. Kumar, "Development of food-grade antimicrobials of fenugreek oil nanoemulsion—bioactivity and toxicity analysis," *Environmental Science and Pollution Research*, vol. 29, pp. 1–12, 2022.

[151] A. N. Rahman, M. S. Abdel, S. A. Shakweer et al., "Silica nanoparticles acute toxicity alters ethology, neuro-stress indices, and physiological status of African catfish (Clarias gariepinus)," *Aquaculture Reports*, vol. 23, p. 101034, 2022.

[152] M. Wang, S. Li, Z. Chen et al., "Safety assessment of nanoparticles in food: current status and prospective," *Nano Today*, vol. 39, p. 101169, 2021.

[153] EFSA Scientific Committee, "Guidance on risk assessment of nanomaterials to be applied in the food and feed chain: human and animal health," *EFSA Journal*, vol. 19, no. 8, p. e06768, 2021.

[154] A. K. Chaudhari, V. K. Singh, S. Das, and N. K. Dubey, "Nanoencapsulation of essential oils and their bioactive constituents: a novel strategy to control mycotoxin contamination in food system," *Food and Chemical Toxicology*, vol. 149, p. 112019, 2021.

[155] S. Jain, A. Kumar, T. Dhewa, and R. S. Majumdar, "Applications of nanotechnology in agriculture—a review: concepts, aspects, prospects, and constraints," *Sustainable Biological Systems for Agriculture*, pp. 3–20, 2018.

[156] S. A. O. Adeyeye, "Food packaging and nanotechnology: safeguarding consumer health and safety," *Nutrition & Food Science*, vol. 49, no. 6, pp. 1164–1179, 2019.

[157] M. Kah and R. Kookana, "Emerging investigator series: nanotechnology to develop novel agrochemicals: critical issues to consider in the global agricultural context," *Environmental Science: Nano*, vol. 7, no. 7, pp. 1867–1873, 2020.

[158] X.-L. Su and Y. Li, "Quantum dot biolabeling coupled with immunomagnetic separation for detection of Escherichia coli O157: H7," *Analytical Chemistry*, vol. 76, no. 16, pp. 4806–4810, 2004.

[159] P. Chugh and S. J. Dar, "Nanotechnology: applications, opportunities, and constraints in agriculture," in *Nanotechnology: Principles and Applications*, pp. 125–148, Routledge, 2021.

[160] A. Gorczyca, E. Pociecha, and E. Matras, "Nanotechnology in agriculture, the food sector, and remediation: prospects, relations, and constraints," in *Environmental Pollution and Remediation*, pp. 1–34, Springer, Singapore, 2021.

[161] K. Neme, A. Nafady, S. Uddin, and Y. B. Tola, "Application of nanotechnology in agriculture, postharvest loss reduction and food processing: food security implication and challenges," *Heliyon*, vol. 7, no. 12, p. e08539, 2021.

[162] K. Kannan, D. Radhika, M. P. Nikolova, V. Andal, K. Kumar Sadasivuni, and L. Sivarama Krishna, "Facile microwave-assisted synthesis of metal oxide CdO-CuO nanocomposite: Photocatalytic and antimicrobial enhancing properties," *Optik*, vol. 218, p. 165112, 2020.

[163] S. Raj, E. S. Nisha, K. R. Anooj, and S. Vallinayagam, "A comprehensive review on regulatory invention of nano pesticides in agricultural nano formulation and food system," *Journal of Molecular Structure*, vol. 1239, p. 130517, 2021.

[164] C. Fajardo, G. Martinez-Rodriguez, J. Blasco, J. M. Mancera, B. Thomas, and M. DonatoDe, Eds., "Nanotechnology in Aquaculture: Applications, Perspectives and Regulatory Challenges," *Aquaculture and Fisheries*, vol. 7, no. 2, pp. 185–200, 2022.

[165] A. Porcari, E. Borsella, C. Benighaus et al., "From risk perception to risk governance in nanotechnology: a multi-stakeholder study," *Journal of Nanoparticle Research*, vol. 21, no. 11, pp. 1–19, 2019.

[166] M. Menossi, C. Casalongué, and V. A. Alvarez, "Bio-nanocomposites for modern agricultural applications," in *Handbook of Consumer Nanoproducts*, pp. 1–38, Springer Singapore, Singapore, 2022.

[167] I. Iavicoli, V. Leso, D. H. Beezhold, and A. A. Shvedova, "Nanotechnology in agriculture: opportunities, toxicological implications, and occupational risks," *Toxicology and Applied Pharmacology*, vol. 329, pp. 96–111, 2017.

[168] M. Eleftheriadou, G. Pyrgiotakis, and P. Demokritou, "Nanotechnology to the rescue: using nano-enabled approaches in microbiological food safety and quality," *Current Opinion in Biotechnology*, vol. 44, pp. 87–93, 2017.

[169] E. Kelechukwu, *Social, Legal, Ethical, Health, Safety and Environmental Aspects of Nanotechnology*, Afribary Limited, Lagos, 2017.