Kurdistan Journal of Applied Research (KJAR)
Print-ISSN: 2411-7684 | Electronic-ISSN: 2411-7706

Review Article

Advancements in Nanotechnology for Enhanced Food Safety and Hygiene: Pathogen Detection, Smart Packaging, and Preservation Applications

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Submitted: 27 October 2024
Revised: 20 November 2024
Accepted: 10 December 2024

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Keywords: Nanotechnology, Food safety, Food hygiene, Pathogen detection, Smart packaging, Food preservation.

How to cite this paper: F. H. Awlqadr, A. B. Altemimi, Q. H. Al-Kaisy, S. A. Qadir, A. M. Faraj, T. A. H. Slih, R. H. Tlay, T. G. Abedel maksoud, F. Cacciola," Advancements in Nanotechnology for Enhanced Food Safety and Hygiene: Pathogen Detection, Smart Packaging, and Preservation Applications", KJAR, vol. 9, no. 2, pp. 86-95, December. 2024, doi: 10.24017/science.2024.2.8

Abstract: Nanotechnology is redefining food safety and hygiene, providing innovative tools to address global challenges. This review delves into the advancements in pathogen detection, smart packaging, and food preservation enabled by nanotechnology. Nanoparticle-based sensors have revolutionized the rapid identification of contaminants like *Escherichia coli*, *Salmonella*, and *Listeria*, offering higher sensitivity and specificity compared to traditional methods. Smart packaging systems equipped with nanomaterials provide real-time contamination alerts and extend shelf life by enhancing barrier and antimicrobial properties. Nanoparticles, such as silver and zinc oxide, are increasingly used in packaging to inhibit microbial growth effectively. Additionally, nanoencapsulation techniques protect bioactive compounds, such as antioxidants and antimicrobials, ensuring their stability and controlled release, which enhances food quality and safety. The emergence of biodegradable nanocomposites and edible films offers eco-friendly packaging alternatives, addressing environmental concerns while maintaining food integrity. Despite these advancements, the high reactivity and small size of nanoparticles raise safety and regulatory challenges, necessitating comprehensive risk assessments and robust frameworks to ensure consumer and environmental protection. This review also explores the potential of utilizing biowaste for green synthesis of nanoparticles, which could further reduce environmental impact. By integrating cutting-edge detection methods, improving packaging solutions, and addressing safety and sustainability challenges, nanotechnology has the potential to transform food safety and hygiene practices. Future research should focus on advancing nanosensor sensitivity, developing sustainable materials, and fostering consumer trust through transparency and education, ensuring a safer and more sustainable food supply chain.

1. Introduction

Nanotechnology is revolutionizing various sectors, including food safety and hygiene. The distinctive characteristics of nanomaterials, namely their small size and extensive surface area, enable novel applications that enhance the detection, preservation, and overall safety of food. This review aims to explore the current advancements and potential future applications of nanotechnology in ensuring food safety and hygiene, also addressing associated risks and regulatory considerations. In addition, pathogen detection is one of the primary applications of nanotechnology in food safety. Nanoparticle-based biosensors and nanosensors have been developed to identify food-borne pathogens and hazardous substances with high sensitivity and specificity. These advanced sensors can rapidly detect contaminants such as *Escherichia coli (E. coli*), *Salmonella*, *Listeria monocytogenes*, thus preventing the distribution and consumption of contaminated food products [1]. Additionally, nanotechnology facilitates the creation of smart packaging systems that change color or emit signals in the presence of pathogens, providing real-time alerts to consumers and retailers [2]. Furthermore, nanotechnology has yielded significant progress in food packaging. Nanomaterials are used in packaging materials to enhance their mechanical strength, barrier properties, and resistance to microbial proliferation. The utilization of nano-enabled packaging can suppress microbial growth, hence extending the shelf life of food products. The packaging materials often contain nanoparticles of silver, zinc oxide, or titanium dioxide, which possess strong antibacterial properties [3]. In addition, the advancement of edible nanofilms and coatings that may be directly applied to food surfaces aids in preserving food quality and safety throughout the process of storage and transportation [4]. Nanotechnology is essential for boosting the efficacy of preservatives and prolonging the shelf life of food products. Nano-encapsulation techniques are employed to encapsulate bioactive chemicals, such as antioxidants, antimicrobials, and nutrients, safeguarding them from degradation and guaranteeing their controlled and sustained release. This method not only boosts the stability and ability of these substances to be absorbed by the body, but also improves the sensory characteristics of food products [5]. Regarding risk assessment and regulatory challenges, nanotechnology improves food safety and hygiene, but it also raises risks and regulatory issues. Due to their small size and high reactivity, nanoparticles could harm humans and the environment if they accumulate in biological systems and the environment. Thus, comprehensive risk assessment studies are needed to evaluate the safety of food nanomaterial. To protect consumers and the environment, food regulators must set clear nanotechnology laws [6]. The aim of this review is also to discuss nanoparticles' pros and cons in food systems. And explore current regulations and the need for strong guidelines to ensure safe and sustainable use of nanotechnology in food safety and hygiene.

2. Classification of Nanomaterials Utilized in Food Safety and Hygiene

Nanomaterials offer numerous advantages in the food industry due to their unique properties such as high surface area, reactivity, and they can be engineered for specific functions, which makes them ideal for applications in food safety and hygiene, including pathogen detection, food packaging, and preservation. Figure 1 shows some types of nanoparticles used for food safety. Here, this review discusses various types of nanomaterials used in these applications. The first category comprises inorganic nanomaterials, such as metal and metal oxide nanoparticles, widely used in food safety applications due to their antimicrobial properties [7]. For example, silver nanoparticles (AgNPs) are highly effective antibacterial agents that can inhibit the growth of bacteria, viruses, and fungi. They are frequently employed in food packaging materials to extend the shelf life of food products by inhibiting microbial contamination [8].

In addition, titanium dioxide (TiO_2) and zinc oxide (ZnO) nano-particles are extensively used. TiO_2 nanoparticles are used for their strong ultraviolet (UV) light absorption properties, which help in reducing food spoilage and degradation caused by UV radiation. ZnO nanoparticles possess antimicrobial properties and are used in food packaging to prevent microbial growth [9]. The second category comprises organic nanomaterials. Organic nanomaterials, such as nanoclays, nanofibers, and nanoemulsions, are used to improve mechanical strength and barrier properties in food packaging materials. Nanoclays are added to polymer matrices to improve the barrier qualities against gases and moisture, hence prolonging the shelf life of food products [10]. Nanoemulsions are employed for the encapsulation and transportation of bioactive chemicals, flavors, and nutrients. They enhance the stability and bioavailability of these chemicals, hence increasing their effectiveness in improving food quality and safety.

In active packaging, nanofibers are utilized to achieve controlled release of preservatives and antimicrobials, thus effectively preserving the freshness of food [11]. The third category comprises carbon-based nanomaterials, including graphene, carbon nanotubes (CNTs), and fullerenes which are utilized more frequently in food safety applications. Graphene and CNTs possess exceptional strength, conductivity, and barrier characteristics. Due to their exceptional sensitivity and specificity, they are employed in sensors for the detection of food pollutants, infections, and poisons [12]. Fullerenes and their derivatives are utilized for their antioxidant properties, which help in preserving food quality by reducing oxidation and spoilage.

These materials are incorporated into packaging and coatings to enhance the shelf life of food products [13]. Finally, the fourth category includes biocompatible nanomaterials such as chitosan nanoparticles and biodegradable polymers that are used for food packaging and preservation. Chitosan, a natural biopolymer, has antimicrobial properties and is used in coatings and films to prevent microbial contamination and extend the shelf life of food products. Biodegradable polymers are used in sustainable packaging solutions, reducing environmental impact while ensuring food safety [14].

