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Review Article

Nanomaterial in Food Packaging: A Comprehensive Review

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Food packaging industry is going through various scientific evolutions as per the preferences of the consumers along with the consumer trends. Current trends focus on not only protecting the food intelligently but also making it visually appealing to the consumer. In recent years, considerable attention is been given to replace nonbiodegradable materials with ecofriendly biodegradable composite material. Nanotechnology is flourishing and has proven to be a great incorporation to the packaging industry, as it can also overcome the drawbacks of the existing methods. Various nanomaterials have been explored and tested for manufacturing of packaging materials. In the present review, we discussed on current trends in food packaging and their drawbacks with respect to over consumption of plastic and how sustainable packaging is being implemented. Furthermore, nanotechnology is becoming a promising and widely used potential in food packaging industry along with nanomaterials currently being used such as zinc nanoparticles, polymer clay nanoparticles, and silver nanoparticles in food packaging. This information will broaden our current understanding on potential and problems associated with nanotechnology in food packaging.

1. Introduction

Food packaging has always been an area of constant development and an industry that is always pressurized to deliver more. The food packaging material acts as barrier for external factor and enable to reach food to consumer in healthy and reliable way. Therefore, the business of processed food items has more emphasis on its packaging. With industrial revolution, the search for new packaging material with several features includes appearance, durability, hygiene, aesthetics, and ecofriendliness became more important development of packaging material [1, 2]. In addition, the major goal in packaging is to improve food quality, safety, and shelf life extension so that it has the potential to be a perfect fit into the current busy lifestyle [3]. The changes in the food such as aroma, flavor due to aroma sorption, and transfer of flavor from packaging materials are an important mechanism involved in deterioration of packaged food [1]. Plastics are most common packaging material used in the food industry due to low cost, light weight, transparent, and less permeability for gas and moisture [2, 4]. However, the most plastic packaging material have low resistance against heat, contain toxic softeners, and nonbiodegradable responsible for environmental pollution [2, 4]. Thus, the selection of packaging material and development of active, intelligent packaging which overcomes the disadvantaged of earlier packaging is pressing need of food industry. After the constant use of nondegradable plastic, the emergence of sustainable packaging gave rise to various technologies and discovery of various materials that possess the right properties for being substitutes of plastic. Nanotechnology is another wellspring of key enhancements for the current difficulties in food security and food maintainability [5].

Recently, the massive development has been done in packaging technologies to enhance the shelf life, food quality, safety, and freshness of products [1]. Among them, biodegradable polymer, bionanocomposite, nanostructured materials, and engineered nanoparticles are used in active and intelligent materials for food packaging [6, 7]. Furthermore, the designed methodologies and equipment facilitate quick in situ analysis, production of environmentally safe and degradable food packaging [8]. Overall, the nanomaterials includes metal nanoparticles, nanoemulsion, and nanoclay possess tremendous potential to utilize as packaging material. The incorporation of these materials in packaging improves the viability and susceptibility of compounds and promotes preservation and protection of packaging [7, 9, 10]. Nonetheless, nanotechnology's application in food packaging is still in its infancy. Currently, the introduction of various functional nanoparticles is rising in the packaging sector to enhance shelf life and ensuring the safety surrounding of packaged food [11].

In the past decade, tremendous development has been done in packaging material along with packaging technology. The present review provides information about types of packaging technologies with their limitation. Moreover, the scope of nanomaterials includes metal nanoparticles, nanoemulsion, and nanoclay in food packaging along with societal concern. The present information shed light on existing trends and scope of nanomaterials in food and beverage packaging useful to design and develop sustainable material and packaging technology to overcome weaknesses of existing technology.

2. Packaging in Food

The basic need of packaging is to protect the different types of food items from any kind of physical, chemical, and biological damage. The food products include fruits, vegetables, milk and milk products, meat, dry fruits, bakery products, and sauces require more emphasis on the shelf life and nutrition quality [12]. In this context, various methods of packaging and materials are used depending on the kind of products packed. The food packaging operations is carried out to encounter several objectives such as physical protection, transportation, marketing, information transmission, anticounterfeiting, and antitampering. Moreover, to protect different kinds of processed and unprocessed food items, a different material and design is required. Also, it serves as a way of increasing revenue of the product company; the more attractive the packaging, the more it sells. The company Paper Boat beverage packaging design is unique and flexible with attractive shape and color as well as durable and easily carriable packaging for their juices (Paper Boat Packaging: Unique Flexible Packaging for Beverages (bizongo.com). As per a report submitted by Market Research Future (MRFR), Food Packaging Market is projected to be worth USD 466.91 billion by 2027, registering a CAGR of 6.17% during the forecast period (2021-2027). The market was valued at USD 310.8 billion in 2020 (Market Research Future-Industry Analysis Report, Business Consulting and Research).

