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Review Article

Current Trends and Future Perspectives of Nanomaterials in Food Packaging Application

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Nanotechnology can improve the mechanical barrier and the antimicrobial (which will not allow the invasion of microorganisms in the food, increasing the food barrier properties, hence can be a very promising material for food packaging. Nanomaterials will keep the food fresh in the food packaging design. Silver nanoparticles and nanoclay represent most of the nanoempowered food packaging available on the market others like zinc oxide and titanium share little of the current market. Zinc oxide enhances nutritional values in food products by adding nutrients. It helps improve the flavour, storage properties, appearance, and texture of the food. Titanium dioxide is used for food safety purposes since it prevents food from spoiling and increases the food's shelf life. In current food packaging, these nanomaterials are used to grant antimicrobial capacity and further develop hindrance properties, broadening packaged food's shelf life and newness. Nanofood packaging has many benefits for general wellbeing. The related harmfulness of migration, particularly in acidic conditions, is extensive. The use of nanomaterials because of their physical and chemical properties makes them broadly accessible in numerous areas. This review summarizes the antimicrobial packaging application, nanomaterials synthesis, and nanomaterial properties in food packaging.

1. Introduction

Nanomaterials are unique structures that have dimensions from 1 to 100 nm. In epitome, the word nano is prompted from an ancient Greek, where the noun—Nanos—is used in the meaning of dwarf. Nanomaterials are mainly powdery and are made up of nanoparticles. Since the size of particles is less related to the macroscopic structures of the identical compound, they have unalike chemical and physical properties (Figure 1). Nanotechnology is the science of the mixture, pattern, and characterization use of small-sized substances. It is the fine art of particle manipulation. It has been called technology at the nanoscale since it produces nanostructured materials with new assets and purposes. It is the growing field in science research and development in nanotechnology and nanoscience [1].

Nanotechnology applications are found in unalike areas such as environmental protection, pharmaceutical industry, new materials evolution, agriculture, food processing, and packaging. It is well known that nanomaterials might be pragmatic in most phases in the production of food, for instance, in the agricultural sector, the use of nanoemulsion pesticides, in the food production sector, the usage of nanoceramic devices for large surface areas, and in the maintenance sector, the use of merged nanoparticles into packages or nanosensors for intensive care and detection. Nanomaterials are used in food packaging and incorporated in many food products like silver dioxide and titanium dioxide used as a color, flavour, taste, and food agent [2]. Nanotechnology is one of the most developing technology in recent times. Nearly 400 companies developed their application on nanomaterials in the food industry worldwide. According to the report on the global market supply of nanoenabled packaging for food and beverages by 2020 has predicted that in 2013, there are around 6.5 billion and excepted to reach approximately 20 billion by 2020 [3].

The most common nanoparticles used in the food industry are metal nanoparticles used for packing materials, storage, shape at the nanoscale for nanosensor manufacturing, united active nanoparticles for migration properties, nanopore filters for purification, and nanoencapsulated additives and nanosized food and nutrients used as supplements. The disease caused by food contamination has increased in the last decade [4]. Food packaging helps stock, protect and conserve food from a microorganism and safely deliver food over a longer distance. It can provide healthy and nutritious food products. For food packaging, many nanomaterials are used, such as titanium dioxide (TiO_2), silicon oxide (SiO_2), nanozinc oxide (ZnO), silver nanoparticle (AgNP), nanostarch, nanoscaled cellulose, carbon nanotubes (CNTs), and nanosilica. Different nanomaterials are zinc, titanium, silicon, and silver, but silver nanoparticles are most productive as they have properties like antibacterial and antiviral and are used as drug disinfectants [5]. Each nanomaterial has a different chemical structure, properties, and characteristics. So each nanomaterial has a different application in food packaging. Silver nanoparticles, starch, and nanozinc oxide have a large surface area than macroparticles and microparticles [6].

Nanoparticles can be used as a nanosensor to notify the consumer if the product is no longer safe to consume as some people are worried about the risks of nanotechnology as it could affect health. For example, for antibacterial milk bottles for babies, barcodes for guaranteed food security are good for most people because it does not affect a person's health. Rather it notifies the consumer about the condition of the food. The use of nanomaterials has both pros and cons. If people are affected by the disease or health risks, they may not consume nanoparticles food. So nanoparticles are more widely used in packaging to reduce health issues. Nanomaterials are economical and eco-friendly to be utilized in food packaging. If the rate of nanomaterials increased, the production would decrease. The usual costs and methods used for the production and improved nanomaterial application will increase the food's shelf life. Innovatory packaging with a higher cost is usual [7].

The main aspect of food packaging is to preserve it from many things like insects, microorganisms, physical damage, and dirt. They should also be easy to distribute and should easy to handle. Nanotechnology can improve the mechanical, barrier, and antimicrobial (which will not allow the invasion of microorganisms in the food, which can then improve the barrier life of the food) properties that can be very promising to be used as the material of the food packaging. The nanosensors can also notify the state of the food during transport and storage, which will be very beneficial. Because of these many reasons, the world's largest food packaging companies are studying and researching it to explore the potential of polymer nanotechnology [8].

Nanomaterials used in food packaging can be divided into two parts.

(1) Improved packaging in these nanomaterials blend with polymer to enhance gas barrier properties' dampness resistance of packaging

(2) Active packaging includes active components in food by using nanotechnology. It will protect food shelf life by interacting carrier components with internal and external factors

Regarding food nanotechnology, an investigation is still in the evolvement of new food supplements and packages with exclusive assets, applications, and purposes due to the participation of nanomaterials in this area. Antimicrobial packaging materials do not allow the invasion of microorganisms in the food, preventing food spoilage and foodborne diseases. We can assume that in the future trends, the active packages might have extra-active packages, as they will have antimicrobial (which will not allow the invasion of microorganisms in the food, which can then enhance the shelf-life of the load) activity, atmosphere control, a protective barrier (which will protect the food), barrier properties (which will help to reduce the requirement of the material needed to make the product as lightweight materials manufacture them), and biodegradability (which is the most important thing so that it does not cause environmental damage), all in one package. The aspect of preserving the food standard and package material of the food should evolves as well,

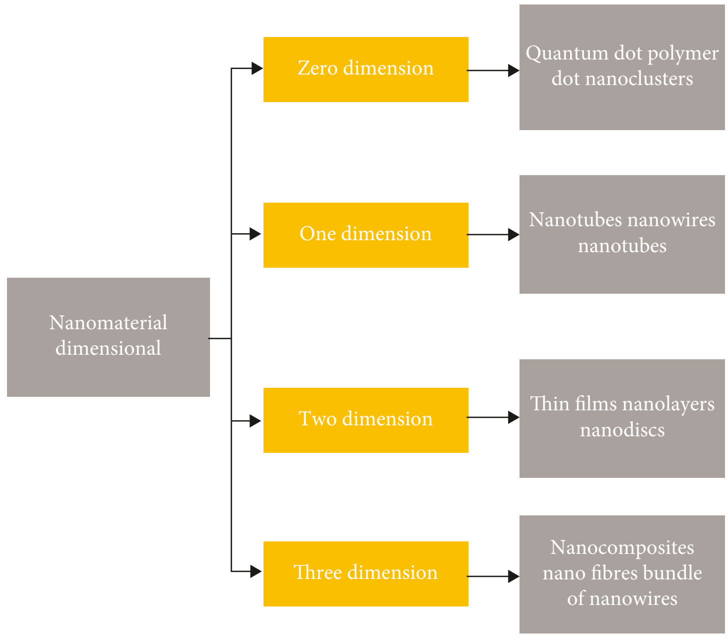

Figure 1: Dimensional classification of nanomaterials.

and some active packages maintain the food shelf life by letting out separate compounds, and there are also the intelligent packages, which notify the consumers whether the food is safe to consume or not. Also, there are antimicrobial packages embodied with probiotics, a new method of biopreservation [9].

Many antimicrobial nanostructures are used for food packaging purposes as they act by different mechanisms and with dissimilar implementations. Despite nanotechnology being so promising in food packaging, many flaws need to be sorted out like the toxicity levels, their migration, and storage by keeping the safety of humans and the environment in mind as there is still very little scientific data about them which should be explained before the product approval for the food market. Discussing food consumed by humans and insufficient information about the safety of several types of nanoparticles, many agencies take the safe approach by migrating the nanostructures into a lower food than the detection limits [10].

It is a fact that the food packaging sector will be benefited from the antimicrobial nanocomposites as they remove (stops growth or kill) microbial growth on the surfaces, but there are some major drawbacks to being nanosized. They have a very large surface area. It can make a very large contact with a great capacity for absorption and migration as well as in cell membranes. As we know, nanostructures can move more freely than higher scale ones. Exposure to nanoparticles in food packaging can be done through 3 methods which are the following: dermal contact, ingestion, and inhalation of the food, and nanoparticles enter the food chain by being eventually released into the environment indirectly as we can deduce that if nanoparticles are in the package of food, then it might eventually come in contact with the food. The migration of the nanoparticles will eventually have some effect which will then promote sensory changes in the food. It necessitates investigating how heat might affect health after the ingestion of nanoparticles [11].

This paper highlights the works done globally in the field of nanomaterial biosynthesis. Plant extracts can synthesize nanomaterials using different parts of the plant like root, shoot, and leaf, which can lead to various nanoparticles, such as silver nanoparticles. Nanoparticles can also be synthesized with the help of microorganisms which reduce the metal salts and accumulate into the small-sized nanoparticles. Furthermore, by the action of bacteria, fungi, yeast, and biological particles, nanomaterials are known to get synthesized. Such nanomaterials are used vastly in the agriculture and food industries [12]. The various nanomaterials were developed in the food industry. For example, nanosalt delivers the nutrients, casein micelles in milk, etc. [3].

Food packaging has many roles in the quality maintenance and safety of food. By combining active substances and food packaging materials, control over food contamination through surface microbial action can be done. One such packaging technique is active packaging, which involves a relation between packing and food by incorporating materials like nanoparticles and nutrients to achieve food quality and safety. Widely used active packaging sums involve antioxidants and antimicrobials. Another type of packaging is intelligent packaging used to monitor the packaged food condition. Another technique is used to ensure increased shelf life and retention of water in the case of fruits called biodegradable coatings, even though they highly affect the taste of the fruits. These are prepared by using natural biopolymers, etc. Organic and inorganic nanoparticles have come into the light to have been used in the active packaging [13].

Silver nanomaterials are one of the newest members of the material design field. These have a better surface area than that of normal silver. Nanosilver enhances the different aspects of food packaging material and antibacterial aspects. These are capable of destroying the bacterial structure and the normal metabolic function. The nanomaterial silver surface can be easily oxidized off, leading to the release of more silver ions that can resist light, heat, and bacteria. Another material used is nanotitanium dioxide which has exceptionally high catalytic and antibacterial properties. It is nontoxic and tasteless and therefore used in fruit and vegetable packaging. It can oxidize and decompose ethylene produced in the storage of vegetables and fruits, eventually leading the fruits to remain fresh for a longer time. Another one is nanosilicon oxide. It has no pollution and is tasteless. It has good compatibility, permeability, and strong thermal stability [14].

Application of nanoantibacterial materials: the most known one is zinc oxide with characteristics of stability and catalysis. It is a kind of wideband gap semiconductor used in food packaging. In the food packaging industry, it is widely used, for instance, in breakfast cereals, bread, etc., owing to its ability to have a remarkable effect on the control of antibacterial preservation of food. For the application of nanobarrier materials, nanoclay's good heat resistance and natural viscosity reduces water absorption and improves rupture rate, and tensile strength increases shelf life. Carbon nanotube-small cylinder of nanometer size-strong mechanical properties still poses a safety problem. Nanocopper is more active, easily oxidized, and has a strong extension, pure substance, superplasticity, and ductility. Nanomaterials' detection technology is pretreatment technology is soaking microwave digestion direct calcination at high temperature. Imaging technology is a microscopic observation to understand the distribution, and component analysis technology is to observe and analyze nanocomponents and distribution in food packaging, chromatography, spectroscopy, and mass spectrometry. Problems of nanomaterials in food packaging design lack screening and separation methods—nanoparticles do not have a physical and chemical performance standard and no functionality linked to toxicity caused by nanoparticles [14].

This review depicts the current employments of nanomaterials in the food area and sums up an outline of the accessible information on the safe usage and possibilities of nanomaterials in food packaging.

2. Understanding the Prerequisite Properties

One of the major aspects of packaging food is the preservation and shielding from many things such as insects, microorganisms, physical damage, and dirt. They should be easy to distribute and should be easy to handle. Nanotechnology can improve the mechanical barrier and the antimicrobial, which will not allow the invasion of microorganisms in the food, increasing the food barrier properties, hence being a very promising material for food packaging. The nanosensors can also notify the state of the food during transport which is a very beneficial application (Figure 2). Because of these reasons, some of the top packaging companies worldwide are now studying and researching to explore the potential of polymer nanotechnology [9].

Nanoparticles can be used by nanotechnology because of their excellent mechanical, thermal, and barrier properties, and it also helps by preventing the invasion of bacteria, which can harm the product [15].

2.1. Types of Nanomaterials

2.1.1. Polymer Nanomaterials. Polymer nanomaterials are particles that can be entrapped with active compounds within or on the surface. Polymer nanomaterial-based food packaging is applied, so that food's quality is enhanced and also safe, economical, increases the shelf life, enhances mechanical and microbial resistance properties, and is also highly advantageous to the environment. It is most commonly used in the manufacturing/packaging sectors for its high yield of products in developed countries. Polymer nanomaterial can enhance the performance over barriers like ultraviolet rays and also adds stiffness, strength, and heat resistance compared to commercial packaging of gases like O_2 and CO_2. Applying polymer nanomaterials in food packaging sectors may increase the barrier properties in food packaging, active packaging, intelligent packaging, and biopolymer degradation. This can be applied to commercial packaging for various products like beverages, carbonated drinks, bakery foods, and meat products. The polymer nanomaterials for food packaging (PNFP) are of two methods: prepolymerization and postpolymerization. Even though PNFPs have many advantages, they have disadvantages, such as causing several health issues like inhalation, penetration into skin, and ingestion [15, 16].

There are 2 types of polymers: biodegradable and nonbiodegradable. Biodegradable is then classified as natural biopolymers: carbohydrates, including starches of wheat and maize and potatoes, and proteins, including animal (gelatin) and plants (gluten). Biodegradable polymers are classified into chemically synthesized (like polyglycolide and polyvinyl alcohol) and microbial (polyhydroxy butyrate). Nonbiodegradable polymers are then classified into nylons, polyurethane, and polyolefin. Nanomaterials are also classified into 2 categories organic and inorganic. Organic is further divided into nanofibers which contain cellulose, starch, and chitin. Inorganic is classified into 2 categories: nanoclay (hectorite, saponite, and organically modified clay) and metallic nanoparticles (silver, copper, and gold). Nanoparticles can spread inside humans via 3 sources which are inhalation, dermal contact, and oral ingestion, and it can be evaluated by checking their toxicities and the particle's size (sell or big), and smaller particles are faster to be absorbed (Figure 3) [17].