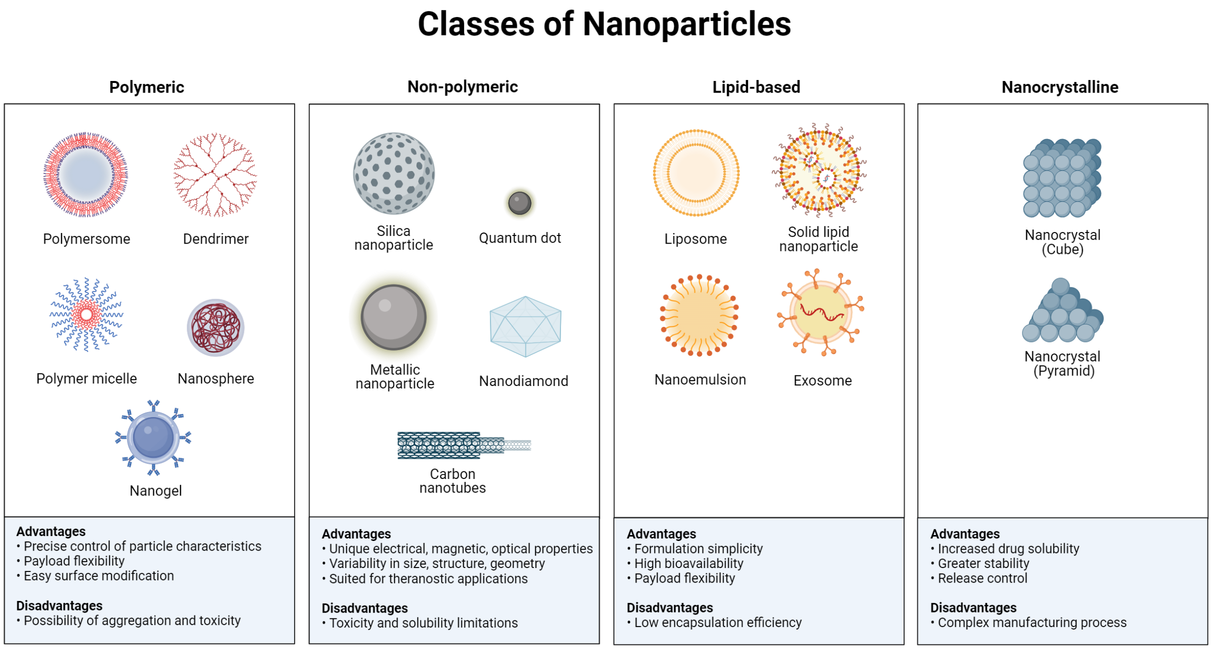

Figure 1: The primary categories of nanoparticles (NPs) utilized for food safety and hygiene, including polymeric, non-polymeric, lipid-based, and nanocrystalline materials [15].

3. Nanomaterials' Uses in Food Safety and Hygiene

Nanomaterials have transformed food industry practices, offering innovative solutions for improving food safety and hygiene through various innovative applications. Their unique properties, such as high surface area, reactivity, and the ability to be designed for specific functions, make them highly suitable for addressing challenges in pathogen and toxin detection, as well as improving food packaging and preservation.

3.1. Pathogen and Toxins Detection

Despite recent food safety improvements, foodborne illnesses remain serious economic and clinical concerns. These problems often result from eating or drinking food or water contaminated with bacteria, viruses, fungi, and parasites. Table 1 summarizes various foodborne infections and their health effects. Pathogen identification is crucial to food safety. Conventional methods like culture-based techniques and PCR are efficient but are often time-consuming and labor-intensive. Due to these limitations, faster, more sensitive, and user-friendly detection methods are needed. Nanotechnology can help solve these problems by developing nanoparticle-based biosensors and nanosensors. These sensors can detect harmful chemicals and microbiological pollutants with high sensitivity and precision. This paper explores the applications of nanotechnology in detecting food pathogens. It describes the many nanomaterials used, their functions, and their advantages over conventional detection methods [16].

Table 1: Summary of different bacterial pathogens, their sources, and health effects on humans [17].

Bacterial Pathogens	Sources	Health Effects
Listeria monocytogenes	Un-pasteurized dairy products, undercooked fish, vegetables	Abdominal pain, diarrhea, bloody stools
Bacillus cereus	Raw meat, vegetables, seafood	Watery diarrhea, abdominal pain, vomiting, nausea
Clostridium perfringens	Contaminated meat, meat products, gravies	Severe abdominal cramps and pain
Clostridium botulinum	Improperly canned and fermented foods	Blurred vision, weakness, slurred speech, difficulty swallowing
Typhi/paratyphi salmonella	Poultry products, undercooked meat, improperly cooked seafood, un-pasteurized milk	Typhoid fever, discomfort, body aches, constipation, dysentery
Shigella species	Vegetable salads, baked goods, ready-to-eat products	Abdominal cramps, muscle pain, fever, vomiting, bloody diarrhea
Vibrio cholera	Contaminated shellfish, oysters, clams	Diarrhea with mucus or blood, fever, vomiting, nausea
Vibrio vulnificu	Contaminated oysters, shellfish	Fever, chills, septicemia
Staphylococcus aureus	Meat, poultry products, cream-filled desserts, dairy products	Nausea, convulsions, abdominal cramps, vomiting
Yerosinia enterocolitica	Seafood such as oysters, unpasteurized milk	Fever, chills, diarrhea, vomiting

The toxins are large proteins that are highly stable, rendering them capable of causing infection. There are two types of toxins: endotoxins and enterotoxins. Clostridium botulinum is an example of bacteria that produce endotoxins. These bacteria emit spores containing botulinum toxin, which causes botulism poisoning when ingested by humans. The bacterial species *Staphylococcus aureus*, *Staphylococcus hyicus,* and *Staphylococcus intermedius* produce a heat-resistant enterotoxin (SETs) that is responsible for causing various foodborne diseases. Pasta, processed meat, poultry, seafood, dairy products, eggs, and salads are among the items that, when consumed, might contain toxins that are the main cause of most outbreaks of food poisoning caused by harmful substances. Abdominal pain, diarrhea, headache, nausea, vomiting, and fever are some signs of SET intoxication [18]. See Figure 2 for food chain pathogens.

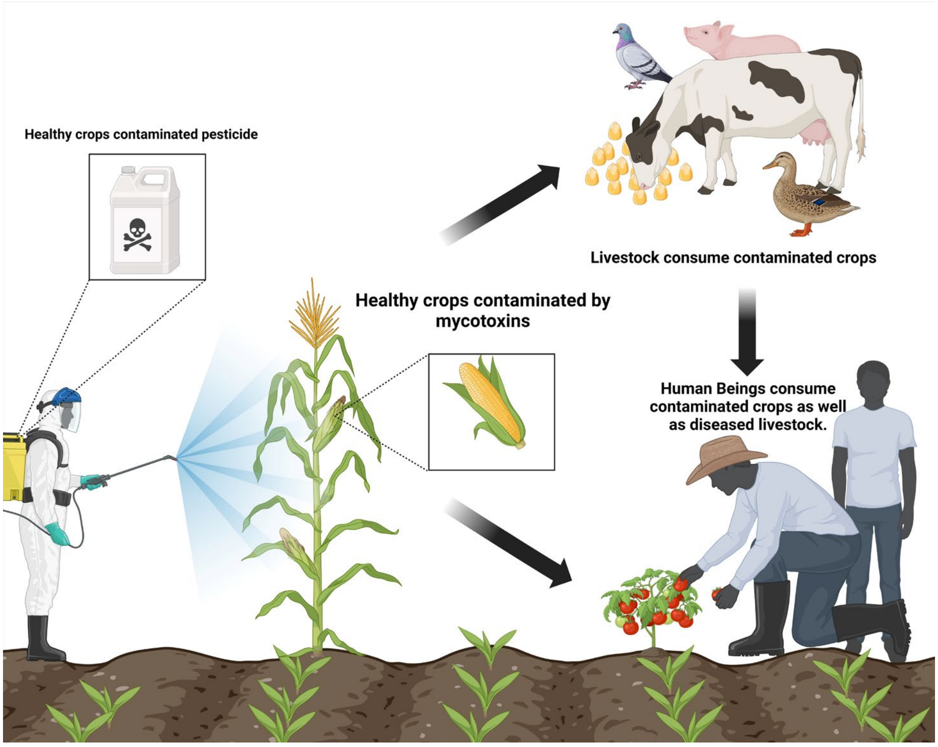

Figure 2: Pesticide and pathogens that cause disease and infection in the food chain.

Pesticides are toxic compounds employed in agriculture to safeguard plants against a range of external hazards such as pests, weeds, and diseases. In addition, they aid in the prevention of vector-borne diseases such as malaria and dengue fever in humans. Examples of pesticides include fungicides, herbicides, insecticides, rodenticides, and plant growth regulators. They assist with the maintenance of public green spaces and sports fields. The primary purpose is to inhibit the proliferation of undesirable microorganisms. Pesticide usage has raised significant concerns due to its potential to generate many environmental and health problems Daily consumed food and beverages, including cooked meals, water, wine, fruit juices, snacks, and animal feed, include traces of these pesticides [19]. Another study detected three bacterial species *E. coli*, *Salmonella typhimurium*, and *Bacillus subtilis* and presented a novel surface enhanced Raman spectroscopy method using silver (Ag) and gold (Au) bimetallic nanoparticles with a positive charge that increased sensitivity and facilitated a simple sample approach without requiring specific protocols [20]. Cho *et al.* [21] devised an expeditious detection technique for *E. coli O157* in ground beef meat by employing a straightforward membrane filter to separate the bacteria-nanoparticle complexes, resulting in remarkable sensitivity. On the other hand, another study suggested a targeted detection approach for Bacillus anthracis spores utilizing peptide-functionalized surface-enhanced Raman spectroscopy (SERS) [22].

Likewise, Cheung *et al.* [23] documented an effective detection technique for similar spores using superhydrophobic wires and minimum sample volumes. Porcine circovirus, a disease responsible for considerable economic losses and health hazards, was identified utilizing a SERS-based immunoassay employing multi-branched AuNPs as active substrates [24]. Another study developed a novel technology for multiplex SERS detection of mycotoxins, such as deoxynivalenol and ochratoxin A, utilizing film over nanospheres as substrates without requiring chemometric techniques [25]. He *et al.* [26] developed a Surface-Enhanced Raman Scattering aptasensor for the detection in peanut oil of Aflatoxin B1, a harmful mycotoxin that threatens human health.

Nanosensors are small devices comprising components that are sized between 1 and 100 nanometers [27]. Nanosensors have gained global academic interest as a potential tool for controlling epidemics stemming from foodborne infections. The work plan for all sorts of nanosensors typically consists of three main steps: The system consists of three main components: (a) identification (b) signal transduction (c) signal acquisition [27]. Nanosensor types include such as Electrochemical nanosensor/biosensors, Amperometric biosensors, Impedimetric biosensors, Bulk acoustic wave resonators, Optical biosensors, Surface plasma resonance, Evanescent field fiber optic sensors, Piezoelectric biosensors, Magnetoelastic biosensors, and Microfluidic nanosensors. All sensors work on specific detection target compounds such as pathogenic , contaminant, bacteria, etc. [28]. Figure 3 shows how nanosensors can be used for food safety applications.

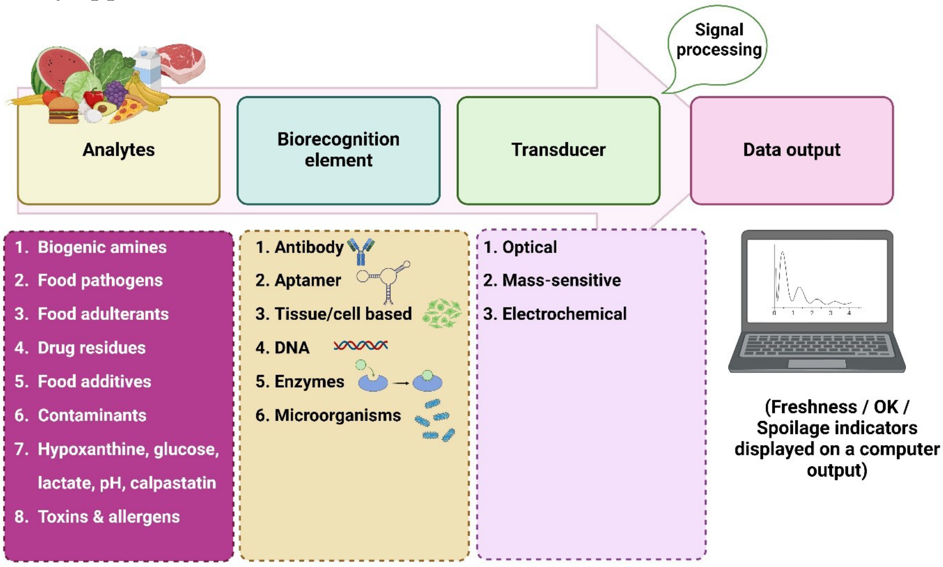

Figure 3: Schematic of a nanosensor system for food safety applications.

The domain of electrochemical nanosensors and biosensors has shown substantial expansion in recent years. These types are fundamentally categorized into two groups based on their sensing methodologies: label-dependent and label-free. Label-dependent approaches utilize specific markers, like enzymes, superconductors, and metal particles, to detect and identify the target substance [29]. Conversely, label-free approaches depend on the direct adhesion of bacterial cells to the electrode surface, resulting in quantifiable alterations in electrical properties. Label-free nanosensors provide expedited and simplified detection with reduced regulatory parameters and minimum resource demands [30]. Nonetheless, they typically exhibit elevated limits of detection as a result of the lack of supplementary amplification.

Amperometric biosensors quantify the current generated by redox reactions taking place on the surface of active electrodes. This approach has been extensively investigated in the realm of electrochemical biosensors, yet it remains relatively underutilized for the detection of foodborne pathogens. Amperometric detection requires the maintenance of a constant potential using a reference electrode, commonly Ag/AgCl, while employing materials such as gold, platinum, modified carbon, and graphite for the working electrode. These biosensors have shown a remarkable capacity to identify bacteria like *E. coli* O157 and Salmonella, with exceptional sensitivity [31]. Furthermore, potentiometric biosensors assess the potential difference that exists between the working and reference electrodes when no current is flowing. The scalability and independence from the electroactive surface area make these sensors particularly beneficial. Potentiometric biosensors utilize ion-selective electrodes and ion-selective field-effect transistors, applying conventional electrochemical measurement methods to identify variations in electrical potential resulting from enzyme-catalyzed reactions. These methods have proven effective in the identification of pathogens such as *Salmonella typhimurium* across a range of samples [32].

Moreover, impedimetric biosensors quantify variations in impedance to identify bacterial presence. This technique, recognized by international analytical communities, is known as electrochemical impedance spectroscopy (EIS) and is utilized for detecting Salmonella typhimurium in food products. EIS demonstrates exceptional sensitivity and enables label-free detection through the immobilization of biorecognition elements such as nucleic acids, antibodies, and enzymes on the surface of the electrode. These biosensors have been created for a range of pathogens, such as *E. coli* O157 [33]. On the other hand, bulk acoustic wave resonators, such as quartz crystal microbalance (QCM) sensors, detect changes in mass on the sensor surface caused by the binding of analytes. These devices use shear deformation produced by an electromagnetic current to generate mechanical oscillations. QCM sensors are durable and sensitive, making them suitable for detecting various pathogens with comparable detection capabilities to SPR and electrochemical biosensors [34].