2.1.2. Biopolymer Nanocomposites. Most polymer nanocomposites and synthetic polymers are hazardous to the ecosystem. So biopolymers can be used as an alternative to synthetic polymers. Biopolymers are synthetical polymers that can be easily degraded in the soil and are eco-friendly to the atmosphere. However, biopolymers exhibit low mechanical and thermal properties. There is a need to enhance the properties by changing the organic structure of clay. This will increase the mechanical properties of the

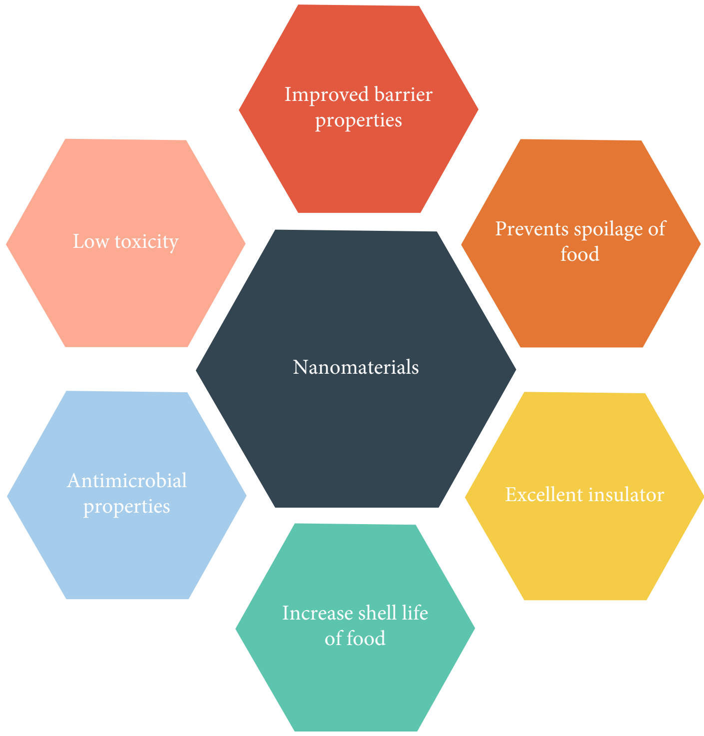

Figure 2: Properties of nanomaterials.

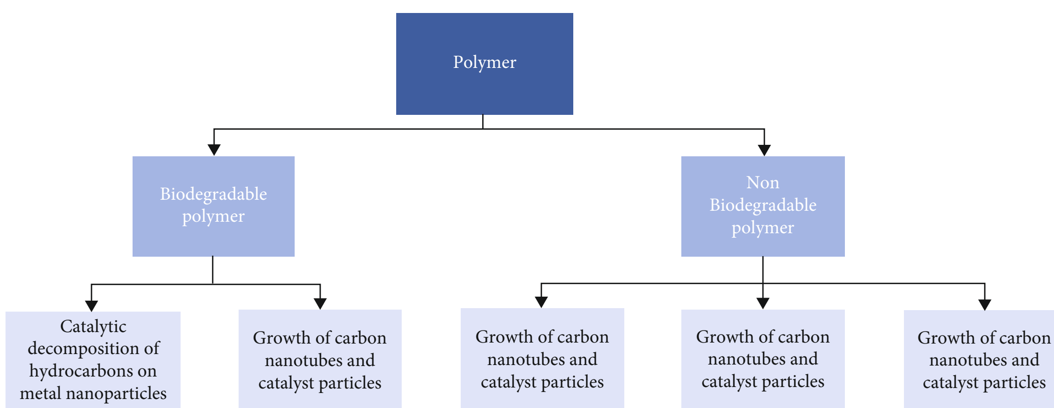

Figure 3: Classification of polymers [17].

biopolymer nanocomposites. For example, modifying the clay structure of montmorillonite into organic ammonium salts (such as hexadecyl tributyl phosphonium bromide, acetyl trimethyl ammonium bromide, and corn starch) makes the biopolymer exhibit high mechanical property. This makes a structure renewable, degradable, cheap, and easy to use. This modified organic structure highly exhibits antibacterial properties, especially against *S. aureus* and *E. coli* (most common food-borne bacteria), which are later visualized and analyzed under X-ray diffraction, Fourier spectroscopy, and SEM [18].

2.1.3. Antimicrobial Nanomaterials. It is the application of active packaging. Antimicrobial packaging materials prevent food spoilage and foodborne diseases by decreasing microbial action. Some examples of antimicrobial nanomaterials are TiO_2, Ag, Fe_3O_4, ZnO, and CuO. Many antimicrobial nanostructures are used for food packaging purposes as they act by different mechanisms and with different extents of implementation. Despite nanotechnology being so promising in food packaging, many flaws need to be sorted out, like their toxicity levels, migration, and storage, by keeping the safety of people and the environment in mind. This should be explained before the approval of the product in the market [19]. Maintaining the quality of the packaging material should evolve as well. Some active packages maintain the food shelf life by letting out separate compounds, and also, certain intelligent packages notify the consumers whether the food is safe to consume. Also, there are antimicrobial packages embodied with probiotics which is a relatively new method of biopreservation. By keeping all these things in mind, we can assume in the future that active packages might have extra-active packages, as they will have antimicrobial properties, atmospheric control, a protective barrier (to protect the food), strong barrier properties (which will help to reduce the requirement of the material needed to make the product as lightweight materials manufacture them), and biodegradability (which is the most important thing so that it does not cause environmental damage), all in a single package [20].

2.1.4. Gelatin-Based Nanomaterials. Nerus has proved that using waste products from the environment, such as fish, prawns, gills, and poultry waste products, can synthesize waste products and produce gelatin, protein hydrolysate, bioactive peptides, and collagen. The gelatin from the poultry waste is largely used because of its high protein composition, distribution of molecular weight, and amino acid content. Gelatin includes the functional groups of COOH, -OH, and NH_2 and amino acids' hydrophobic and hydrophilic structures. This can be further blended with other polymeric functional molecules. Gelatin can be engineered with nanocomposites to produce the gelatin-based nanocomposite for food packaging. The gelatin-based nanomaterial for packaging has many beneficial properties like high physic-chemical nature, flexibility, brittleness, biodegradability, water resistance, lower costs, natural abundance, high moisture content, and renewability does not cause any adverse effect on humans as well as on the environment [21].

2.1.5. Cellulose-Based Nanomaterials. The advancement of biobased materials is used in various fields for its unique characteristics. They are eco-friendly, nonhazardous, and have easily binding properties. Likewise, the biobased materials are incorporated with nanocomposites to form nanocellulose material structures that exhibit high physical and mechanical properties and can be applied in food packaging sectors. The structure of nanocellulose is distinguished in two ways: cellulose nanocrystals (CNC), which are also known as microcrystalline cellulose (MCC), and cellulose nanofibrils (CNF), also known as cellulose microfibrils. For the bacterial cellulose nanofibrils/nanocrystals (BCNF/BCNC), the enzymes were processed to increase the thermal stability (against acid hydrolysis by 184°C) and tensile strength to fulfill the basic requirements of assured food quality, improve shelf-life, enhance water resistance, and to avoid the formation of films in humid food products. The coating property of nanocellulose materials (biopolymers) needs to be improved and is irreplaceable over conventional packaging methods because of its low performance [22].

2.1.6. Electrospinning of Nanofibers. Electrospinning is an electrohydrodynamic process, a simple technique to produce nanofibers material from a viscoelastic fluid with an electrostatic field. It helps to produce electrospun nanofibers with secondary structures and functions. It contains four major factors:

(1) A high-voltage power supply

(2) A syringe pump

(3) A collector

(4) A spinneret

The viscoelastic fluid pushed in a firm of a droplet through a spinneret the tip of the syringe. The power supply is sufficient to overcome the surface tension, the droplet formed into a conical shape. A jet is ejected from a cone and then elongated partly in the form of an expanding helix. Finally, the nanofiber is received on the grounded collector by stretching a polymer solution droplet. The surface of nanofibers has functionalized with nanomaterials during the electrospinning process. The electrospun nanofibers have air and water purification applications, protecting the environment, storing energy, food packaging, and drug delivery. The electrospinning has a nonthermal process, which allows the heat-sensitive compounds to enhance the stability of food during processing, handling, and storage [23, 24].

2.1.7. Microstructure of Nanomaterials. In green products, the only antimicrobial bacteriocin used by more than 40 countries worldwide is nisin (which is produced by 3.5 kDa of a cationic polypeptide from lactococcus lactis strain) known as antimicrobial peptide (AMP) to enhance the biopreservation property of food products. The biobased structure of the nisin microstructure was encapsulated with nanoliposome to produce the biodegradable coating material and films. This encapsulated material will ultimately increase the film thickness, tensile strength, and oil resistance, maintains moisture content oxygen permeability, and blocks CO_2 and transparency against ultraviolet (UV) rays. Unlike some structures, this will form a stable structure because of liposome binding property and targeting to regions. Also, this is more eco-friendly and does not cause any harmful effects [25].

For the packaging of liquid foods like water, juice, and other organic solvents, the surface should have the superhydrophobic (SHP) property with a high contact water angle of more than 150° and a sliding angle of less than 10°. The silica nanoparticle is coated over the paper material in this packaging process by a one-step spray coating method. This can be controlled by the top-down method for repellency of liquids to avoid contact, self-assembling, self-cleaning, and compatible and to existing surfaces. This process can be analyzed or tracked with the device of nanosensors. The microstructure with nanoparticle deposition combines to form the inherent structure of fluorinated silica nanoparticles, exhibits high mechanical performance, polymer matrix, anti-icing/antifreezing, and water/ice repellency, and is very useful to protect the liquid food from retaining the same structure [26].

2.1.8. Bimetallic and Trimetallic Nanoparticles. Two or three different metals/metal oxides are combined to form the bimetallic and trimetallic nanoparticles (NPs), which can be widely used in the food packaging sector because of their improved physic-chemical properties compared to monometallic NPs. Multimetallic NPs are made up of bi and trimetallic nanoparticle (CuPd, PtPd, AuPd, and FePd,) which exhibit the enhanced property of high heterogeneous catalytic activity, optical, heterodimer, and nanoalloys over monometallic NPs. Most of the commercial method of packaging is difficult, time-consuming, and costly, so many food packaging sectors are looking up for the alternatives like green methods (using plant extract, enzymes, and also cellulose), facile, and simple approaches to have the properties of high physical and mechanical performance, cheap, and efficient. When it comes to food packaging, food safety is much more important. The hybrid method of NPs will also work under top-down and bottom-up methods to protect the food packages, increase shelf-life, and be eco-friendly to the environment. This nanoparticle can be applied to food packaging to minimize contamination, increase the shelf life, maintain the moisture content, and many more. For example, it can be applied to meat, fish, vegetable, fruits, bread, cake, and dairy food which can be stored for a long time. However, it has many advantages in various ways (like cheap, easy, and maintaining food safety), but it is very hazardous to human health because of the migration of nanoparticles which may settle in the central nervous system (CNS) and trigger the whole body immune system [27].

2.1.9. Graphene Green-Based Nanomaterials. Graphene has been synthesized from a single layer of graphite, it is the mother of all carbon atoms, and carbon atoms are hexagonally positioned. It is a strong material but thin in size. The large graphene family contains nanoplatelets, chemically modified, and reduced graphene oxide. There are properties of graphene, for instance, high melting point, high, large surface area, thermal conductivity, antimicrobial properties to improve food packaging application, and high resistance. Incorporating graphene oxide into the food packaged material promotes thermal and light stability and withstands transport and handling. To make graphene a barrier in the production of food packaging, the graphene is transformed into graphene oxide, which forms very thin layers of films. Then, the graphene oxide is reduced, forming thick barrier films [28, 29].

Table 1 accumulates the types of nanomaterials mentioned above and exhaustively explains their advantages and disadvantages.

2.2. Nanomaterials Deployed in Food Packaging. Nanomaterials like clay, zinc oxide, titanium dioxide, silver, carbon nanotubes, copper, and copper oxides are commonly used in food packaging. These can enhance the physic-chemical qualities (color, odour, flavour, measured weight, moisture content, and physical texture), microbial resistance, especially for food-borne diseases, eco-friendliness, and Trojan horses [15].

2.2.1. Clay Nanoparticles. There are many applications of clay nanoparticles in the system as antioxidants and carriers for vitamins. Clay nanoparticles have the properties to purify the blood, reduce food contamination, and cure stomach ulcers antidiarrheal drugs. The single layer of nanoparticles contains tetrahedral and octahedral sheets, and these arrange themselves like pages of a book. Nanoclays can reduce the permeability up to 50% carbon dioxide and 30% of moisture. The oxidation of lipids is reduced, and the shelf life of meat products is extended. Low specific gravity and thigh aspect ratio leads to less compatibility. Therefore, packing is not possible [37].

2.2.2. Silver. Silver is well known for its antimicrobial properties. Degradation of lipopolysaccharides can happen when silver binds itself to the cell's surface, and the membrane develops a pit. It has been reported that silver contains low-density polyethylene, which prolongs and preserves the shelf life. Silver can have a synergic effect and atmosphere packaging modified with 50% N_2 and another 50% CO_2 for extending the shelf life of Fior di latte (cheese) by using or not using the traditional covering liquid [38]. Silver nanoparticles are ideal for creating packaging films. They showcase remarkable thermal performance and mechanical properties. They can significantly reduce the flammability significantly, and the transparency of the polymer matrix is always maintained. There is always a risk because the nanoparticles in the food can migrate and can cause an imbalance in the use of biomass for producing food [39].

2.2.3. Zinc Oxide. Zinc oxide is mostly used for degrading microorganisms and other organic molecules as a photocatalytic agent. Zinc oxide enhances nutritional values in food products by adding nutrients to them. It helps improve flavour, storage properties, appearance, and texture of the food and is like a fortifier. Growth, nucleation, and aging mechanisms determine zinc oxide properties. ZnO nanoparticles bind together and form agglomerate, reducing some functional properties. Melanin is a biologically active compound with much functionality and acts as a stabilizing agent. Zinc oxide contains a lot of mineral elements. Zinc oxide exhibits strong antibacterial activity. Zinc oxide enhances barrier properties and hydrophobicity. Zinc oxide is visible on the skin as an opaque white layer. Zinc oxide leads to noneco-friendly byproducts. Some reactive oxygen species are thus formed, mitochondrial disconcertion occurs, protein denaturation can also happen, and there is a slight chance of phagocytosis function disruption [40].

2.2.4. Gold. It has been shown that gold nanoparticles can be used in food packaging. As a stabilizer, ionic silsesquioxane is used in the solution to reduce gold salts. This results in the formation of gold nanoparticles. Nanoparticle synthesis requires the use of this stabilizer. In addition, it contains quaternary ammonium groups that can be dissolved in water and are renowned for their antimicrobial properties. This system is very promising for fabricating bioactive films. Biofilms are enhanced mechanically, optically, and morphologically by gold nanomaterials. It showed strong antibacterial activity against food-borne pathogens. A tendency for temperature integrators to freeze over time causes irreversible agglomeration of gold nanoparticles and loss of red color. They are more expensive than the other nanomaterials [41].