In addition, optical biosensors have been widely researched and recently commercialized for detecting foodborne pathogens. They employ techniques like fluorescence, SPR, chemiluminescence, and light absorbance to convert analyte interactions into measurable optical signals. These sensors use functional groups or biological units as identification elements, making them highly effective for pathogen detection [35]. Surface Plasmon Resonance (SPR) is an optical method that identifies alterations in the refractive index on a sensor surface. SPR sensors are categorized into propagating and localized varieties, with the former employing continuous metal layers and the latter utilizing metal nanoparticles. SPR sensors provide instantaneous, label-free identification of pathogens and depend on the efficacy of trapping units such as DNA, antibodies, or aptamers for specificity [36]. They identify mass alterations at the nanogram scale, which frequently proves inadequate for sensitive detection, hence necessitating mass amplification techniques. QCM sensors have been employed to detect several infections, including *E. coli* O157, with significant sensitivity [37].

Finally, magnetoelastic (ME) biosensors are nanosensors possessing magnetic properties due to their ferromagnetic alloy composition. These sensors detect changes in resonance frequency caused by the increased mass when target microbes bind to the sensor surface. ME sensors are wire-free and suitable for in-field monitoring, making them practical for real-time pathogen detection. Then, microfluidic nanosensors manipulate small fluid volumes for pathogen detection, offering enhanced detection speed, reduced chemical use, and the capability for multiple detections. These sensors have been used to identify pathogens like *Salmonella enterica* and mycotoxins in various food samples, providing mobility and accessibility for onsite testing [38]. Table 2 and Table 3 summarize nanosensors used for detection of pathogens and toxins.

Table 2: Nanosensors for the identification of foodborne microorganisms and toxins.

Foodborne microorganisms and toxins	Nanomaterials Utilized	Limit of detection	References
E. coli	Silica nanoparticles	400 cell/ml	[39]
	AuNPs	1.2×10^2 coliform/ml $10^2 - 10^7$ coliform/ml	[40, 41]
	Peptide nanotubes	-	[42]
	Magnetic nanoparticles	10^4 cells/ml	[43]
	Silver nanoparticles	$5–10^9$ cells/ml	[44]
E. coli, Listeria, Salmonella	Cysteine-loaded nanoliposomes and Gold NPs	6.7 atto-mole	[45]
Salmonella typhimurium	Gold NPs–GBP-ProA protein	10^5 cells/ml	[46]
Salmonella paratyphi A	Magnetic nanoparticle aptamers	15 coliform/ml	[46]
S.enterica	(SWNTs) and DNAzyme–Apt22	10^3 coliform/ml	[47]
Enterobacter sakazakii	CNT	1.6×10^4 coliform/ml	[48, 49]
Listeria monocytogenes	MNTs & TiO_2 nanocrystals	100 coliform/ml	[50]
Brucella	Multiwalled carbon nanotubes (MWCNTs)	$4.57 \times 10^3–3.27 \times 10^3$ coliform/ml	[51]
Staphylococcus aureus	Thiol–gold nanoparticles	0.015 nanog/mL	[47]
Campylobacter jejuni	Silica nanoparticle	50 µL/ml	[52, 53]
Vibrio parahemolyticus	Multicolor UCNPs–MNPs–aptamers	25 coliform/ml	[51]
Aflatoxin	Gold Nanoparticles	10–100 nanog/dL	[54]

Table 3: Nanosensors for identifying foodborne pathogens and toxins.

Biological Contaminants	Nanomaterials Used	Detection Limit	References
Aflatoxin B1 and Ochratoxin A	Magnetic Upconversion NPs	0.01–10 ng/mL	[55]
Ochratoxin A	Single-walled Carbon Nanotubes	25–200 nanoM	[56]
Mycotoxin	Nanostructured Zinc Oxide	0.006–0.01 nanoM	[57]
Cholera Toxin	Glyconanoparticles	54 nanoM	[58]
Brevetoxins	Gold Nanoparticles - Poly(amidoamine) Dendrimers (PAADs)	0.03–8 nanog/mL	[59]
Microcystin-LR Toxin	CNTs coated with anti-MCLR Antibodies	0.6 nanog/mL	[60]
Parathion, carbamate (pesticides)	Liposome, selenide zirconium dioxide nanoparticles	-	[61, 62]
Norovirus	Concanavalin	60 copies/mL	[63]
Diazinon	DNA aptamers	-	[64]

Recent advancements in nanosensor technology have significantly improved the detection of foodborne pathogens and toxins. For instance, as shown in Figure 4, beverage samples can be effectively analyzed using gold nanoparticles conjugated with specific antibodies to detect *Salmonella enteritidis*. The presence of the pathogen is indicated by a fluorescence signal, facilitating rapid and accurate identification. Similarly, agricultural products such as peanuts, soybeans, and corn utilize aptamer-conjugated gold nanoparticles (AuNPs) for pathogen detection. This method employs a colorimetric assay that provides a clear visual indication of positive (red) or negative (green) results, making it a practical tool for ensuring food safety. These nanosensor-based approaches highlight the potential for enhanced sensitivity and specificity in pathogen detection across diverse food matrices [65].

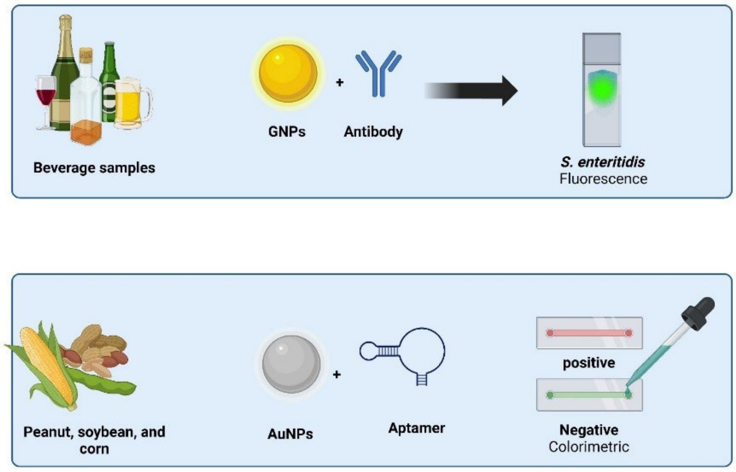

Figure 4: Detection of pathogens in beverages and food using nanosensors.

3.2. *Food Preservation*

The role of food packaging is crucial in preserving the quality of food. Effective packaging serves to protect food from exposure to light, air, and moisture. Furthermore, it extends the time that food stays consumable and offers insights into its nutritional composition. Packaging materials must exhibit stability, temperature resistance, and mechanical strength. Previously utilized packaging materials have included biopolymers like polylactic acid and polystyrene, along with degradable copolymers such as ethylene-vinyl alcohol, polyethylene terephthalate, and polyimides [66]. Nonetheless, due to the global issue of climate change, traditional packaging materials fall short in protecting food from bacterial contamination and degradation resulting from elements like O2, CO2, and various other factors. The domain of nanotechnology is undergoing a rapid expansion that is playing a significant role in advancing future packaging solutions. For example, a case study of nanocomposite polymers applied improvements to silicate nanocomposites [67].

Biodegradable and thermally stable nanocomposites made from calcium carbonate and potato starch are being explored as alternatives to polystyrene packaging. These nano-composites demonstrate impressive heat resistance and effective gas barrier properties. Combinations of zinc oxide (ZnO), titanium dioxide (TiO2), chitosan, silica, organic clay, inorganic clay, polysaccharide, and cellulose with polymer matrices have been aimed at producing packaging materials that exhibit enhanced pliability and adaptability. The five primary categories of food packaging include biodegradable, edible, active, antimicrobial, and intelligent/smart packaging. There is an increasing emphasis on the development of biodegradable polymers derived from renewable materials to tackle environmental issues [68]. Figure 5 depicts the role of nanoparticles in various types of food packaging. Polymers are synthesized by linking monomers via chemical processes termed polymerization reactions. They have varied applicability throughout multiple domains. These inexpensive, adaptable, and protective materials are essential for packaging. They are, however, composed of petroleum-derived polymers such as Low-Density Polyethylene, Polypropylene, Polystyrene, High-Density Polyethylene, Polyvinyl Chloride, and Polyethylene Terephthalate, and are non-biodegradable. Consequently, the packaging industry requires more sustainable and recyclable options [69, 70].

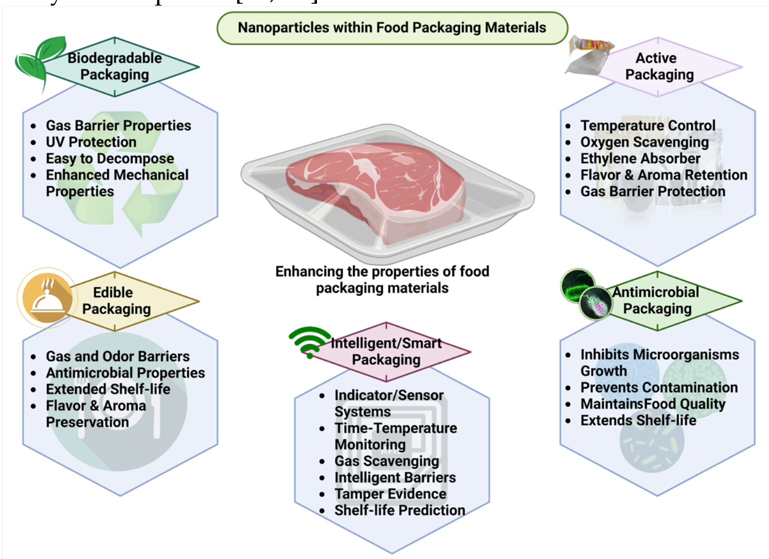

Figure 5: Illustrates the involvement of nanoparticles in several forms of food packaging.

Conventional (Non-Biodegradable) and Biodegradable polymers are characterized by their environmental degradation ability (Figure 6).Traditional polymers degrade slowly, contributing to plastic pollution [71]. Biodegradable polymers decompose naturally, providing a solution. The packaging industry faces unsustainable manufacturing, regulatory restraints, and a lack of knowledge. Teaching consumers about packaging's benefits boosts product trust and emphasizes its relevance to quality. Maintaining effective water, mist, and gas barriers is difficult, especially when various materials are utilized. Perishable goods require controlled oxygen permeability, while processed goods require gas transfer [72]. Nanoparticles, which are 1 to 100 nanometers in size, are used in food packaging nowadays. Nanoparticles improve food packaging by increasing strength, durability, and preservation. Their ability to block air and water helps preserve food. Nanoparticles also prevent chemicals from penetrating biodegradable materials. Adding nanoparticles like nanocellulose and nano-silica to a biodegradable matrix makes packaging more impact-resistant. They improve thermal stability, reducing degradation under varied conditions [73]. In addition, hydroxyl groups make biomass-derived polymer biodegradable films hydrophilic, increasing water vapor permeability and plasticizing. Nanoparticles make these materials stronger and tear-resistant, improving food protection. Nanoparticles block oxygen and water vapor, preserving food quality, and also protect light-sensitive foods from UV radiation. Nanoparticles and biodegradable materials improve package performance without compromising its environmental friendliness. Essential oils give these films antioxidant and antibacterial characteristics [74]. In water, enzymes and degradable polymers enhance biodegradation. Plasticizers improve flexibility but also have side effects [73]. Production employs casting, extrusion, and molding techniques, with synthetic biodegradable polymers such as polylactic and polyglycolic acid providing several packaging options through controlled chemical decomposition in water [69, 75].

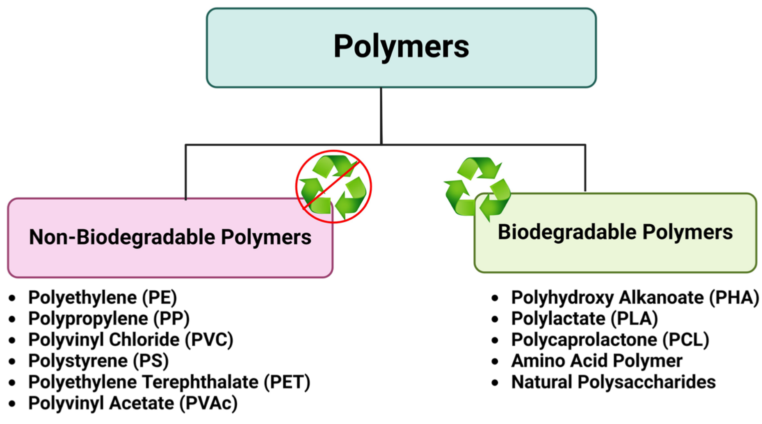

Figure 6: Conventional (Non-Biodegradable) and biodegradable polymers are characterized by their environmental degradation ability.

Kumar *et al.* [76] and Erfani *et al.* [77] developed biodegradable nanocomposite films utilizing CMC derived from sugarcane and MgO nanoparticles. The degradation rate of a film containing nanoparticles (CMC-2) was observed to be slower than that of a film lacking nanoparticles. Magnesium oxide nanoparticles improved tensile strength and opacity, while decreasing moisture, solubility, and elongation at break. Glycerol enhances the elasticity of films. The integration of MgO–NPs with CMC improves the characteristics of the biodegradable film. A film composed of biodegradable materials including PVA, Ag Cl, and spirulina was produced. Spirulina had an impact on the level of moisture and solubility, but the presence of Ag Cl nanoparticles enhanced the antibacterial activity. Spirulina enhances the levels of antioxidants. The material exhibited a photochromic response to sunlight and UV radiation, indicating its photochromic, biodegradable, antibacterial, and antioxidant properties [78]. On the other hand, edible packaging offers biodegradability and environmental benefits, minimizing waste and enhancing food quality. The primary advantages of this method are the enhancement of food quality and the extension of shelf life. Edible films can incorporate antioxidants and antibacterial agents because of their adaptability. Nanoparticles enhance the strength and tear resistance of food packaging materials. Nanoparticles serve as effective barriers against oxygen, water vapor, and harmful gases, thereby maintaining the freshness and safety of food. The capacity to absorb flavors and obstruct UV light enhances the sensory experience for the consumer. Packaging that is consumable and derived from organic polymers exhibits strength and adaptability. The incorporation of active functionalities in edible films, along with the use of plant extracts and oils in packaging, enhances food quality and promotes consumer well-being [69].

Ifmalinda *et al.* [79] conducted a study to examine the effects of varying concentrations of zinc oxide nanoparticles on edible films based on corn starch. The most favorable characteristics were obtained when the concentration of ZnO reached 12%. This resulted in improved tensile strength, elongation, and resistance to water. Nevertheless, an increased concentration of ZnO resulted in a gradual decline in biodegradability. Zhang *et al.* [80] improved an innovative edible film known as NSPP/CH through the integration of nanoparticles derived from Sar-gas-sum pallidum polysaccharide and chitosan. The coating exhibited improved mechanical properties and elasticity, successfully protecting cherries by reducing respiration and preventing weight loss. Thymol enhanced the antibacterial properties of the NSPP/CH material; however, it significantly impacted its mechanical durability and water vapor permeability (WVP). The combination of thymol with NSPP/CH demonstrates promise as a sustainable approach for prolonging the shelf life of fruits.