Table 1: Various types of nanomaterial and their properties, advantages, and disadvantages.

Materials	Properties	Advantages	Disadvantages	Ref.
Clay nanoparticle	Clay nanoparticle materials were created primarily to improve UV and gas barrier characteristics while also providing heat resistance, stability, strength, and stiffness; as a result, they are utilized in food packaging. Clay nanoparticles improve their characteristics by determining the morphological arrangement based on enthalpic and entropic variables.	Nanoclays can lower moisture and carbon dioxide permeability by 30% and 50%, respectively. Meat products' lipid oxidation is reduced, and their shelf life is extended.	Low specific gravity and thigh aspect ratio leads to less compatibility. Therefore, packing is not possible.	[30]
Silver	Antimicrobial packaging, carbon dioxide absorbers/emitters, ethylene removers, and oxygen scavengers. Silver mechanisms include adherence to the cell surface, DNA damage in bacteria, penetration into the cell of the bacterial, further antimicrobial Ag+ ions are released, and formation of pits in the membranes.	Silver significantly improves its mechanical properties, barrier, and antimicrobial properties. They can significantly reduce flammability while maintaining the polymer matrix's transparency.	Containers containing Ag nanoparticles prevented microbial growth for up to 10 days. Extending the shelf life of food packaged items reduces waste creation.	[31]
Zinc oxide	Zn improves antibiotic, antibacterial, and antifungal capabilities. The antibacterial activity and potential activity of ZnO-NPs on Salmonella typhimurium and Staphylococcus aureus in prepared poultry meat have been found to prevent food from bacterial contamination and are thus beneficial in food packaging.	Photocatalytic agents and UV blockers disinfectants, zinc oxide acts. Zinc oxide contains a lot of mineral elements. Zinc oxide exhibits strong antibacterial activity.	Zinc oxide is visible on the skin as an opaque white layer. Zinc oxide leads to noneco-friendly byproducts.	[32]
Gold	The influence of the different factors on the lower critical solution temperature (LCST) on a solid-water interface is determined using gold nanoparticles.	A coating on PET bottles will allow delicate juice or beer drinks to be packaged more effectively.	Freezing is caused when the gold nanomaterials are agglomeration is irreversible, leading to the loss of the red hue in time-temperature integrators.	[33]
Titanium dioxide	The oxidation of fatty acids and polyunsaturated phospholipids in the microbial cell membrane generated reactive oxygen species and hydroxyl radicals on the surface of TiO_2. It was discovered that the color recovery rate and degree of oxygen exposure were proportional.	The addition of TiO_2 to polylactic acid increases in shell life of mangoes by up to 15 days. TiO_2 is inert and nontoxic.	Rancidity is caused by TiO_2 migration into the lipid matrix.	[34]
Tin oxide	SnO_2 was employed as a photosensitizer for oxygen indication in which the film color changes depending on the amount of oxygen present.	Tin oxide is used because they are feasible for packing. Compactness, high density, unrivaled toughness.	It is used widely in the EN system for the food quality analysis.	[35]
Starch	Starch is commonly utilized because of its poor barrier characteristics, water sensitivity, and brittleness. The mechanical characteristics of titanium oxide are improved, and UV protection is provided.	Starch is inexpensive and widely available	Starch cannot be used directly; it must be added with other nanomaterials.	[36]

2.2.5. Titanium Dioxide. White foods such as dairy products are enhanced and brightened with titanium dioxide's food-grade form. Titanium dioxide is used for food safety purposes since it prevents food from spoiling and increases the sensitivity food will increase shelf life. Also, it is extremely hot—its melting point is 1,843°C, and its boiling point is 2,972°C, so it occurs naturally in solid form and is insoluble in water even when in its particle form. It also acts as an insulator. This prevents the spoilage of food and increases the shelf life. It acts as a UV light filter. TiO_2 is inert and nontoxic. Biodegradable films can change their properties, and it is not toxic, inexpensive, and photostable.

Titanium dioxide and other nanomaterials are the chief sources of nanoparticles or nanoparticles released to the environment through the production, waste treatment, use, and disposal processes for these products. Migration of TiO_2 into lipid matrix results in rancidity [42].

2.2.6. Tin Oxide. Titanium oxide is a colorant used to brighten and improve the color of white foods like dairy products. Titanium oxide is used for food safety to stop deterioration and extend the shelf life of foods susceptible to UV radiation. It also has a melting point of 1,843°C and a boiling temperature of 2,972°C, thus in particle form. TiO_2 is an insulator. It can alter the characteristics of biodegradable films that are low-cost, nontoxic, and photostable [4].

2.2.7. Starch. Starch is found in many plants as a source of stored energy, plant roots, cereals like rice, corn, wheat, potato, and barley. Starch nanoparticles have been prepared using the ultrasound method without adding corn, plant roots, and wheat. Starch contains barrier properties to protect food from contamination, humidity, and microorganisms. It helps to increase the food shelf life. Starch is inexpensive and widely available. Starch cannot be used directly; it must be added with other nanomaterials [43].

2.2.8. Silicon Dioxide. Many foods and supplements contain silicon dioxide. Essentially an anti-clumping agent, it prevents the clumping of foods. The powdered ingredients are prevented from sticking together with the help of silicon dioxide. Barrier properties and mechanical properties are increased by adding SiO_2 particles. It can act as a disinfectant photocatalytic agent, UV blocker, and water retention. It may be hazardous during the production, application, and disposal process. Because of its high cost, silicon is a significant obstacle to its eventual usage [44].

2.2.9. Iron Oxide. Magnetic iron oxide nanoparticles have been employed in various disciplines because of their unique characteristics, massive surface area, and easy separation with magnetic fields. They have been applied for enzyme immobilization, protein purification, and food analysis in food-related applications. Iron particles were distributed in a silicone matrix, demonstrating a tenfold increase in adsorption capability over commercial iron-based scavengers. Their property is oxygen scavenging ethylene detection by confined molybdate in the nanopores. Iron oxide has low toxicity. Iron oxide has improved the bioavailability of vitamins. Iron has outperformed microsized iron in terms of decreasing O_2 and water vapor permeability. Hydroxyl radical formation takes place [45].

Each nanomaterial has a different chemical structure, properties, and characteristics. So each nanomaterial has a different application in food packaging. It has more benefits when used in food packaging than internal use in food (Figure 4) [45].

2.3. Alternatives for Nanomaterials in Food Packaging. Though nanomaterials have high physical and mechanical properties in the food packaging sectors, they are not widely used in the packaging industry. Nanomaterials are still the emerging sector in the food packaging industry. Some of the alternatives for nanomaterials in the packaging of food are briefly mentioned below:

2.3.1. Glass. Glass bottles and jars have a long history in food packaging. They are impenetrable to insects, microorganisms, water vapor, odours, and passage of gases, keeping up with the food freshness for more time. The blowing process is used to manufacture glass bottles and jars. It requires silica (sand), sodium carbonate (the melting agent), limestone/calcium carbonate, and alumina (stabilizers) to be combined into a mixture based on the properties [46]. The mixture melts into a thick liquid mass at high temperature and then is poured into moulds. It becomes a molten material. Glass containers are reusable, rigid, recyclable, refillable, and heat processed. The advantages of glass containers are that they are virtually inert, environment-friendly, odourless, chemically inert, and impermeable to gases and vapors. The disadvantages are heavyweight, breakable, high transportation cost, and heat transparency. Glass bottles and jars are used in packing foods such as juices, jams, pickles, sauce, spreads, syrups, wines, meat, fish, coffee, and dairy products [47, 48].

2.3.2. Metals. Metals are the most used products in food packaging. Metal containers such as cans, tubes, films, and caps store food. Cans are made from aluminum or steel because of their lighter weight and are tamper-proof. Magnesium and manganese are added to aluminum to strengthen their strength and barrier properties [46]. The advantages are that when sealed with a double-seam, they provide total protection to the product, heat processed, recyclable, natural covering of aluminum oxide (Al_2O_3) gives successful barrier properties with the impacts of the air, temperature, dampness, microorganisms, and synthetic assault. The disadvantages are higher cost, heavier than plastic containers, and bleaching pigments in food [47]. Aluminum foil is produced by rolling an aluminum sheet in a rolling mill into very thin sheets. The thin foil is used to wrap cold food, and the thick foil is used in food trays. Aluminum is used to pack soft-drink cans, cereals, pulses, oils, juices, cooked food, pet food, fruits, and vegetables [48].

2.3.3. Plastics. Plastics are made through polymerization or polycondensation processes from cellulose, salt, coal, natural gas, and crude oil. Various plastics are being used to pack food, including polyolefin, polyester, polystyrene, ethylene-vinyl alcohol, polyvinyl chloride, and polyvinylidene chloride. Polyolefins and polyesters are commonly used in food packaging [46]. Plastic is used in bottles, bowls, pots, trays, bags, foils, cups, and pouches to pack foods like chips, fresh salads, jams, juices, vegetables, fruits, cold meats, and snacks. It is used widely because of its low cost, thermostability, inert, odour-free, microwave ability, flexibility, ease of transport, and highly economical. It has disadvantages like non-biodegradable, sensitivity to a chemical reaction, durability, and shrinks when heated [49].

Plastic materials have caused many waste disposal problems because they do not get degraded and remain ungraded

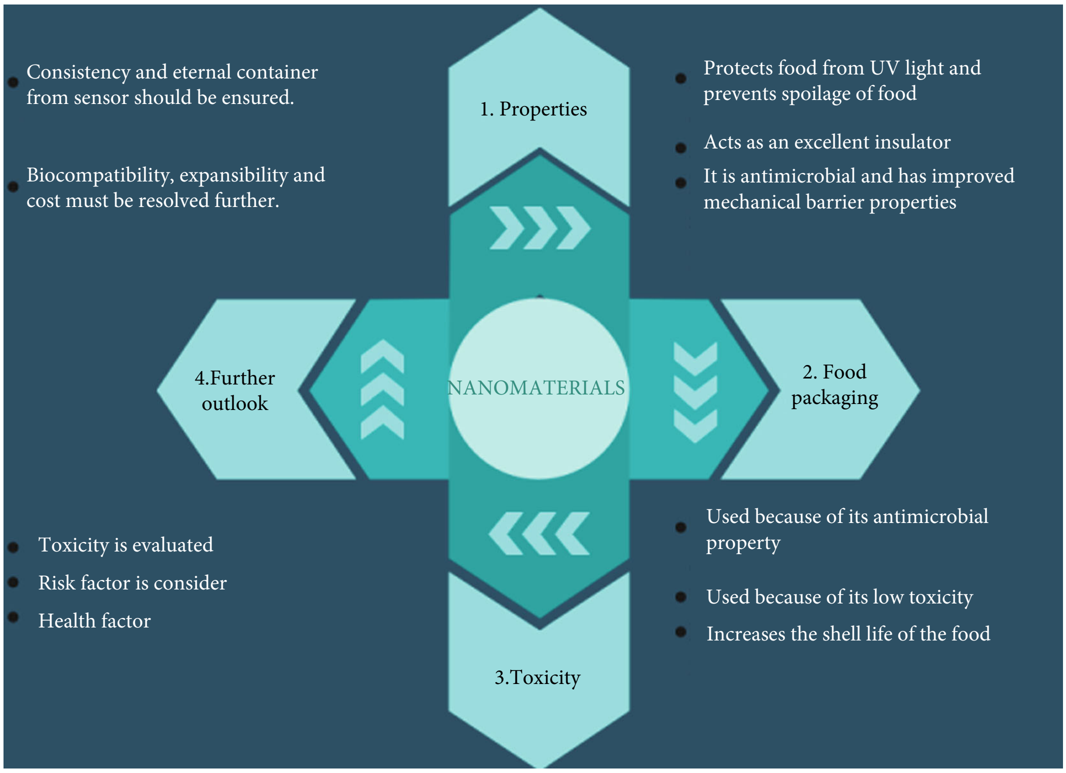

FIGURE 4: Overview of nanomaterials in food packaging.

far like a century, which contaminates the ocean and affects wildlife. So, to overcome this crisis, we need an alternative to plastics which are biodegradable polymers. Unlike plastics that do not degrade for like a century, Biodegradable polymers degrade when left in the environment. Biodegradable polymers have undergone many tests and investigations to ensure they can be used as an alternative for plastics to minimize environmental issues [50].

2.3.4. Bioplastics. Living organisms degrade biodegradable plastics into the water and carbon dioxide within a certain period. Bioplastics are derived from renewable resources and are considered to develop eco-friendly food packaging materials. Bioplastics are produced based on renewable resources such as cellulose, starch, and PLA, directly obtained from agro wastes [51]. Its limitations include poor mechanical and barrier properties, high cost, brittleness, and high vapor permeability. The mechanical and barrier properties can be improved by mixing two or more biopolymers [52]. Table 2 lists the types of bioplastics and their properties.

2.3.5. Paper. Paper and boards are made from wood pulp, cotton, sugar cane waste, flax, bamboo, and wheat straw. It is the oldest packaging material. Plain paper is not used to secure food for more time. Paper is used to making boxes, paper plates, folding cartons, tubes, sacks, cups, bags, leaflets, and wrapping paper. Various types of paper are used to pack food, such as (1) sulfate treatment process makes Kraft paper. The main benefit of Kraft paper is that it is a naturally biodegradable product, has more durability, has a lower material cost, and is lightweight. It is used to pack foods like dried fruits and vegetables, wrap meat, flour, and sugar. (2) Parchment paper is made from acid-treated pulp. It is free from impurities like starch, gelatin, casein, and formaldehyde. It has high density, stability, excellent grease, and moisture resistance. It is utilized to pack foods such as butter and lard.

Paper boards are thicker than paper. It is used to provide containers for shipping. Different types of paper boards are as follows:

(1) Whiteboard is suitable for direct food contact because it is coated with wax for heat-sealability. It is used in chocolates, ice-creams, and frozen food cartons

(2) Solid boards possess high strength and durability. It is used to pack milk, fruit juices, and soft drinks

(3) Chipboard is made from recycled paper. It is unsuitable for direct contact with food. It is used in the outer layer of food such as cereals and tea [46, 49]

2.3.6. Leaves. Leaves are cheaper, eco-friendly, biodegradable, and easily disposed of. It is used to wrap cooked foods that are quickly consumed. Banana leaves are used to wrap traditional foods to make food more delicious. Banana leaves are large, thick, and easy to pack foods. They are waterproof and easy to clean because of their slick nature. In Indian tradition, eating on leaves has many health benefits. Leaves are made into plates, bowls, and cups. Banana leaves are used to wrap guava cheese. Betel leaves are an antiseptic,

Table 2: Types of bioplastics and their properties [51, 52].

Types of bioplastics	Properties	Example
Natural polymers derived from biomass	Biocompatibility, biodegradable, lack of toxicity	Starch, cellulose, chitosan, protein
Synthetic polymers or polymers chemically synthesized from biobased monomers.	Recyclable, lack of conductivity	Polylactic acid
Microbial polymer derived from microorganisms.	Biodegradable	Polyhydroxyalkanoates

antioxidants, and a breath freshener. It is used to wrap pan and spices [53].