The study by Bautista-Espinoza *et al.* [81] examined food covering by combining chitosan, quinoa protein, lemongrass, and cinnamon essential oils with mesoporous silica nanoparticles. This coating prolonged the shelf life of sourdough bread by inhibiting staling, preserving its color, and restricting the proliferation of dangerous microbes for 10.5 days. Furthermore, it garnered favorable remarks on its flavor and consistency. Rasheed *et al.* [82] developed AgNPs that significantly improved the coated samples' antibacterial, antifungal, and antioxidant activities. Multiple strains of bacteria and fungus showed that fruits and vegetables have higher antioxidant activity. Nanomaterial toxicity and food migration need further study. Unlike conventional methods, active packaging innovations quickly engage food ingredients. Plants absorb unwanted chemicals including CO_2, moisture, O_2, smells, and ethylene and produce substances that fight oxidation and bacteria. Plants' dual role helps preserve food [73, 78]. Chemicals like antibacterials and antioxidants promote food preservation in active packaging. Inorganic and organic nanoparticles, proteins, and carbohydrates are among the additions. Plant-based essential oils, extracts, and phytochemicals are often used for their benefits [83]. Antimicrobial nanoparticles and active packaging materials create a barrier to prevent food contamination and extend shelf life. Oxygen-scavenging nanoparticles protect oxygen-sensitive foods against deterioration. Nanoparticles absorb ethylene, extending the shelf life of perishable food. Nanoparticles enhance taste, protect against UV rays, and regulate temperature. They improve gas barrier qualities, preserving food quality. Additionally, nanoparticles that change color reveal the packaging's condition and food's freshness, improving the consumer experience. Plant-derived antioxidants are powerful antioxidants with antibacterial properties. Using natural materials to make packaging is difficult. Light causes thermal instability and degradation of antioxidants [83, 84]. Another type of packaging, antibacterial active packaging, can protect food from bacterial contamination [73]. Antibacterial agents such as chitosan and essential oils may be integrated into packaging materials by using direct mixing, layer application, encapsulation to effectively amalgamate various antimicrobial components [72, 85].

Nanotechnology in chemistry has produced accurate and effective synthetic and natural antibacterial compounds. Metal or oxide nanoparticles are food-safe and antimicrobial. Technology is enhancing our understanding of antimicrobial chemicals, making food packaging safer. Synthetic antimicrobials include oxide nanoparticles (zinc oxide, copper oxide, TiO2), metallic nanoparticles (silver, sulphur, Copper), clay nanoparticles (bentonite, montmorillonite, cloisite), volatile chemicals (chlorine oxide2, SO2) alcohol, chelating agents, and organic acids. Selection depends on the packaging application. Antimicrobials come from human and bacterial proteins, polysaccharides, enzymes, bacteriocins, nisin, and pediocin. Extracts and oils from garlic, ginger, thyme, clove, oregano, coriander, and cinnamon are antimicrobial. These sources' active ingredients fight various infections and may promote health as dietary supplements [72]. Adding natural antimicrobial nanoparticles like silver or copper to packaging materials releases ions that limit microbe development on food and packaging surfaces. This protects against dangerous compounds and prolongs food safety. Microorganisms cannot pass from packaging to food because these nanoparticles suppress bacterial growth. This enhances food safety and decreases contamination risks. They suppress spoilage-causing bacteria to keep food fresh, prolonging storage time, minimizing waste, and increasing product value. These nanoparticles help preserve food under various storage conditions and their inclusion reduces chemical additives, promoting organic and environmentally friendly packaging. They also prevent biofilm formation, keeping packaging clean. Antimicrobial nanoparticles inhibit microbe growth, preserving food's nutritional value and taste, thereby maximizing the food's flavor and benefits. Anti-microbial packaging extends food preservation, increasing sustainability, reducing food waste, and addressing environmental challenges.

Active packaging with antibacterial nanoparticles protects food from decomposing microbes. Consumers benefit from longer freshness and convenience. Adding nanoparticles makes packaging materials lighter, stronger, and less permeable [73]. Nanoparticles are ideal for nanocomposite applications due to their antibacterial, UV-blocking, and oxygen-eliminating capabilities [86]. They provide biodegradable, antibacterial chemicals that keep products fresh and hinder microbe growth. The product's antibacterial activity disrupts cell structures or metabolic pathways, enhancing packaging and food safety. Finally, sensors, RFID tags, and indicators are used in intelligent packaging to identify, track, record, and display food quality and history during packing and transportation [86]. This technology uses sophisticated electronics in packaging to sense temperature and humidity and send data to consumers or companies. Intelligent packaging assesses food edibility and issues warnings, unlike active packaging, which enhances food quality. It can store and send food quality data, exceeding the conventional function of packaging by communicating environmental changes. Intelligent packaging offers safety, logistics, and marketing benefits, making it a possible future alternative. However, there are still challenges in using lab capabilities in the real world [69].

As needed, active components release antioxidants or antimicrobials to protect food quality. Packaging-food partnerships provide nutritional integrity. Food quality and safety are monitored using TTI, leakage, and pH sensors [87]. These easily understood technologies, which use color variations or light patterns, let us determine food safety. They help detect food decomposition or degradation due to storage conditions. Fan *et al.* [88] developed a colorimetric approach for shiitake mushroom quality assessment. A polyvinyl alcohol (PVA)/polylactic acid (PLA) indicator made by incorporating composite dyes into a PVA matrix changed color when exposed to CO2 in packaging, which was visible without instruments. This signal has been strongly correlated with retained mushroom quality, suggesting intelligent packaging could monitor carbon dioxide and freshness. Dong *et al.* [89] investigated a versatile film possessing antibacterial, antioxidant, and pH-responsive properties. The agar-sodium alginate polymer matrix was supplemented with chitosan nanoparticles containing purple sweet potato extract and quercetin.

This film tracks the freshness, antioxidant qualities, and preservation of animal-derived products in real time, showcasing its potential for smart packaging. In a separate investigation, Li *et al.* [90] created functional films from chitosan, nano-ZnO, and purple tomato or black wolfberry anthocyanins. Anthocyanin and nano-ZnO increased tensile strength, antioxidants, and antibacterial properties of the films. Intelligent food packaging might use the films' chromatic fluctuations in response to pig product deterioration. These changes strongly affect food quality in terms of its appearance and chemistry. These signals help us identify food's texture, look, flavor, and odor, reducing the risk of foodborne illnesses [87]. Smart packaging has real-time monitoring, damage detection, and better consumer contact thanks to technology. Despite obstacles, intelligent packaging development promises improved safety, quality, and consumer satisfaction. Table 4 lists food packaging types that use nanoparticles.

Table 4: Overview of advanced food packaging technologies and materials.

Packaging Type	Description	Examples	References
Nanocomposite Polymer	Uses nanoparticles to improve strength, durability, and preservation	Silicate nanocomposites, ZnO, TiO2, chitosan, silica, organic and inorganic clays.	[69, 86]
Biodegradable Nanocomposite	Combines biodegradable materials with nanoparticles to enhance heat resistance and gas barrier properties.	Calcium carbonate, potato starch nanocomposites, polyglycolic acid, polylactic acid	[69, 73, 74]
Edible Packaging	Eco-friendly alternative that incorporates active ingredients like antioxidants and antibacterial agents	ZnO in corn starch-based films, nSPP/CH with chitosan, chitosan with essential oils	[69, 74, 80]
Active Packaging	Uses additives to interact with food products and improve preservation.	Essential oils, extracts, inorganic and organic nanoparticles like Ag, ZnO	[73]
Antibacterial Packaging	Incorporates antimicrobial nanoparticles to prevent contamination and prolong freshness	Silver or copper nanoparticles, chitosan, essential oils	[73]
Intelligent Packaging	Employs sensors, RFID tags, and indicators to monitor food quality and provide real-time data.	PVA/PLA indicator for CO2, films with purple sweet potato extract and quercetin-loaded chitosan.	[87, 88, 90]
Biodegradable Packaging	Provides an alternative to traditional plastics with natural decomposition properties	Polylactic acid, polyglycolic acid, sugarcane-derived CMC and MgO-NP films, PVA with AgCl and spirulina	[69]
Antioxidant Packaging	Utilizes natural antioxidants to preserve food quality and extend shelf life.	Films with essential oils, plant extracts, polysaccharides, proteins	[73]
UV Protection Packaging	Uses nanoparticles to block harmful UV radiation, preserving light-sensitive foods	Films with ZnO, TiO2, and other UV-blocking nanoparticles	[74, 80]
Photochromic Packaging	Changes color in response to environmental factors to indicate food quality and freshness.	PVA/PLA indicators, films with anthocyanins from purple sweet potato or black wolfberry	[88]

3.3. Nanoparticls Used for Food Waste Mangment

Figure 7 illustrates various food waste materials used for synthesis of nanomaterials, including banana peel, coconut coir, egg-shell, groundnut shell, mango peel, onion peel, pomegranate peel, sapota peel, rice husks, watermelon rind, orange peel, tamarind shell, human hair, algal extract, tea waste, marine waste, and abattoir waste.

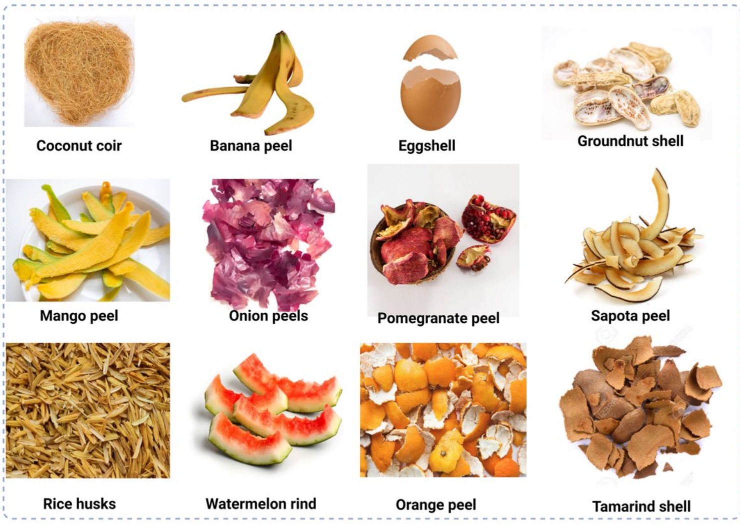

Figure 7: Biowastes commonly utilized for nanoparticle production.

Orange peel accounts for 50–65% of the fruit's weight. It contains various proteins, bioflavonoids, soluble fibers, and insoluble fibers, compounds of which could produce nanoparticles. Skiba *et al.* [91] synthesized silver nanoparticles from plasma chemically extracted orange peel extract and methylene blue degradation under the influence of the sun. Nuts can produce nanoparticles sustainably. Waste nut residue from nuts' shells, kernels, and extracts comprises hemicellulose, lignin, and cellulose. As an environmentally benign reducing agent and bio nanocatalyst, it can help produce bionanomaterials and provide a cheaper catalytic system for oxidation reactions, hydrogen evolution reactions, hydrolysis, and pollutant degradation. This is beneficial since it is natural, sustainable, cost-effective, and reduces waste [92]. Recently, eggshells have been recognized as agricultural waste. Biowaste from eggshells is created daily worldwide; the smell of eggshells is abrasive, it attracts flies, leading to the loss of valuable items from the environment [93]. Households, restaurants, and bakeries generate most eggshell waste. Eggshells, primarily calcium carbonate with little porosity, can be used to make many useful products. Waste egg shells can produce nano-calcium oxide via the sol-gel technique [94]. The eggshell membrane's hierarchical and porous structure makes magnetic $CuFe_2O_4$ nanoparticle synthesis possible. Industrial water treatment benefits from these nanoparticles' catalytic and antibacterial properties [95].

Co-pyrolysis, volarization, anaerobic digestion, and recycling of waste paper biomass can save landfill space and incineration. This method produces value-added items while reducing air pollution [96]. Cellulose, the most abundant biopolymer, is recycled [97] and used to make nanocrystals [98]. Cellulose nanocrystals are used in medication delivery, catalysis, biomedical engineering, and materials research. Isothermal reactions at 1000 °C for 2 hours produce highly porous carbon nanoparticles from waste paper. The major cellulose component of scrap paper is subsequently treated with hydrochloric acid (HCl) to create highly porous carbon nanoparticles, carbon nanopores [99]. The study demonstrated that high-porosity carbon nanoparticles had the capability to eliminate colors and heavy metals from wastewater as a notable reduction in the concentration of dye molecules and Pb + 2 ions was observed. Human hair qualifies as biowaste as it consists of lipids, water, protein, and colors. Burning hair is the customary method, which has a detrimental impact on the environment. Human hair keratin can be used to synthesize Ag as well as Au nanoparticles. Cysteine amino acid, which has amine and thiol functional groups similar to those found in hair, acts as a capping agent to stabilize these molecules. Silver and gold nanoparticles had inhibitory effects against *Pseudomonas aeruginosa, Staphylococcus aureus, Klebsiella pneumoniae,* and *E. coli* [100]. Algal extract from microalgae with cyanobacteria acts as a living cell factory for green nanoparticle manufacturing. Its low energy need, lack of hazardous byproducts, and biomolecules (enzymes and pigments) that reduce and cap are unique advantages. Heavy metal hyperaccumulation and faster development are also observed in the algal extract [101]. An aqueous extract from Marine Algae Sargassum myriocystum can create silver nanoparticles, which is promising. They hinder the Aedes aegypti and Culex quinquefasciatus mosquito carriers, HeLa cells, in their ability to cause cancer, and clinical human disease-causing microorganisms. Subsequent research has demonstrated its efficacy in the treatment of cancer and bacterial infections. Additionally, it demonstrates potential in the process of decomposing methylene blue dye through photocatalysis [102]. Tea waste polysaccharides, caffeine, and tannic acid stabilize metal and metal oxide nanoparticles because of their reducing and capping capacity. Tea trash aqueous extract produces silver nanoparticles that catalyze cationic organic dye degradation [100].

Fisheries waste exceeds 20 million tons per year, comprising 25% of processed fish waste and production, including mistakenly obtained non-target species. Chitin, collagen, bioactive peptides, pigments, and gelatin are important in fish biowaste. Fish biowaste can be used to make carbon dots and nanocarbons from chitosan [103]. Chitosan consists of amino polysaccharides from marine sources. It is essential for the creation of nitrogen-doped carbon nanostructures, which cleanse liquids and gasses, act as catalysts, and capture carbon dioxide [104]. N-doped carbon-covered nickel nanoparticles were produced in another work. These nanoparticles were made by pyrolyzing chitosan for carbon and nitrogen. By providing adsorption sites, nitrogen doping in the carbon nanotube network creates densely connected, extremely stable, and homogeneous nickel nanoparticles. It also enhances molecular hydrogen diffusion and nitroarenes adsorption by providing several reactive sites. Thus, it is an effective and reusable catalyst for selective hydrogenation of nitroarenes into their amines [105]. Although humans eat a lot of meat, much of the animal is wasted. After processing, 50-54% of cows, 52% of sheep or goats, 60-62% of pigs, 68-72% of chickens, and 78% of turkeys are used for meat. The rest is garbage (Regulations 2003). After evisceration, removing the heart, lungs, intestines, and kidneys is difficult. Natural processes break down most slaughterhouse waste. Lack of knowledge or comprehension prevents proper disposal; therefore, it is permitted to decay, releasing pollutants and spreading disease-causing microorganisms. This practice has spread worldwide to become a global issue. To achieve a highly efficient and helpful end product, waste must be recycled, reused, and repurposed. Zinc oxide nanoparticles can be synthesized from goat slaughter waste [106]. In addition, some applications of green synthesized nanoparticles are illustrated in Figure 8. First identified for its anticancer activity, pineapple peel waste extract was used to produce silver nanoparticles (Ag NPs) that demonstrated antioxidative, antidiabetic, and cytotoxic effects on HepG2 cancer cells [107], as well as antibacterial activities. It is efficacious in treating acute ailments and in the production of pharmaceuticals to combat diseases such as cancer and diabetes. Additionally, it is utilized in the field of wound dressing and the management of bacterial infections.