2.3.7. Chitosan Biopolymer. The active packaging of biomaterials involves cellulose, chitosan, starches, gums, and lipids are polysaccharides abundantly found in nature [54]. Chitosan is the derivative of deacetylated chitin which can act against antibacterial, antifungal, yeast, and moulds and exhibit properties of increasing shelf life, biodegradable, biocompatible, nonvolatile, and nontoxic. The chitosan biopolymer is safe, maintains the quality of life, and is environment friendly. Nowadays, people are aware of using plastic and chemical also their side effects on human health and the environment. These will be the best alternative for plastics. The main reason for most food product spoilage is caused by microbial action on food by changing the pH, moisture content, oxygen, and carbon dioxide activity which leads to losing more than 25% of food across the global market. Chitosan biopolymer is the desirable method of the active food package to maintain the food quality and freshness and enhance the shelf life of food also can be utilized as additives or protection. The chitosan is the structure of deacetylated chitin which can be found in the cell wall of fungi having the excellent characteristics of mechanical property, strength, and elongation property. The FDA approves Chitosan-based food packaging for food preservation and biodegradable films. Applications in beverages, cosmetics, agriculture, pharmaceuticals, and biotechnological uses [55, 56].

3. Synthesis and Processing Technologies for Food Packaging Grade Materials

3.1. Synthesis of Nanomaterials. Nanomaterials can be synthesized artificially or naturally. Nanomaterials exist in a wide assortment of shopper items like energy drinks, beverages, doughnuts, milk, and candy. Numerous adverse impacts have been related to chemical techniques because of the presence of some toxic substances retained on a superficial level. Biological techniques are eco-friendly replacements to chemical and physical nanoparticle synthesis methods utilizing microorganisms, enzymes, parasites, and plant extracts. Different strategies are used to synthesize nanoparticles like coprecipitation, inert-gas condensation, microemulsion, template synthesis, pulsed laser ablation, hydrothermal synthesis, sonochemical, spark discharge, and biological synthesis (Figure 5). In nanotechnology, the synthesis of nanoparticles is evolving into a significant part, mainly silver nanoparticles, which have many applications [57].

Nanoparticles can also be synthesized with the help of microorganisms, reducing the metal salts and accumulating small-sized nanoparticles [57].

3.2. Coprecipitation. It is an important method for synthesizing composites containing at least two sorts of metal components. The reaction includes the concurrent event of nucleation, development, coarsening, and agglomeration measures. The advantages of coprecipitation methods are high product purity, easy control of particle size, low temperature, energy efficiency, reproducibility, and economic friendly. Disadvantages are as follows: time-consuming and not appropriate to uncharged species [58].

3.3. Sputtering. It is an interaction through which minute particles of an objective material get catapulted from its surface after the siege of energetic particles of gas or vaporous plasma. It is a force move process in which molecules form a cathode or target are driven off by assaulting particles. Sputtered atoms store to form the ideal layer by traveling until they hit a substrate. Advantages are as follows: used for almost all material types, change the properties of the materials, and higher packing densities. Disadvantages are as follows: low thermal evaporation, high cost, and low deposition rate [59].

3.4. Sol-Gel. It is a technique for delivering solid materials from atoms. The synthesizing MNPs consistently blends the natural substances in the liquid stage. In order to frame a steady and transparent sol framework, do hydrolysis and polycondensation responses. Colloidal particles gradually increase after maturing sols to form a gel with three-dimensional structures. After different cycles like drying and sintering, materials with micro and nanostructures might be ready. Advantages are as follows: low temperatures, high purity, easy to prepare different sizes, and less energy consumption. Disadvantages are as follows: longer reaction time and high cost [59].

3.5. Hydrothermal Synthesis. Hydrothermal synthesis is the synthetic reaction of substances in a fixed warmed solution over the encompassing temperature and pressure. It is the most used method for the preparation of nanomaterials. In hydrothermal synthesis, the development of nanomaterials can occur in a wide temperature range from room temperature to exceptionally high temperatures. Advantages are as follows: most substances can be made dissolvable in a fitting dissolvable by warming and forcing the system close to its fundamental point, low melting point, and high fume pressures. Disadvantages are as follows: expensive autoclaves can be needed. Safety was maintained during the reaction process [59].

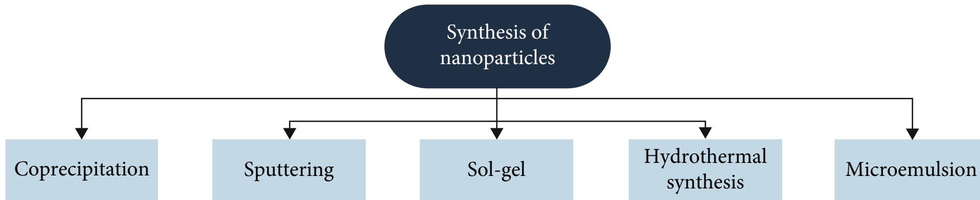

Figure 5: Schematic representation of the synthesis of nanoparticles.

3.6. Microemulsion. This method is one of the best methods for arranging inorganic nanoparticles. This is one of the preparation methods which empowers to control the molecule properties like molecule size control, morphology, homogeneity, and surface region. Advantages are the following: easy to prepare, thermodynamicstability, bioavailability, and a high degree of molecule size. Disadvantages are the following: requires large amounts of surfactant and restricted solubilizing limit for substances with high dissolving focuses [58, 60].

3.7. Bottom-Up and Top-Down Method. The nanomaterial can be delivered by two hierarchical order methodologies, including top-down and bottom-up techniques (Figure 6). This method helps protect the food packages, increase shelf-life, and be eco-friendly to the environment [57].

Nanomaterials are synthesized from two main methods: top-down and bottom-up approaches. Bottom-up synthesis techniques are named "wet" methods, including clumps of solvents and different compounds. The method depends on nucleating microscopic particles into the possible nanoparticles. While the specific synthesis technique relies upon the material's creation, some normal ways incorporate the Turkevich strategy (citrate decrease), gas stage, block copolymer, and microbial synthesis. Top-down techniques, where a mass material is burst to make more atoms, incorporate photo and flash ablation and milling (Table 3) [57].

The top-down method can be achieved by diminishing the size of materials as shown in Figure 7 (grinding and abrasion), and the bottom-up technique can be achieved by individual molecules or atoms [57].

3.8. Colloidal Synthesis of Nanomaterials. Nanoparticles are combined using wet science procedures, which fuse delivering the particles in a solution, drop-projecting the wet particles onto a substrate, and taking out the dissolvable, surfactants, and various materials from the particles. This wet amalgamation strategy requires a great deal of time and compound substances, and the resultant material might be contaminated with stores from the solution [57, 62].

Colloidal nanomaterial (Figure 8) synthesis is a conventional technique for combining inorganic nanocrystals like semiconductors and metals [62].

3.9. Biosynthesis. Biosynthesis of nanomaterials by microorganisms is a green and eco-friendly advancement. Different microorganisms like prokaryotes and eukaryotes blend metallic nanoparticles like Au, Ag, Pt, Pd, Fe, Cd, and metal oxides like TiO_2 ZnO. These microorganisms consolidate microscopic organisms, actinomycetes, bacteria, and parasites. The blend of nanoparticles may be intracellular or extracellular according to the space of nanoparticles [57].

3.10. Synthesis of Metal and Metal Oxide Nanomaterials in Food Packaging. Metal and metal oxide nanomaterials are viewed as protected materials for food and medication organization, so they are used as food added substances. The metal and metal oxide nanoparticles have shown magnificent biocidal properties and food packaging application and safeguarding. Polymeric lattices have joined to update the biocidal property just as packing property [3].

The metallic nanomaterials like Au, Ag, Cu, Pt, and metal oxide nanomaterials like ZnO, Fe_2O_3, and Al_2O_3 have been used in the application of food packaging. The interest in innovations to control foodborne microorganisms has expanded fundamentally in recent years [63]. In that capacity, food packaging plays a significant part in providing safety and keeping up with the food's nature. Food packaging with the latest capacities is called active packaging, created because of consumer interest for wellbeing and more normal items with a more extended timeframe of realistic usability, better money-saving advantages, and accommodation [39]. Antimicrobial packaging interacts with the harmful entities inside to diminish, prevent, or hinder the advancement of microorganisms that may be accessible from the surface of the food. The joining of antimicrobials into bundling materials allows the slow dissemination of target bactericidal or bacteriostatic combinations into a food network, which dispenses with the prerequisite for additional groupings of antimicrobials straightforwardly on the food thing. Most antibacterial inorganic materials are metal nanoparticles and metal oxide nanoparticles [3, 64].

Food packages delivered with nanomaterials, "nano food packaging," have recently opened up on the market. The utilization of nanoparticles is expanding in food packaging applications, and worry over toxicity affects customer discernment and acceptance. Much packaging of nanofood is covered with inorganic materials like nanosilver and nanomud. A few investigations have shown the shot at nanomaterial relocation from bundling or compartments to staples. The conversation is yet consistent among researchers about the level of relocation, whether or not it is immaterial and safe. Alongside the growing business sector example of nanocomposites, packaging of food has come to an addition openly stress over conceivable harm to human wellbeing. A couple of examinations have displayed the logical movement lead of nanomaterials from the polymer lattice. Some preliminary investigations have shown that the movement sum is extremely little related to further migration rates [3].

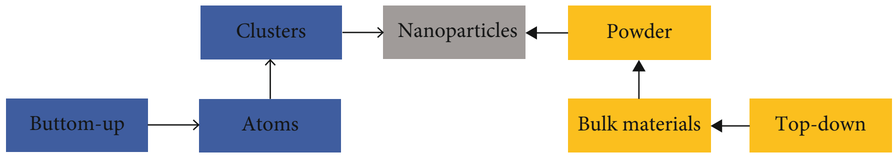

Figure 6: Flow diagram for the bottom-up and top-down method of nanoparticles.

Table 3: Various procedures to prepare nanomaterials.

Group	Procedure	Nanomaterials	Ref.
Bottom-up procedure	Sol-gel	Based on carbon, metals, and oxides of metal	[61]
	Chemical vapor deposition	Based on carbon and oxides of metal	[61]
	Spinning	Organic polymers	[61]
	Pyrolysis	Based on carbon and oxides of metal	[61]
	Biosynthesis	Based on organic polymers and oxides of metal	[61]
Top-down procedure	Thermal decomposition	Based on carbon and metal oxide	[61]
	Nanolithography	Based on metal	[61]
	Mechanical milling	Based on metal, oxide, and polymer	[61]
	Sputtering	Based on metal oxide	[61]
	Laser ablation	Based on carbon and oxides of metal	[61]

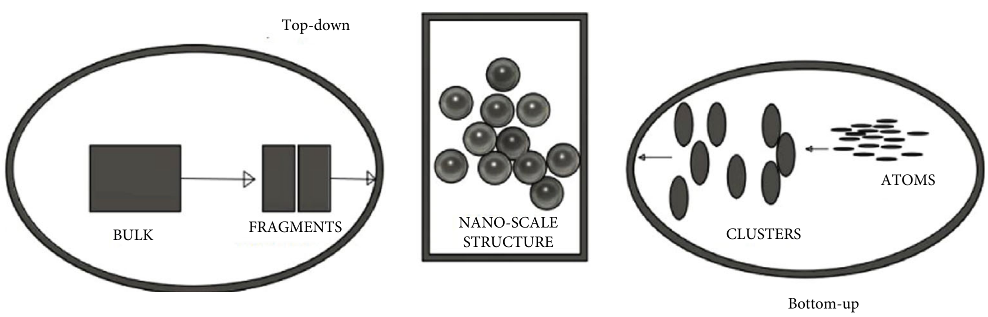

Figure 7: A schematic representation of bottom-up and top-down approaches.

Biosynthesis is called the “eco-friendly” synthesis of metal, and metal oxide nanoparticles are expensive, basic, repeatable, and natural materials giving upgrades further regular techniques. The green science theory has become an original course for biochemists and compound scientists to create nonhazardous substance combinations [65]. Polymeric metal and metal oxide nanoparticle synthesis use organic assets like plant extract, parasites, fungus, and microorganisms by a high pace of nucleation and development control (Table 4). Nanoparticles can be delivered by intracellular or extracellular courses utilizing microorganisms [66]. Gold nanoparticles were incorporated by Sastry and associates using the organism Fusarium oxysporum and actinomycete Thermomonospora sp. It is with various nanostructures (cubic, round, and octahedral) were synthesized by Cyanobacteria from their precursors Au (I)-thiosulfate and Au (III)-chloride complexes and concentrated on their arrangement mechanisms [67, 68].

AgNPs (silver nanoparticles) are synthesized by microorganisms to create environment-friendly nanofactory surroundings [86]. AgNPs were synthesized as a film/arrangement by aggregating on the outer layer of its cell when the organisms like Verticillium, Fusarium oxysporum, or Aspergillus flavus [87] were utilized. The various organisms lessened the silver ions to frame silver nanoparticles' acquired particles in a spherical shape. Also, alloy nanoparticles have more applications because of their reactant and electronic properties and are utilized in optical materials and coatings [67].

Magnetic nanoparticles were created because of their unique misconfiguration, paramagnetic, high insistent power effects, their possibility for expansive applications in natural partition and biomedicine fields. Magnetic NPs like Fe_3O_4 (magnetite) and Fe_2O_3 (maghemite) are biocompatible. They have been researched for the treatment of cancer, immature microorganism arranging and control, drug delivery, DNA examination, and gene therapy. The mesoporous structure of magnetic Fe_3O_4 particles was blended by coprecipitation technique utilizing yeast cells as a layout [88].

Nanoparticles were found to have a compelling antimicrobial action against Gram-positive and negative microorganisms. Silver nanoparticles showed antimicrobial movement in very low fixations [88]. The antibacterial action of ZnO nanoparticles relied upon the focus and

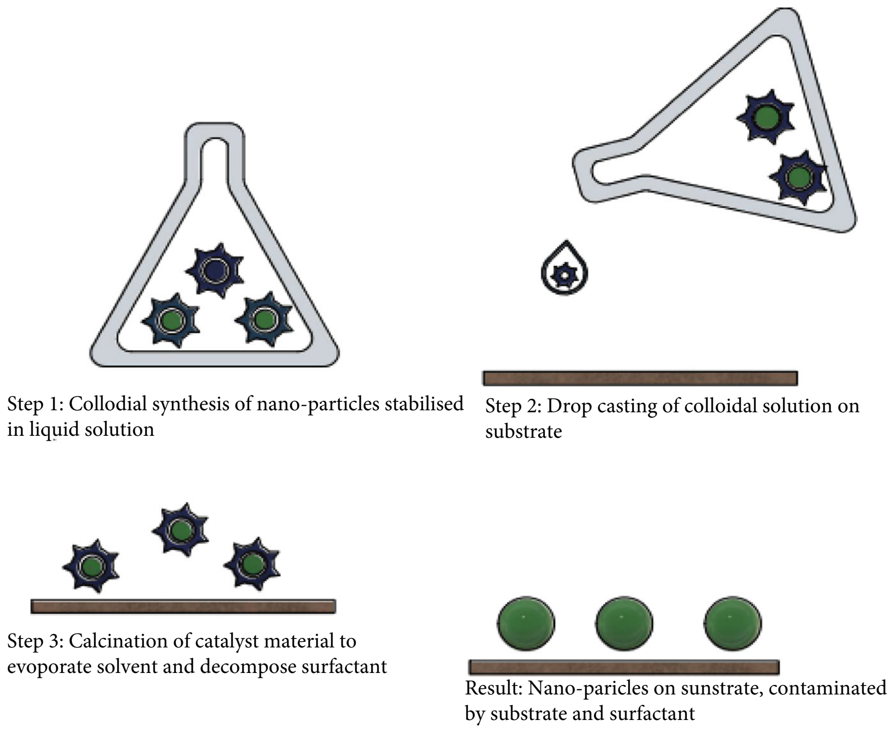

Figure 8: Colloidal synthesis for the preparation of nanomaterials.

Table 4: Metal synthesized by utilizing different microorganisms.

Microorganisms	Nanoparticle synthesize	Shape	Size (nm)	Reference
Brevibacterium casei	Gold, silver	Spherical	10–50	[69]
Escherichia coli	Au	Triangles, hexagons	20–30	[70]
Phaenerochaete chrysosporium	Ag	Pyramidal	50–200	[71]
Yeast	Au/Ag	Irregular polygonal	9–25	[72]
Desulfovibrio desulfuricans	Palladium	Spherical	50	[73]
Aspergillus fumigatus	Silver	Spherical	5–25	[74]
Yarrowia lipolytica	Gold	Triangles	15	[75]
Plectonemaboryanum	Gold	Cubic	<10–25	[68]
Enterobacter sp.	Mercury	Spherical	2–5	[76]
Sargassum wightii	Gold	Planar	8–12	[77]
Spirulina platenensis	Silver	Spherical	11.6	[78]
Rhodococcus sp.	Au	Spherical	5–15	[67]
Pediastrum boryanum UTEX 485	Au	Octahedral	10 nm–6 μm	[79]
Fusarium oxysporum	Au/Ag	Spherical	5-50	[80]
S. cerevisiae	Sb_2O_3	Spherical	2–10	[81]
Lactobacillus sp.	$BaTiO_3$	Tetragonal	20–80	[82]
S. oneidensis MR-1	Fe_2O_3	Rhombohedral/irregular	3043	[83]
Jania rubins	Silver	Spherical	12	[84]
Corynebacterium glutamicum	Ag	Irregular	5–50	[85]

surface region. ZnO nanoparticles in more concentrations and large area regions showed better antimicrobial action. CuNPs, because of their exceptional antimicrobial actions like natural, synthetic, and physical properties, just as the minimal expense of preparation, is of incredible interest to researchers [89].

Appropriate covering materials and techniques to limit food losses and give protected and healthy food items have consistently been the primary interest in the food packing industry (Figure 9). The metal-nanocomposite synthesis incorporates liquid infiltration, solidification process, chemical and physical vapor deposition, high-energy ball milling,

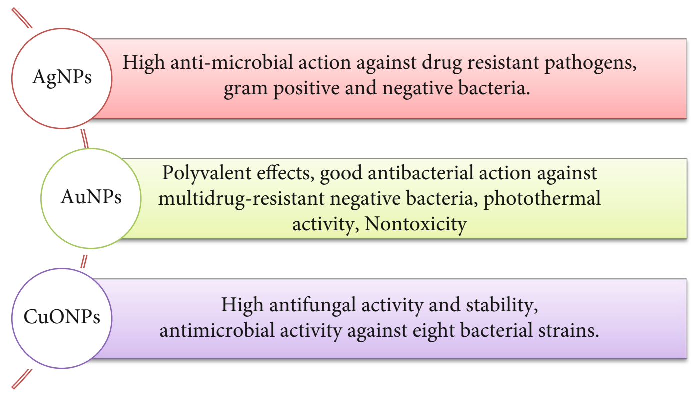

Figure 9: Effects of antimicrobial actions of metal and metal oxide nanoparticles.

and chemical processes like sol-gel and colloidal. The ceramic nanocomposite synthesis incorporates the dust cycle, polymer antecedent interaction, and the sol-gel process. Food packaging is one of the most engaged nanocomposite innovation growth because of the further developed presentation in the application of nanocomposite packing materials, like (1) enhanced thermal stability, (2) high mechanical strength, (3) better gas barrier properties, (4) recyclability, (5) good optical clearness, (6) heat obstruction, (7) hydrocarbon permeability, (8) biodegradability, and (9) electrical conductivity [3].

3.11. ZnO Nanoparticle Synthesis. Two primary techniques accomplish the production of ZnO nanoparticles: (A) mechanochemical handling (MCP) and (B) physical vapor synthesis (PVS) [90].

(A) Mechanochemical processing (MCP)

MCP is a method for nanoparticle synthesis which joins an actual size reduction process in an ordinary ball mill with the chemical reaction activated at the nanoscale during grinding. The use of MCP is a basic method for preparing ZnO nanoparticles. In this method, the zinc chloride (ZnCl2) and sodium carbonate (Na2CO3) are processed in a ball mill to deliver zinc carbonate (ZnCO3) and sodium chloride (NaCl) through ball–powder collision and chemical reaction. The ball mill goes as a low-temperature substance reactor where the reaction interaction results from local heat and strain at contact surfaces at the nanoscale. The NaCl is utilized as an inert diluent added to the antecedents. The item is considered a nanocomposite, with NaCl acting as the matrix phase [91]. The size of the acquired ZnO nanoparticles relies upon the processing time and the heat treatment temperature. Increasing the heat treatment temperature causes an increase in the size of the ZnO nanoparticles. The size of ZnO nanoparticles increases gradually from around 18 nm at 400°C to 21 nm at 600°C but increases quickly over 600°C, reaching 36 nm at 800°C. MCP is appropriate for the large-scale production of ZnO nanoparticles because of its effortlessness and minimal expense. The disadvantage of this method is molecule agglomeration during milling, which is then eliminated through calcination by a basic washing methodology [92].

(B) Physical vapor synthesis

In the PVS method, plasma curve energy is applied to an antecedent to create vapor at a high temperature. The plasma curve gives the energy needed to initiate responses that lead to supersaturation and molecule nucleation when the precursor is infused into the plasma. In this method, a reactant gas is added to the fume, cooled at a controlled rate, and dense to shape nanoparticles. The nanoparticles created by the PVS cycle are completely thick particles of characterized crystallinity. This strategy commonly creates particles with normal sizes from 8 to 75 nm [93].

Food packaging materials created with nanotechnology are the biggest current nanotechnology applications for the food area. In food conservation, the utilization of nanotechnology can broaden and further develop packaging capacities, which customarily have been regulation, protection, conservation, advertising, and correspondence, prompting another sort of active food packaging. In polymer science, composites are made of a polymeric framework known as a continuous stage and a discontinuous stage known as a filler. Strands, platelets, and particles have been utilized as fillers to improve polymers' mechanical properties and heat opposition [94].

In the past few years, researchers have shown interest in the investigation of metals and metal oxides like silver (Ag), gold (Au), titanium dioxide (TiO_2), zinc oxide (ZnO), and copper oxides (CuO) because of their solidness at high temperatures and antimicrobial action. Silver and ZnO nanoparticles have a few likenesses like their inorganic nature, synthesis techniques, and toxicity. A few benefits to ZnO nanoparticles consolidated in polymeric grids when contrasted with silver nanoparticles give answers for more secure and more reasonable antimicrobial food packaging. The application of ZnO nanoparticles for food packaging materials incorporates giving antimicrobial action. The presence of ZnO nanoparticles in the polymeric matrix permits the packaging to interface with the food and has a powerful role in their preservation [95]. Metal and metal oxide nanoparticles help improve packaging properties like mechanical strength, high surface area, barrier properties, optical properties, and stability. Metal and metal oxide nanoparticles have been included in various incorporation techniques, such as glass, LDPE, paper, polypropylene, polystyrene, and chitosan [96].

3.12. Synthesis of Silver Nanoparticles. It is synthesized using biological strategies utilizing the leaf stock of Capparis zeylanica that gives no harm to the ecosystem and a basic and effective course for synthesis. The synthesized AgNPs were mixed with PVA/PEG biopolymer mix. It has been affirmed by FTIR, moisture assimilation, and antimicrobial investigation. This composite film shows good properties in all capable perspectives for food packaging and biomedical applications [97].

Biopolymers are separated from living creatures which comprise a biodegradable compound that is a natural compound present in the ecosphere. Biopolymers are made out of living materials. These polymers can diminish the carbon dioxide levels in the environment. Polymer blending is one of the most contemporary ways to advance new polymeric materials, and it is a helpful method for planning materials with a wide assortment of properties [98]. The real tendency in packaging is to make and propel the utilization of "bioplastics," which help decrease garbage removal and are acceptable replacements of petrol, a nonsustainable asset with lessening amounts. The issues in discarding the immense amounts of waste produced by imperishable food packing have prompted the investigation of biopolymers to be utilized as edible coatings. For more regular items, biobased films, or biopolymers, working on the nature of numerous items is essential to fulfilling the consumer's demand of all the harmless packaging alongside keeping it safe for the environment [99].

4. Toxicity of Nanomaterials Used for Food Packaging

Nanoparticles used in food packaging may leach into food products. Nanoparticles may enter the human body through inhalation, ingestion, and skin (Figure 10). It may cause various diseases. The toxicity of nanoparticles increases with an increase in large surface area. The distribution of nanoparticles in the human body may function in their size surface area characteristics like polarity, lipophilicity, hydrophilicity, and catalytic activity [100].

In the experiment of Blasco et al. [101], which involves the coating process, there are different polymer functionalization methods, such as the activation of esters to form peptide groups, organic chemistry, and adding isocyanates to alcohol. The former is a promising technology because the amide bond exhibits high stability and compatibility with different parts in different environments. The working and stereotactic methods make chemistry useful, and it produces nontoxic byproducts that are easy to remove. Although it involves adding alcohol, we can note that it is a good technology because of quick kinetics and its excellent performance, yet its properties restrict it by the toxicity of isocyanides and the instability of polymer/isocyanide mixtures.

There is immense concern regarding the toxicity of the nanoparticles, while it has more advantages. The important route of human exposure to nanomaterials is ingestion, directly through food and drinks [61].

4.1. Silver (Ag). In the next experiment of Echegoyen et al. [102], silver is present in polypropylene and polyalkene bags. Two food conditions were used to evaluate Ag migration, together with ethanoic acid 3% and ethyl alcohol by 50%; then, we can notice that after 10 days, it remains at 40°C; also for 2 hours, it remains at 70°C, respectively. In addition, Duncan [103] reported on an experiment on particle size that microorganisms significantly depend on the particle's size, and an excellent microbicidal agent is associated with nonaggregated and completely scattered Ag NPs. Except for experiments conducted by Jokar et al. [104], nanosilver is an active agent based on low-density polyethylene. Here the method used was melt mixing and layering of silver. The migration of Ag particles out of the nanocomposites to the food simulant and the juice of fruits like apples was below the cytotoxic level in all cases for more than 30 days. Therefore, the outcome shows by which migration of Ag NPs in ethanoic acid (10 days at 40°C) is greater than that of ethanol (2 hours at 70°C). Although silver migration is observed, silver migration is below the standard limit of European regulations.

4.2. Zinc Oxide (ZnO). The experiment of Silvestre et al.'s [16] report shows that zinc oxide is more effective and appealing than silver nanoparticles because of cost-effectiveness and lower toxicity. Compared to AgNPs, ZnONPs are better in packaging. The approach taken is mainly appealing since they are not hurtful to humans and animals, and also, they are easily available. Although bulk ZnO is not toxic [105], zinc oxide NPs are carcinogenic for human beings. Furthermore, to evaluate the decomposition rate of apples that were cut freshly [106], several indicators like malondialdehyde, polyphenol oxidase activity, and pyrogallol peroxidase activity were used. In contact with ultraviolet radiation, zinc oxide nanoparticles can oxidize ethylene to H_2O and CO_2 and reduce MDA accumulation, oxidized polyphenol, and POD activity. Therefore, zinc oxide nanoparticles can be used for commodities to provide extended shelf life. ZnO nanoparticles show genotoxicity in human epidermal cells.

4.3. Chemical Vapor Deposition. Chemical vapor deposition [107] exists as the temperature of the substrate. The properties of CVD are completely natural, compatible, rigid, and tough NPs. The thin layer of gaseous reactant deposition is carried out on the substrate. The deposits are removed in the reactor system combining gas molecules at room temperature. Then, when a heated substrate is in contact with the accumulated gas, a chemical reaction occurs. This reaction produces a cloud of byproducts later. This will be

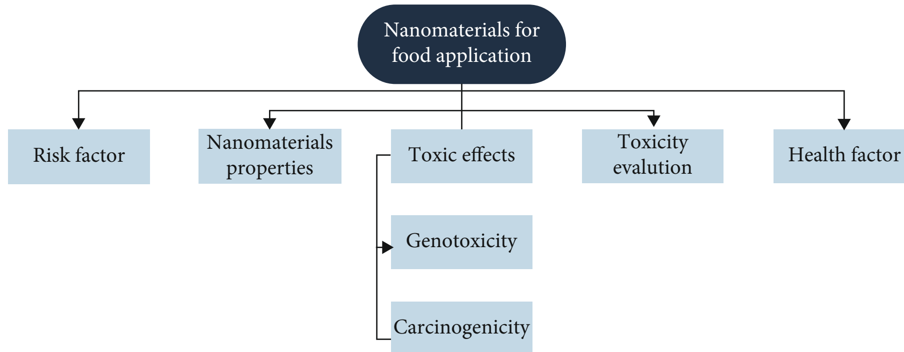

Figure 10: Toxicity of nanomaterials.

utilized on the outside part of the item once it is recycled. However, its disadvantages include the need for unique machinery and cloud byproducts that are extremely toxic for the environment. Therefore, the use of CVD in packaging is not safe.

4.4. Carbon Nanotubes. Carbon nanotubes [109] were converted to polymers lately, and mainly smart and antibacterial sensors were carefully studied for packaging. Toxicity levels of some bacterias are high in levels for a single-walled (SWCNT) to tolerate, possibly leaving minor residues behind. In addition, the concept of smart packaging is integrated. This type of packaging is sprinkled along a gaseous from related to CNT's sensor manufactured slim translucent film inserted along with a wireless chip, so one can communicate with customers or marketing managers before the food spoils. In addition, it might be carcinogenic at the processing stage, but not to consumers, so its migration into food must be controlled carefully.

4.5. TiO_2. Titanium dioxide [110] owns the potential to change the characteristics of nontoxic, inexpensive, and nontoxic as well as light-resistant films. Another function of TiO_2 is commonly used in food packaging, like the color and sheet preservative. White TiO_2 NPs can completely separate light. Whereas titanium dioxide is not harmful and inert, it is safe to the human body and can oxidize the unsaturated polyphospholipid components of microbial cell membranes, thus producing biocidal effects. TiO_2 may cause lung tumours [111].