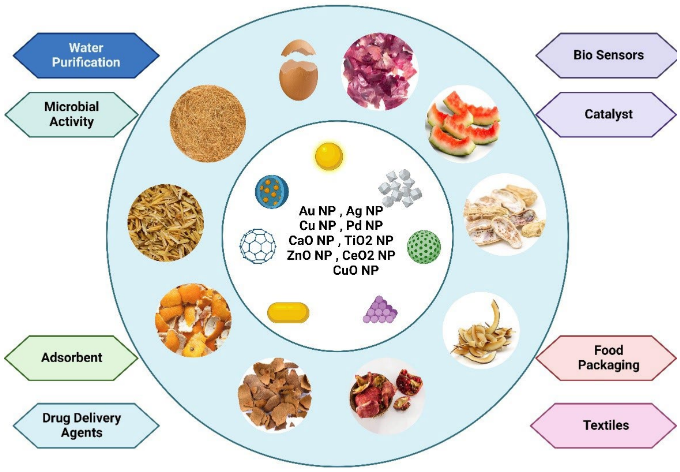

Figure 8: Applications of nanoparticles produced by the green synthesis method using extracts from biogenic waste.

MgONPs were produced using aqueous extracts derived from brown seaweed Sargassum wightii, whereas another study used A Trapa natans peel extract to produce bimetallic nanoparticles. Trapa peel extract yielded 15- and 25-nm silver and gold nanoparticles. These nanoparticles may kill many cancer cells [108]. Bimetallic nanoparticles merge the properties of silver (Ag) and gold (Au) nanoparticles, making them more advantageous than unimetallic ones. Research suggests bimetallic composite nanoparticles (NPs) could replace p53. They cause mitochondrial stress and apoptosis, which mediates p53-independent death in cancer cells via ROS. Due to its efficacy, cost-effectiveness, and simplicity, bimetallic composite nanoparticles could be used in Nano medicine for cancer treatments [109]. The synthesized nanoparticles measured 45–65 nanometers and eradicated both gram-positive and gram-negative bacteria. The bacteria referenced include *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, and *Pseudomonas aeruginosa.* ZnO nanoparticles released Zn^{2+} ions that adhered to the bacterial cell membrane and produced reactive oxygen species (ROS). Reactive oxygen species (ROS) influence bacterial cellular functions via denaturing proteins, lipids, and DNA. Zinc oxide nanoparticles (ZnO NPs) can suppress biofilms of *Pseudomonas aeruginosa*, rendering them suitable for medicinal water disinfection and food preservation. Furthermore, AgNPs synthesized from grape pomace extract (GPE) have shown efficacy against *E. coli* and *S. aureus*. The research investigated the antibacterial response mechanism by identifying bacterial cell membrane rupture and the presence of cytoplasmic components such as nucleic acids, proteins, and reducing sugars [110]. The study showed that GPE-AgNPs combined with conventional antibiotics effectively treated human pathogenic bacterial infections. This study found GPE to be a new source for AgNP biosynthesis, which could provide new nanomedicine options [111].

P. Lestari *et al.* [112] found antibacterial activities in rambutan peel waste extract ZnO nanocrystals. Antibacterial nanocrystals can be used in biomedical nanotechnology to fight pathogens. AgNPs can be made from rambutan peel waste, which inhibits *Salmonella parathypi A*. AgNPs suppress this bacterium, which causes paratyphoid fever (enteric fever), by 4 mm. The third application relates to antiviral activity. It appears that Ag and Au are the most effective metallic nanoparticles against enveloped viruses. Antiviral algae-based silver nanoparticles can be employed in wound dressings, surgical equipment, implants, and more [113]. Many applications have been developed using silver nanoparticles. Studies show that silver nanoparticles have become increasingly important, especially during the COVID-19 pandemic. Antiviral silver nanoparticles (Ag NPs) can reduce SARS-CoV-2 replication [114]. AgNPs impede virus nucleotide replication by bonding with microorganism enzyme electron donor groups such as sulphur, oxygen, and nitrogen. The enzymes denaturate, rendering the cell's energy supply inefficient, killing the bacterium quickly [115]. A different study found CuO-NPs effective against HSV-1. In the Vero cell culture system, CuO-NPs prevented HSV-1 infection by blocking HCV infectious virions from entering and attaching to hepatic host cells [116]. Finally, De *et al.* [117] developed an eco-friendly and cost-effective way to synthesize silver and gold nanoparticles from water waste. These metallic noble nanoparticles were made from discarded corn-cob aqueous extract. Catalytic characteristics of biosynthesized nanoparticles included nitrophenol reduction and organic dye degradation, making them effective water treatment catalysts. Methylene blue is a positively charged thiazine dye. It dissolves easily in water and is used in photography, printing, and textiles. Ocular burns, nausea, heavy sweating, cognitive disarray, methemoglobinemia, and emesis can arise from methylene blue toxicity in humans and animals. The report found that ZnO nanoparticles produced from dragon fruit peel extract and exposed to sunlight reduced Methylene blue dye concentration by 95% in 120 minutes. This cost-effective, beneficial, and sustainable technology removes organic pollutants from water-based solutions utilizing sunlight [118]. Tea waste extract can form iron nanoparticles, according to Gautam *et al.* [119]. The iron nanoparticles displayed a zeta potential of -45 mV at pH 10, indicating their aqueous stability, while the average particle size of tea extract iron nanoparticles was near 98 nm, and their zeta potential was -45 mV. Iron nanoparticles from tea extract can adsorb phenol red from an aqueous solution at pH 8. Cauliflower waste contains silver nanoparticles that can efficiently degrade the methylene blue dye through photocatalysis and also enhance the sensitivity of detecting mercury ions. Silver nanoparticles (AgNPs) that possess the appropriate size and shape exhibit a significant surface area-to-volume ratio, rendering them highly suitable as catalysts for the degradation of dyes [120].

4. Conclusions

Nanotechnology offers transformative potential in enhancing food safety and hygiene through various innovative applications. It enables rapid pathogen detection, improves food packaging, and extends shelf life while also posing some regulatory and safety challenges. Future research should focus on advancing nanotechnology applications, developing sustainable and biodegradable nanomaterials, and establishing robust regulatory frameworks. By addressing these challenges and leveraging the unique properties of nanomaterials, nanotechnology can significantly contribute to the safety, quality, and sustainability of the global food supply.

5. Future Directions

Nanotechnology in food safety and hygiene is a rapidly evolving field with significant potential for future developments. Key areas for future research and innovation include:

- Enhanced Pathogen Detection: Development of more sensitive and specific nanosensors to detect a broader range of foodborne pathogens and toxins with higher accuracy.
- Smart Packaging Solutions: Integration of advanced nanomaterials into packaging that can provide real-time monitoring of food quality, such as changes in freshness or contamination levels, through visual indicators or electronic signals.
- Sustainable Nanomaterials: Focus on developing biodegradable and eco-friendly nano-materials that can reduce environmental impact while maintaining or enhancing food safety and quality.
- Regulatory Frameworks: Establishing comprehensive guidelines and regulations for the safe use of nanotechnology in food applications to ensure consumer safety and environmental protection.
- Consumer Acceptance: Addressing public concerns and improving understanding of nanotechnology applications in food to gain consumer trust and acceptance.

Author contributions: Farhang Hameed Awlqadr: Project administration, Writing – original draft. **Ammar B. Altemimi:** Writing – original draft. **Syamand Ahmed Qadir:** Writing – review & editing. **Tablo Azad H. Salih:** Data curation, Formal Analysis. **Aryan Mahmood Faraj:** Investigation. **Rawaa H. Tlay:** Writing – review & editing. **Tarek Gamal Abedelmaksoud:** Formal Analysis. **Franscesco Cacciola:** Writing – review & editing.

Conflicts of interest: The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Funding: The authors did not receive support from any organization for the submitted work.

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