4.6. Starch. Although we can use starch [112], Oladebeye is a natural, renewable, ecological, nontoxic polysaccharide. It is due to its inexpensiveness, ecofriendly, and sufficient supply have been widely used in food and papermaking. Therefore, starch can be used to package food to obtain crystalline starch granules composed mainly of two glycoside macromolecules, called amylose and amylopectin. There are several methods for the extraction process of amylose, namely, enzymatic hydrolysis [113], acid hydrolysis [114], precipitation [115], and the use of mechanical microfluidizers [116].

The various applications of nanomaterials are currently in use and the chemical categorization and toxicological assessment methods (Figure 11) [117].

The nanomaterials like silver, zinc, titanium, and CNTs may enter the circulatory system, and their insolubility may cause accumulation in organs like the lungs, stomach, and heart (Figure 12) [118]. Table 5 lists the characteristics of nanomaterials that can be toxic or not suitable for human consumption in food packaging applications. Table 6 lists the desired properties for food packaging and the most suitable nanomaterials according to all the requirements.

5. Heating Effects on Nanomaterials in Food Packaging

Nanomaterials contain physical and chemical properties that differ from corresponding mass particle properties. The energy in nanomaterials is high compared to bulk materials because the nanomaterials have a large surface area. The melting temperature of nanomaterials has been anticipated based on size-dependent cohesive energy. The melting temperature of nanomaterials is proportional to the particle size [121].

Polylactic acid is a type of polymeric nanoparticle used in food packaging. It is economically friendly, biodegradable, easy to produce, and toxic-free. It is used to pack sensitive food products in the food industry [122]. It is produced by sustainable resources and low carbon emission processes, mainly derived from corn starch, sweet potato, rice, sugarcane, and wheat. It has more properties like high thermal processability, antibacterial, flame-retardant, good heat sealability, and oil- and water-resistant properties. The polylactic acid with many nanoparticles like silver, zinc, and titanium helps to keep the food fresh and preserve the cooked food and yogurt cheese [123].

Zinc oxide nanoparticle is inorganic metal oxide. It is used as a food preservative and medicine. Zinc oxide nanomaterials are present as clusters. It has antimicrobial properties, UV resistance, nontoxicity, and low cost. When ZnO is mixed with the polymer matrix, it acts as reinforcement. It boosts nanomaterials' thermal, barrier, and mechanical properties [124, 125].

5.1. Preparation of Composite Films. The solvent evaporation method is used to prepare the polylactic acid/zinc oxide composite films. Synthetic samples investigate the release

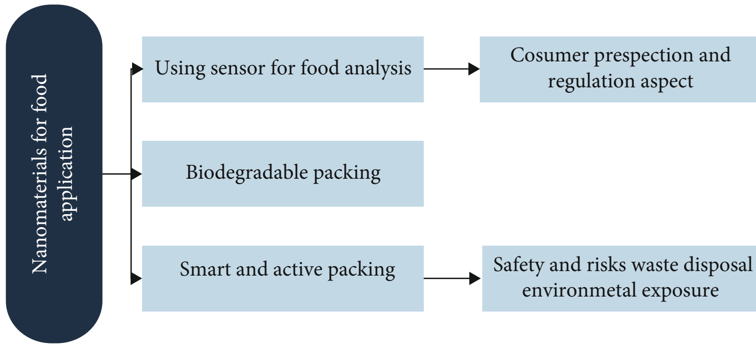

FIGURE 11: Application of nanomaterials in food packaging.

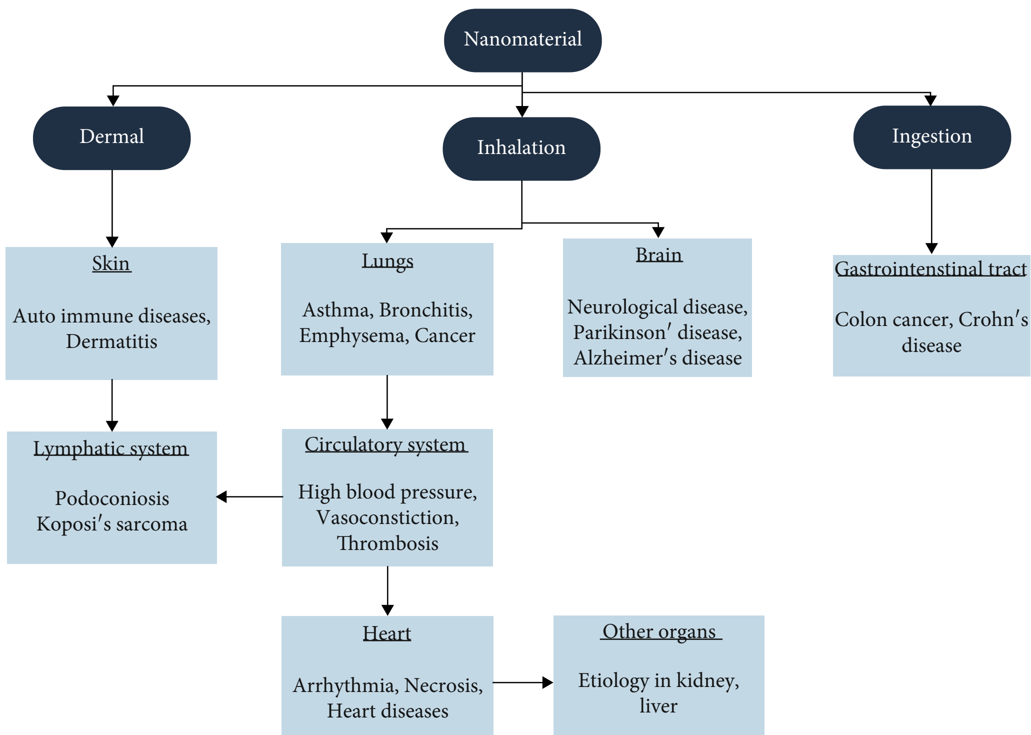

FIGURE 12: Toxic effects caused by nanomaterials on the human body.

TABLE 5: Characteristics of toxic nanoparticles and their risk factors.

Characteristic of nanoparticles	Risk factors related to nanoparticles	Ref.
Size and its reactivity	The reactivity and agglomeration of the nanoparticles depend mainly on the particle size. It is familiar that in smaller particles, the agglomeration process will occur at a gradual pace. Once nanoparticles have been synthesized, it is impossible to retain their original size. Therefore, the box turns out very unavoidable in the nanoparticles mixture. When classifying nanoparticles according to particle size, the special dependency on then size is on properties of a nanoparticle is different from classical colloidal chemistry. Nanoparticles can be loaded by functionalization or voluntary degradation reactions.	[119]
Aggregation or agglomeration	Change of phase has high chances of getting corroded, and dissolvability is high to nanomaterials leads to worsening, and structural support becomes more difficult.	[120]
Pollutant dissociation and its recycling and discretion	Following their high reactivity, nanoparticles are combined with contaminants, so encapsulation is needed to supply the stability of nanoparticles, and the polluted product that is leftover contaminants within the nanoparticles is observed as an important hazard aspect. The possible toxic-related issue is still in doubt. Therefore, the uncertainty of the effect of nanomaterials has not yet formed a persistent disposal and recycling policy.	[120]

Table 6: Nanomaterials and their selection in brief.

Desired property	Effective nanomaterial	Ref.
Removal of enzymatic browning	Thiol-functionalized silica nanomaterials	[4]
Antimicrobial nature	Silver nanoparticles (AgNPs), ZnO nanostructures, titanium nanoparticles (TiO_2 and tin)	[4]
Moisture barrier enhancement	Nanoclays	[4]
Reinforcement or filler properties	Starch nanocrystals Cellulose nanostructures	[4]
Sensors	Carbon nanotubes	[4]

of composite films to food products. Preparation of composite films by solvent evaporation method is as follows:

(i) Polylactic acid -2 g

(ii) Acetyl tributyl citrate- (ATBC-) v10%wt

(iii) ZnO (0-15%wt) dissolved in 100 ml methylene chloride

The solution was stirred completely with a magnetic stirrer at room temperature for 8 hours. The PLA and ZnO particles were completely dissolved in the solution. The solution was kept at an ultrasound bath treatment for 30-35 minutes. The solution was filled into the polytetrafluoroethylene (PTFE) boards and left drying for 5 hours. Then, the composite films were kept in the oven for a day at 40°C. The PLA/ZnO composite films were prepared and named PLA-0, PLA-3, PLA-9, and PLA-15 [124, 126].

5.2. Starting Substance of Zinc Oxide in PLA Nanocomposite Film. The composite films were washed with pure water and cut into pieces of 2 g samples of different composite films. The films were put into the digestive tank with the addition of concentrated nitric acid (8 ml), and the tank was placed at an acid eliminator at 100°C for 30 minutes. Then, the films were taken out and cooled at room temperature and put into the microwave device for digestion with nitric oxide (NO). The zinc substance was estimated by flame atomic absorption spectrometry [124, 126].

5.3. Overall Migration Test. Overall migration test utilized isooctane and 10% (v/v) ethanol as food substitutes. The overall migration amount is evaluated based on the equation:

$$M = (W_2 - W_1)W, \quad (1)$$

where M is the overall migration quantity, W_2 is the mass of the conical flask (μg), W_1 is the mass of the empty conical flask, (μg), and W is the mass of the film sample (kg) [123, 124].

5.4. Specific Migration Test. It used the same food substitutes as the total migration experiment. Specific migration amount is evaluated based on the following:

$$M = W_1 = W, \quad (2)$$

where M is a specific migration amount, W is the initial mass of zinc (kg), and W_1 is the mass of zinc migrated to the solution (μg) [123, 124].

The heat of PLA/ZnO composite film was measured by differential scanning calorimeter (DSC) [124].

6. Edible Food Packaging Using Nanomaterials

Food packaging strategies that are edible are an important topic of study to improve food standards and safety. There is a tendency toward more eco-friendly and edible packaging and extending the life of the shell. At the same time, both the barrier to moisture, oxygen and other contaminants from and to the food can be a carrier of active compounds. Edible packaging typically uses biodegradable material applied as a consumable coating around the food [127, 128]. Several recent researchers have looked into the value of edible materials as an added value to packaged foods. Nanomaterials have become a good procedure for providing antimicrobials, vitamins, and other ingredients that could potentially improve the functionality of edible packaging [129].

In earlier times, usage of edible packaging for coatings and films has progressed to intensive and complex synthesized biomaterials [130]. From the use of wax for encouraging a delayed dehydration of citrus fruits, and edible coatings to stop meat shrinkage, various inventions have resulted in a lot of options for edible synthetic polymer packaging after extensive research.

6.1. Benefits of Edible Packaging. The authors of [131] provide the most up-to-date data on the latest technological breakthroughs in edible packaging of food, their creative uses, and examples of current research in which edible packaging plays a key role.

In the active food packaging industry, edible packaging is viewed as a sustainable and biodegradable alternative that improves food quality compared to regular packaging. Coatings are commonly used to enhance mechanical qualities, reduce respiration in fruits and vegetables, give antibacterial properties, increase sensory attributes, and increase the product's storage life [132]. The value of edible packaging can be demonstrated in its ability to preserve food quality, prolong storage life, decrease scrap, and provide packing material efficiency. Because of its adaptability, ability to be manufactured from a range of materials, and ability to carry diverse, active ingredients such as antimicrobial agents and edible films are among the most promising disciplines in food science. In recent years, this has aided in the growth of the study on this field, with many issues highlighted as needing to be addressed prior to a safe and sufficient for wide manufacturing of edible food packaging. Few steps entailed plasticizers, colors, antimicrobial agents, and tastes could be included in this procedure. Film compounds might be used for food using a variety of processes, including dipping, panning, spraying, and brushing.

At last, the other process that will be done is drying [133]. Agar is polysaccharide agarose and a heterogeneous collection of compact molecules termed agaropectin [134] used to make edible foods. In the cellular walls of seaweeds, agar appears to be a helping system for shape [135]. Agar is used to gelling, sustain, quality, and thicken liquids, among other things. Because agaropectin is frequently eliminated throughout agar production, the gel's strength with agar powder is produced.

6.2. Different Components Mixed with Agar for Edible Packaging. Due to various interactions within the components, many edible films formed of biopolymer will be brittle and rigid. Tiny safe, eco-friendly persistent compounds are utilized as plasticizers in the structure of edible films. They will be settled within polymer chains, decreasing cohesive forces and successfully lowering the film's brittleness and glass transition temperature. They also improve extendibility flexibility and decrease the price of finished dried films in a few circumstances [136]. This mixture is totally safe, technically nontoxic, low-cost, and environmentally acceptable, and these properties are the reason why it is a good alternative for increasing the mechanical properties of agar film.

In addition to that, mixed biopolymers can effectively change the useful characteristics of every biopolymer film. Single-phase, two-phase separation, and dispersion are the three types of structures generated based on the nature and intensity of this correspondence for preparing edible active packaging.

However, other compounds such as starch, proteins, and lipids are also used. For instance, starch is cheap and widely available, collected from branches and linear segments [137]. This is expected to get good shape and similarity of the result, whereas proteins are used from gelatin are usually mixed with agar for enhanced properties. On the other hand, lipids enhance the water-resistance property [138].

6.3. The Process Involved in the Making of Edible Active Packaging. The process can be divided into wet and dry processes. There are casting, dipping, spraying, and spreading techniques for the wet processes. For the dry processes, the following will be thermopressing and extrusion. The key variation between wet and dry processes will be that the wet processes need a step that includes drying, which is not the same as the dry process. Films are usually prepared through casting, extrusion, and thermopressing. Coatings are prepared through dipping, spraying, and spreading [139].

Extrusion is a low-cost technology, but it demands a large beginning funding in apparatus and ongoing preservation. Aside from the plasticizers, this approach includes low solvent concentration, the ability to use viscous polymer, and calm temperature and pressure control. However, because of the moisture constraint of this process, some polymers might not be suitable for usage. To increase the qualities of the films, the extrusion process can be used with several layers [140].

6.4. Examples of the Components

(i) *Polysaccharides*: starch, pectin, agar, and chitosan

(ii) *Proteins*: collagen, gelatin, soy protein, and wheat gluten

(iii) *Lipids*: paraffin wax, mineral oil, fatty acids, and vegetable oils

(iv) *Composites*: bilayers and blends [141]

Tiny safe, eco-friendly persistent compounds are utilized as plasticizers in the structure of edible films. The use of edible packaging is a step toward environmental safety. For instance, bionanocomposite like nanoclay is safe and highly available [142].

Edible coatings are gaining popularity due to the environmental aspect, novel storing methods, and emerging markets for underutilized agricultural products. Unlike packaging materials made from nonrenewable energy sources, biopolymers do not cause any difficulties in the ecosystem; hence, edible coatings and films are environmentally beneficial [142]. Compared to more typical noneco-friendly packaging components, edible films and coatings can improve the recyclability of packaging materials and might replace synthetic polymers. Due to their biodegradability, food-grade antibacterial packaging films are promising food packaging materials (Figure 13) [143].

Agar-based packaging materials are also completely safe and nontoxic. Natural building blocks, organic (e.g., peptides or proteins), or inorganic (e.g., minerals) elements are joined with revolutionary self-assembly synthesis methods that create edible materials that self-repair even if there is harm made in the ecosystem, ensuring that the food is safeguarded without all the time [143].

Food packaging advancement necessitates the creation of toxic-free, biodegradable, or edible packaging materials which should be both safe for humans and the ecosystem because of the possible threat posed by nanoparticle migration into food, and a lack of knowledge about the effectiveness and impact of nanomaterials on the environment and human health is of the major problem. The use of nondegradable and nonrenewable materials such as glass, plastics, and metals in packaging applications has raised environmental concerns, necessitating a requirement for the safe handling of these materials. Annually, large amounts of materials used in packaging requests for use and dumping are formed. After consumption, the traditional method of dealing with plastic garbage is to burn it and clear land, which is hazardous to human health and the environment [144]. Constraints on fossil fuel supplies, on the other hand, the economy put pressure to give attention to other sources such as forests and agriculture [46].

Figure 13: Properties of nanomaterials in edible food packaging.

Ecosystem is a factor to worry about. The impact of traditional food packaging materials and the desire to prevent new food waste due to degradation have prompted the search for alternative packaging materials and formulae, primarily plastics, metals, paper, or glass [46].

Global production of oil-based packaging materials is produced at 8% per year, yet only 5% are reused. The slow collection of plastics in the ecosystem has become the main reason for waste disposal of plastic. This is a critical issue for the planet, and growing problems about plastic pollution have led to the creation of biodegradable packaging materials. Because of their capacity to restrict moisture and oxygen, shifting between food and the surrounding atmosphere, synthetic films can be useful alternatives for plastics in various applications [130, 145]. As a result, the use of food-safe films has risen significantly to preserve the quality of various meals. Various biodegradable goods, like drinking cups, panels, and purge films, are currently being manufactured and distributed in supermarkets [146].

To promote food mobilization, harmful packaging materials that are harmless for persons and the environment must be developed for free, degraded, or collectible. A producer must appropriately examine the dangers to the human, animal, and environmental health before putting a novel nanomaterial-based product in the food system [147].

7. Materials Used to Avoid the Environmental Concerns

Biodegradable films made from renewable resources are attracting much attention. According to an article, the toxic decomposable polysaccharide was constant and translucent films and heat resistance. In addition to agar, however, as compared to plastic-based plastic wrapping materials, agar is less visible and has low flexibility, poor heat stability, medium gas barrier qualities, and high blood pressure, limiting its industrial applications [148].

As a result, several researchers have concentrated on enhancing the agar film's functional properties by combining it with other biological polymers or including nanozotes, particles, and antioxidants into its form. It can be concluded from the study's findings that, while including various materials into agar films may improve some of the film's properties, it may also negatively impact others, such as translucency, viability, thermal stability, or mechanical strength. In order to improve the features of agar based on its specific application, more study is required in this area [134]. Compared to more typical eco-friendly packing, edible films and coatings can improve the reusability of packaging materials and may replace synthetic polymer films [149].

Polylactide acid (PLA) plastics, sugar cane pulp, starch-based films, and other materials are some of the materials that are being used to create sustainable packaging. Biopolymers have existed for billions of years, far older than manmade polymers such as plastic. They are made from renewable natural resources, are frequently biodegradable, and are not hazardous to make. Moreover, the bulk of sources used are nonbiodegradable petroleum plastic polymer-based materials (about 8% of world gas output, and the fossil is used to produce synthetic polymers), representing a huge environmental hazard [129]. By using biodegradable or edible materials, plant extracts, and nanocomposite materials, the advancement of renewable or green packaging can alleviate the negative environmental impacts produced by synthetic packaging.

Three important issues to be considered in the evaluation of packaging sustainability and environmental aspects are as follows:

(1) The materials used for packaging will not be dependent on transferring from one part to another to avoid dumping for the whole packaging period

(2) The packaging of the products will be minimized as much as possible to avoid any harm done to the ecosystem while producing the packaging

(3) Ecosystem, people, and business impact the triple bottom line, followed by convenient packing, including the efficient, clean, and cyclic [133]

In addition, these materials are not regarded as "environmentally friendly," as most of them are nonrenewable and nondecomposable, resulting in their dumping in the land or the oceans. Furthermore, using these materials used in food packaging will affect the ecosystem, leading to bad consequences, and a few of them would be CO_2 and other toxic elements released during burnings, dependence on nonrenewable petroleum products, and the possibility of harmful burnings in-between potential reusable food or plastic [150].

8. Material Selection

Nanoscience is one of the most emerging fields, especially in the food and pharmaceutical industries. The top 3 countries researching nanomaterials are China, the United States, and India [151]. The engineered nanomaterials for the food industries are approved by the European Commission (EC), Food and Drug Administration (FDA), and the International Organization of Standardization (ISO) for their definite structure and composite formed from the atoms or molecules [152]. The various nanomaterials can be selected and used for different suitable conditions.

8.1. Removal of Enzymatic Browning in Fruits and Vegetables Using Thiol-Functionalized Silica Nanomaterials. Enzymatic browning is when fruits and vegetables produce a brown color when they contact the enzyme polyphenol oxidase (PPO). The reaction usually only occurs in fruit or vegetable cells when wounded or crushed.

The natural enzyme, polyphenol oxidase, lives within the cells of these plants and is given off from damaged tissue. These enzymes could be found through injuries to plant tissues such as cracks, bruises, and cuts but also can be found on plant surfaces due to plant damage done by insects like weevils and beetles that feed on them. Thermal therapy, avoiding oxygen exposure, using low temperatures, and irradiation are all physical ways for controlling enzymatic browning. Because enzymes are made of proteins, heat treatment, such as blanching, can easily impair enzymatic activity. However, these methods can be quite expensive, and it is a little farfetched to go to these extremes to avoid enzymatic browning in fruits and vegetables. So, the easiest and most obvious way to avoid this phenomenon is to pack these fruits or vegetables in packaging material. Most of the packaging materials widely available in the market can inhibit contact with oxygen and, most importantly, cannot avoid contact with PPO. Much research was done to find a suitable packaging material to pack such fruits and vegetables, and one such research done by Muñoz-Pina and team found out that enzymatic browning can be avoided when thiol-functionalized silica nanomaterial is used as the packaging material. Eight materials made out of the supports UVM-7, MCM-41 nano, Aerosil 200, MCM-41 micro, and UVM-7 were utilized with two functionalities: thiol groups and silanols. PPO may be immobilized and inhibited using mesoporous materials. The finest inhibitory properties are provided by the combination of micro and mesopores present in materials such as UVM-7 and thiol groups. Therefore, among all the materials tested, the combination of UVM-7-SH is found to give maximum protection against enzymatic browning in fruits and vegetables and can be used effectively. Even when the material was eliminated by filtration after a five-minute contact stage, the suppression of enzyme browning in juices lasted up to a month [153].

8.2. Silver Nanoparticles. AgNPs are silver metallic atom complexes principally used in antibacterial and sterilizing applications. AgNPs have a greater surface area per unit mass than microscale silver nanoparticles or large volume silver material; thus, they may release more silver ions. The application of AgNPs as antimicrobial agents is predicted to be most prevalent in active and intelligent food packaging. Because the nanosized particle behaves like a molecule, it may readily pass through bacteria's strong and stiff cell walls, disrupting critical chemical processes. Compared to commonly used antibiotics to which bacteria grow resistance, it becomes more efficient to kill bacterial cells depending on their size. Synthesized AgNPs demonstrate substantial dose-dependent biological activities and have a higher sensitivity to positive gram bacteria (15 mm zone of inhibition) than negative bacteria (5 mm zone of inhibition). In particular, the silver nanoparticle (AgNP) is gaining attention owing to its interesting characteristics related to reduction power, photochemical activity, and electrical conductivity. Many biological uses of AgNPs have been discovered, including antioxidant, antibacterial, and anticancer properties. Chemical applications in organic synthesis and chemical processes, such as gas sensing and catalytic activity, are also well recognized. In order to incorporate AgNPs into polymeric polymers for packaging, a variety of techniques can be used. Silver ions, as an example, can be incorporated or entrapped in a porous-like substrate like zeolite before being applied to polymers. Commercially available silver ion-exchanged zeolites (Ag-zeolites) are widely utilized in active packaging film. Trapped silver ions can be discharged onto microorganisms by extruding Ag-zeolite into a polymer matrix or incorporating it into a thin layer (3–6 mm) on the packaging's surface where the food comes into touch with it. Several biological materials, including microbes, enzymes, and their extracts, are also used as green media in the production of AgNPs [4].

8.3. Zinc Oxide Nanoparticles. ZnO, like nanosilver, has strong antibacterial capabilities and biocidal activities. ZnO nanostructures have already been more productive against Bacillus atrophies, E. coli, and Salmonella aurous than other metal oxides such as copper and iron. ZnO may create a lot of hydrogen peroxide when exposed to UV light, inducing oxidative stress in bacteria. Some studies present that zinc ions play an important role in inhibiting bacteria proliferation (bacteriostatic, for example) instead of killing bacteria (Ex: bactericidal). When the size of the nanoparticles of ZnO is reduced to the nanometric range, it can engage with the surface of the bacteria and core, entering the cell and exhibiting a variety of bactericidal activities. The interactions between these unusual materials and bacteria are usually harmful, which has led to antimicrobial uses in the food sector. Several investigations have found ZnO-NPs to be nontoxic to human cells, necessitating their use as antibacterial agents, hostile to microorganisms, and having high biocompatibility with human cells. Nanomaterials' antibacterial activities are mostly attributable to their high specific ratio of surface area to volume and unique physicochemical characteristics. However, the specific processes are still being debated, despite numerous potential methods being offered and implemented. Antibacterial nanomaterials, primarily ZnO-NPs, would benefit the field of nanomaterials research, as well as the mechanisms and phenomena that underpin nanostructured materials. Compared to AgNP, ZnO is more appealing for its uses for packaging for being less expensive, and animals and people are less harmed [4, 154].

8.4. Titanium Nanoparticles. One more type of nanoparticle widely used as a packaging material or coating is the titanium nanoparticle. TiO_2 is most often utilized as a coating and pigment component in food packaging. TiO_2 particles are white, and the coated item's opacity, brightness, and whiteness are achieved by scattering visible light. Coextruded HDPE and PET bottles are frequently combined with TiO_2 in pasteurized milk packing to reduce the negative impact of light on milk quality. Researchers have been more interested in TiO_2-coated and TiO_2-embedded antibacterial food packaging since the biocidal properties of plastic films containing TiO_2 nanoparticles were found. Under fluorescent and UV light irradiation, LDPE films coated with nano-TiO_2 films may inactivate E. coli, and it appears that nano-TiO_2-coated films will be used in food and sanitary packaging shortly. Antifungal characteristics of TiO_2-coated polypropylene (PP) plastic film for fruit packing are reported to be excellent. Besides antimicrobial properties, packaging materials made out of TiO_2 are said to act as oxygen scavengers. Films made from NC-TiO_2 colloidal paste demonstrated the quickest scavenging and oxygen reduction kinetics. For $[O_2(g)] > 5\%$, the kinetics of oxygen reduction and the rate of oxygen scavenging were shown to be independent of oxygen concentration. Along with TiO_2, tin is widely popular too. It is chemically inert, nonflammable, nonvolatile, and insoluble completely in foods and its simulants when solidified as a thin layer. Tin nanoparticles are commonly encountered as nucleating agents or reheat additives in PET thermoforming trays and bottles. PET's crystallization rate can be accelerated by adding tiny quantities of nano-tin, while higher amounts can increase abrasion and impact resistance [155, 156].

8.5. Moisture Barrier Enhancement Nanoclay. It was one of the initial materials to hit the market and polymer nanocomposites for food packaging. Nanoclay is now the most widely utilized nanoparticle, accounting for almost 70% of total market value. It is now the most frequently utilized nanomaterial in the packaging industry. Nanoclay is majorly used to improve the physical characteristics of plastic packaging and the gas and moisture barrier capabilities. Clays are found in nature, available at low cost, and are environmentally benign materials that can be used for a wide range of uses. Clay minerals have been extensively investigated in various fields, including agriculture, geology, engineering, building, processing industries, and environmental applications. They can provide an appealing option for soil, subterranean water, sediment, and industrial effluent decontamination. Nanoclay is also widely utilized for beverage packaging due to its excellent properties. Because of their weak gas barrier function, plastic bottles could not effectively preserve the taste of beer/soda and the gas in the past. This problem has been solved by incorporating the polymer matrix with nanoclay. Montmorillonite (MMT) is a nanoclay in which an alumina (octahedral) sheet is fused with two silica (tetrahedral) sheets in an edge-shared structure. High aspect ratio fillers are particularly intriguing because they result in superior nanocomposite material reinforcement. Nanoclay is already being used in beer bottle manufacturing, multilayer films, fizzy beverages, and thermoformed industrial containers. Nanoclay in plastic bottles is also said to keep the juice fresh and has a 30-week shelf life. Because of its high cation exchange capacity, superior swelling behaviour, and broad surface area, it is widely employed in polymeric composites. Thus, a nanoclay composited coating can keep food wet inside while preventing oxygen and carbon dioxide penetration from the outside [4, 157].

8.6. Reinforcement Materials of Starch Nanocrystals. Starch nanocrystals are utilized in food packaging for purposes like fillers and reinforcement. Nanocrystals made of starch are potential alternates to the widely popular synthetic emulsion latex as an unnatural and low-cost binder. The nanobiopolymer binder made out of starch (e.g., glyoxylate polyacrylamide) might be made with cationic starch, which is frequently used to replace dry strength synthetic resins in wet-end processes. Furthermore, starch nanoparticles differ significantly from ordinary cooked starch in that they create a flexible transparent film rather than a brittle one. As a result of its resistance to breaking from folding and scoring, it is widely used in coating cardboard. Because starch is very sensitive to hydration, moisture typically affects several characteristics of native starch. These unfavorable native starch behaviours can be eliminated or minimized by rearranging the starch granule structure, improving their physicochemical characteristics. Selecting nanostarch is ideal if the requirement in the packaging is to bind or fill gaps as it operates similar to emulsion latex that is similarly used for this purpose [4].

8.7. Cellulose Nanostructures. The most typical application of cellulose nanostructures is as reinforcing phases, although they may also be utilized as matrices in various materials, such as food packaging films. Cellulose nanoscaled fibers, cellulose nanowhiskers, or microfibrils are other names for nanoscaled cellulose. In general, cellulose's structure consists of alternating amorphous and crystalline threads. The crystallized area is created by a strong hydrogen bond network, which stabilizes cellulose as a polymer. Because of the complicated hydrogen bonding system, cellulose chains can have greater axial stiffness required for a filler to be composited. As a result, they are commonly used as reinforcing fiber additions since their characteristics and performance significantly outperform traditional fillers such as glass fibers and talc. Nanocellulose may enhance the stiffness and strength of a polymer with a small amount because of its high aspect ratio. Nanocellulose appears to be a potential replacement for standard petroleum-based materials due to its exceptional characteristics and high biodegradability. Another feature that CNCs may alter is the water sensitivity of hydrophilic films. Even though water vapor permeability and its sensitivity are connected to the hydrophobicity of the material, they are two distinct characteristics. Different experiments, including water solubility, water sorption, and water absorption, have been used to assess the impact CNCs make on the hydrophilic films regarding their water sensitivity. The heat stability of biopolymers like alginate and PLA has also been improved using CNCs. The majority of research employing CNF reinforcements has focused mostly on tensile characteristics; however, studies found many other benefits like a significantly lower swelling degree, VWP and PVA film solubility in water, and chitosan's enhanced thermal stability. Therefore, nanocellulose in either form (CNC and CNF) can be used as an active filler or reinforcement in food packaging materials [22].

8.8. Sensors

8.8.1. Carbon Nanotubes. Carbon nanotubes (CNTs) have received great interest since their discovery due to their unusual physicochemical and electrical characteristics. CNTs in recent times are being mixed with polymers like PP, PVOH, PLA, and Nylon and investigated for packaging applications, notably antibacterial and smart sensor applications. CNTs are divided into nanotubes, a single atom thick, and multiple concentric nanotubes. Combined with a polymer matrix, both kinds produce tremendous tensile strength with a large elastic modulus. Toxic to *E. coli* bacteria are carbon nanotubes with pure single-walls (SWCNTs) with little metal wastage. CNTs are regarded as an incredibly excellent electrode material due to their capacity to enhance charge transfer processes and have been widely used for electrode modification. MWCNT is significantly less expensive to create than SWCNT. The production of chemical moieties on the surface of carbon nanotubes (CNTs) changes their physical and chemical characteristics, resulting in improved performance for certain applications. Single-layer CNTs are vulnerable to gases like NH_3, NO_2, and several volatile organic compounds because of a shift in conductivity caused by gas-particle adsorption on the surface. These gases are harmful to packaged food and can sometimes be toxic to consumers. Electron transport from NH_3 to the tube causes the formation of a spatial charge region on the surface of the CNT and thus an elevation in its resistance value. The addition of organic compounds, nanostructured materials, oxides, and polymeric materials to carbon nanotubes alters their electrical characteristics and enhances their selectivity and sensitivity to certain gases. It is worth mentioning that the way target molecules interact with different functional groups or additives varies a lot. CNT is frequently changed due to the addition of a carboxyl group-H. This forms various sections that can be reactive near the CNT's edges and sidewalls, where active interactions with different chemicals occur. CNTs can help detect the presence of such harmful gases in the packaging or around the food and signal an alert. This property is very useful for ensuring the food is not spoilt or sometimes poisoned by these gases. Therefore, one can select carbon nanotubes to be the packaging material to check the presence of such gases [158].

9. Conclusions

Researchers are aware that nanotechnology is fetching a very important role in food packaging because of its superior mechanical, physic-chemical, thermal, and barrier properties which will enhance the packaging materials but there has always been a problem with the food industry is the time which is put in order to quality control analysis is still not sort out, although the nanosensors have been developed in order to detect gases and microorganism with the use of nanoscale enzyme immobilization systems which are very useful for the food packaging. Nanocomposites are used in food packaging, but the consumer's safety is not fully studied or evaluated. The diffusion matrix of the nanoparticle is not known experimentally, and the migration of nanoparticles is crucial to address that the solution would eventually affect the polymer structure. As we are talking about food consumed by humans and having lesser knowledge about the safety of several types of nanoparticles, many agencies take the safe approach by migrating the nanostructures into a specific food lower than the detection limits.

The packing of silver nanoparticles has been replaced by titanium.

(1) *Reinforced packaging*: high barrier capacity, better mechanical properties, thermal stability, and UV-blocking

(2) *Active packaging*: antimicrobial activity, scavenging capacity, and release of nutrients

(3) *Intelligent packaging*: detection of food-borne pathogens, detection of gases and chemicals, time and temperature monitoring, and controlled release of active compounds

Multilayered packing is actively used as it acts as a unique barrier.

Different tactics and procedures may be used to create a wide range of nanoparticles. The most important thing to remember when it comes to the synthesis of nanoparticles is to identify the best circumstances for working on repeatability and quantity. The biosynthesis of nanoparticles by plant microorganisms includes microbes, yeast, and actinomycetes. It is a perfect, nonharmful, and environment-friendly "green chemistry" strategy. Nanomaterials have displayed a scope of extraordinary components considered unique to their bulk materials. Nanomaterials have high surface regions, attraction, microbial movement, and high thermal and electrical conductivity. Metal nanoparticles show incredible antimicrobial impacts. NPs of metal oxides are constrained in usage due to their toxicity in larger quantities. Some antibacterial methods might benefit from the use of these NPs. These antimicrobial nanoparticles can be used in sanitizers, covering-based applications, and food readiness measures. We accept that the improvement of basic and minimal expense inorganic antibacterial agents like metal and metal oxide NPs, an option for customary antitoxins, may be promising for the eventual fate of food packaging and medication. Two fundamental methodologies are used for the synthesis of nanomaterials. One of the fundamental methodologies includes the top-down method, which comprises different techniques, including electrospinning, lithography, sputtering, milling, and laser removal strategies. The second methodology consists of the bottom-up method, which incorporates hydrothermal synthesis, sol-gel, and converse micelle strategies. With the new advancement and the continuous endeavours to further develop the synthesis of particles and investigate their uses, it is trusted that their business uses in medication, medical care, and food packaging will occur in the years to come.

The abundant availability of nanomaterials is a good choice for large-scale production for different applications.

Active, edible packaging, and biodegradable materials are considered one of the food industry's main objectives due to the growing need for alternate packaging materials that are recyclable, renewable, easily degradable, and require little or almost no disposal.

Food packaging that does not even contribute to pollution and items made effectively utilizing sustainable technology is growing increasingly popular. As a result, there has been a greater focus on improving innovation, biodegradable and edible materials will enhance food quality and safety, and increased studies on edible material made and manufacturing aspects will be added on the subject. To increase the shelf life of edible films, cellulose derivatives, chitosan, lipids, plant-based proteins, and starches can be used. Biocompatibility and gas barrier capabilities, pollutant, and toxic-free characteristics are advantages of such polymers.

Furthermore, creating nanofibers' innovative packaging will provide the consumer with valuable information and allow proper production systems. NFC is used in medical equipment, pharmaceuticals, packaging of smart food, and various other applications. Nanofibrillated cellulose has also been identified as a promising resource. Moreover, the use of such nanocellulose fiber in packaging can overcome cost-effective challenges by minimizing packaging material residue generation due to its reusability and innovativeness.

The different technologies and trends associated with the part packaging have been reflected. Due to the deterioration of food, a large part of society does not get even the minimum quantity. Smart packaging reduces the deterioration of food and detects any traces of pathogens in the stored food. Techniques like active packaging are the most efficient ones, which aid in controlling the quality and richness of the food. Devices like nanosensors are used in intelligent packaging, smart materials, and nanomaterial barriers. Even though nanomaterials are expensive, active packaging can serve all the basic needs while being inexpensive and efficient.

On reviewing the used nanomaterials and their applications in agriculture and food, it is noted that the most used organic nanoparticles are nanocarriers. Only a few techniques can detect nanomaterials in food and biological samples due to their high reactivity. On the other hand, toxicological assessment requires in vitro alternatives and approaches due to the vast diversity of nanomaterials. These assessments are conducted to check or act as a screening tool to flag the concerning use of nanomaterials and enable one to set a guide to take regulatory measures to design such nanomaterials.

The works are done globally in the field of nanomaterial biosynthesis. Plant extracts can synthesize nanomaterials using different parts of the plant like root, shoot, and leaf which can lead to various nanoparticles such as silver nanoparticles. Nanoparticles can also be synthesized with the help of microorganisms which reduce the metal salts and accumulate into the small-sized nanoparticles. Furthermore, by the action of bacteria, fungi, yeast, biological particles, nanomaterials are known to get synthesized. Such nanomaterials are used vastly in the agriculture food industries.

In conclusion, nanomaterials offer a wide range of economic benefits, are environmentally friendly, are decomposable, and are renewable packing materials that are gaining an alarming rate of attention and demand as a means of addressing environmental pollution and food shortage problems and to make sure it will be reached out to all people. It is worth noting that some basic research on ecotoxicity and toxicity and analysis on migration and management of risks in using nanomaterials is yet to be fully studied. As a result, edible nanomaterials may perform better in food packaging.

10. Future Developments and Possibilities

Although research on nanomaterials to improve quality has been conducted, research on freshness and toxicity is still beginning. More research is needed before the potential of nanomaterials is discovered.

Beginning with methods must be advanced so that the properties of nanomaterials can be characterized and measured to know their biotransformation in food. Due to its expensiveness, the lack of determining a huge amount of tests, and the convolution of the food matrix, methods are rarely used. More research should be done to assess the harmful properties of NPs, whether it is counted as an edible ingredient or exposure to food.

Furthermore, for it to be implemented successfully, the issues of cost, biocompatibility, and expansibility need to be resolved further. In the future, an attempt should be made to ensure the consistency and eternal container from the sensor under surrounding constraints, along with technical verification. Migration of NPs from food packing along surroundings is another issue that needs to be better understood. Problems like these should be assessed in the way of development. Moreover, the lack of a regulatory framework for using nanotechnology in food has made the customers unwilling to use nanofoods.

Lastly, because of excellent quality and improved analysis, classifying and naming the nanoproducts are all required to address customers' requirements and administrative problems, ultimately leading to quick financial approval. Topics must regularly organize special meetings to discuss the utilization possible to execute nanotechnology; this work will increase in the future.

In short, nanotechnology contributes to innovation for improved features, manufacturing, preservation, and food analysis. However, health factors and their effect on the environment might be questioned because of the involvement of toxicity. This analysis summarizes recent developments and potential applications and emphasizes the risks and advantages of these techniques. In the future, an attempt should be focused on ensuring that nanotech is safely used for a good impact [159].

Nanotechnology is widely used in food industries because of its developed fields in protecting food from pathogens, improving food quality, increasing shelf life, altering the composition and organic compounds, and even forming edible films in fruits and vegetables. Encapsulating bioactive compounds will increase the stability of the product to control the pesticides, and organic compounds (i.e., plant-based) will not cause any effect on humans and the environment. The application of liposomes in the food industry showed the best results in improving the shelf life of food. It also provides flavours and nutrients to the food products. Another bioactive-based nutraceutical compound known as prolamin or zein can be used to form biodegradable plastics when engineered with nanobeads or nanomaterials [160].

Most of the biopolymer is renewable sources classified into 3 groups depending on the raw materials used, such as directly extracted natural material, a classical chemical derived biobased monomer, and fermented microorganism [161]. Mostly, these biopolymers are poor in exhibiting the mechanical property, performance, and cost. Encapsulating the biopolymers with nanomaterials (like nanocomposite or nanoparticle or nanofillers) will increase the mechanical property and reduce the production cost. Plastic materials/synthetic polymers have demand and more usage in recent days. The disposal of plastic material (nondegradable) may result in global waste, so using degradable polymers is more important [162].

We can use natural biopolymers instead of nanometals in food industries like silicon dioxide and titanium dioxide for food color, fragrance, flavour, and texture [163]. The nanoencapsulated products have to maintain the flavour of the food from various factors such as spoiling, increasing shelf life, and stability. Most of the baking process, the flavours are mostly added in powdered form for easy blending. For instance, lipids and proteins are fabricated into nanoscale architectures. Later it will interact with compounds based on physiochemical properties. Other than the bakery product, most of the flavours were added in the liquid form (dispersed in an aqueous phase) at ambient conditions. For example, milk protein was added to increase food flavour retention by hydrophobic interaction. It will give the food a pleasant aroma and influence the pH, temperature, and ionic strength. Starch is very important for improving the texture of the food. The complex structure is formed by amylose with volatile compounds. Starches can control the flavours [164].

Nanoencapsulated products are released to maintain the culinary balance of the food items. Most of the plant encapsulated products are an unstable example, anthocyanin. Cyanidin-3-O-glucoside of ferritin subunit from soybean kernel can improve the thermal property, stability, UV radiation, and photostability by encapsulating the ferritin nanocages. The encapsulation of curcumin compounds exhibits antimicrobial and antioxidant property and also found it is stable to pasteurization and ionic strength, for example, Curcuma longa (turmeric) [165].

Fabricating CNF (cellulose nanofiber) with brown algae will frame a weak gel-like structure through hydrogen bonds by absorbing the casein micelles. This fabricated CNF can help to thicken the milk [166, 167]. Naringinase is an enzyme produced from various microorganisms (mainly by fungal stains) that can reduce the bitterness in grapefruit juice and some citrus fruit juice. Naringinase cellulose acetate nanofibers can be used to debitter the grapefruit juice to enhance the wine's aroma [166, 168]. Rosin and chitosan can be used for their excellent antimicrobial property. Encapsulation of CNF with asafoetida and curcumin will enhance the formulation of gut health [166].

They are available at lower costs, lightweight, ecologically beneficial, and easier to recycle when contrasted with most nanoparticles. Wood is the most frequent source of CNs and the most industrially important cellulose resource. Due to their extremely crystalline structure, CNCs are rigid materials with aspect ratios exceeding 100 (L/d ratio). CNC dimensioning is influenced by various manufacturing factors. CNC length, for example, diminishes as hydrolysis duration increases. TEMPO oxidation is a typical preprocessing that is important for manufacturing CNCs and CNFs. The cellulose is pretreated with TEMPO, which converts the hydroxyl groups in the cellulose into moieties of carboxyl. It enhances crystallinity, stimulates nanofibrillation, and improves CN dispersion in water. While CNFs have been used to make most CN-based films, CNCs may also be used. According to a study that looked at the modulus of CNC films and percolation threshold made from various primary sources, the film's stiffness rose as the aspect ratio increased. Information gaps must be addressed to enhance safety and public impression, along with introducing techniques to identify and characterize CNs as food ingredients, the formulation of dosage measurements, and the identification of goods presently on the market that utilize CNs in the packaging of food [168].

CNC has been acknowledged for more than 5 decades, and their limitless potential and application advantages have been increasingly found. Their distinct nanostructures provide CNC with exceptional physical and chemical characteristics, allowing them to perform critical roles in the food sector. The application of CNC has been thoroughly investigated in the food sector. However, numerous obstacles must yet be overcome. For starters, microbes and marine items are relatively new sources of biodegradable materials. These sources might be utilized to increase the yield, quality, and pricing of CNC. Then, to look into CNC fermentation in human digestion, CNC may interact with the gut microbiota and impact its metabolism in the distal ileum and colon. Researchers must continue to work on their technological and nutritional characteristic evaluation, safety testing, and, most significantly, the topic of food application regulation [167, 169–173].

Data Availability

All data are included in the inside manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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