2.1. Biobased Packaging. The current trends in the consumer market moving toward greener packaging, waste reduction, biobased materials in the sustainable packaging industry have seen substantial growth. The topic of sustainability is critical, prompting policy-makers, academics, and businesses to develop sustainable and suitable alternatives for saving resources for the future generations, with a focus on biodegradable and biorenewable materials [13]. In this context, the major focus on biobased plastic materials synthesized from organic macromolecules obtained from biological resources that are manufactured for food packaging [14]. The commercialization of innovative biopolymers with better characteristics and new functionalities for packaging films and coatings, as well as textile applications, has been a priority. Biopolymers can be made in different ways, including directly from natural sources such as polysaccharides and proteins, or by polymerizing monomers derived from biomass, such as PLA (polylactic acid) from lactic acid. Microorganisms can also create biopolymers like polyhydroxyalkanoate (PHA) [15]. There are two types of biopolymers essentially used for biobased packaging; synthetically produced biopolymers and nonsynthetically produced biopolymers. Other materials used as starch, proteins, lipids, waxes, cellulose, and its derivatives. There are a number of options for improving packing materials with several feature such as long-term viability, appearance, and ecofriendliness. One option is reduction in the amount of raw material required by thinning the packing film or by designing the packaging to use the least amount of material. These techniques have several advantages which includes the following: minimizes the amount of plastic required; lighter weight; and saves material, money, and energy [15]. The other way in which use of postconsumer recycled material or reusable packaging, which helps to increase packaging recycling [16]. Furthermore, multilayer packaging was used to improve the performance of sustainable packaging even more. The multilayer packaging capable to provide diverse barrier properties and reduce material requirements for packaging. However, all of the suggested approaches are limited and inadequate for manufacturing a truly sustainable packaging material that meets the needs of a circular (bio)economy [13]. Therefore, the development of biodegradable material is evolving as a viable alternative in food packaging.

2.2. Active Packaging. Customers' changing lifestyles have increased demand for clean, high-quality, fresh, minimally processed, and ready-to-eat items with a long shelf life, necessitating the development of new packaging technology. Today, the new technologies, namely, intelligent packaging (IP) and active packaging (AP), are increasingly applied in the food industry, but in multiple cases still in development and not been commercialized yet. The IP systems are used to improve safety and showcase various warnings about potential problems inside the food packaging environment [17]. Also, IP systems are designed to detect storage condition, expiration date, safety diagnosis, quality, monitor microbial growth, and to determine freshness of food. Conversely, the AP system alters ambient conditions during the preservation time of packaged foods and difficult to keeping the safety and sensory aspects of packaged foods along with their quality [8]. Recently, the research conducted by scientists for better packaging is aimed at becoming the solution to two major concerns of the food industry, first is to provide good and fresh quality food to the customers which is free of any damage and secondly, to minimize the collateral and economic damage that the industry faces every year due to spoilage of food. Every year, tons of food gets wasted due to improper and inefficient packaging methods. Grand View research company (San Francisco, California, United States) in its report declared that the revenue for the packaging market will reach $6 billion in the United States for AP and around $3.45 billion for IP in the year 2024 (https://www.grandviewresearch.com/).

2.3. Drawbacks of Current Trends. All of the packaging materials used in the past were made from plastics and glass are nonbiodegradable. The packaging materials are made from paper, glass, and plastics, with more than two-thirds of them are utilized in the food industry alone [3]. The present environment is being jeopardized because of extensive use of these nonbiodegradable packaging material. Furthermore, the food packaging is at the top list in nonbiodegradable use of plastic for packaging. Due to changes in food consumption habits, patterns, and preparation styles, along with the beneficial growth of various places and markets around the world, this number continues to rise. The packaging industry utilizes the greatest amount of plastic generated globally and is the primary source of waste plastics that is rapidly entering the environment [18]. This is because of the one-time-use plastics and the rise of ready-to-eat snacks and ready-made meals, which need the use of durable plastic packaging material only once. Thus, the demand for development of environmentally friendly sustainable packaging materials for food packaging that have the appropriate physical, mechanical, and barrier properties is growing [19].

Other major difficulties in food packaging include poor barrier characteristics to water vapor and gases. The fresh, alive products (e.g., vegetables, fruits, and meat) must be packaged in O_2 permeable materials with an ideal transmission rate, whereas products that are processed do not demand such mass transfer. It is difficult to provide barrier protection to specific items in order to lengthen their shelf life with the restricted commodity thermoplastics available. Even though polymer blends and multilayered composite structures have been developed to increase the functional qualities of thermoplastics, issue-related recycling and high cost remain unsolved. Many food producers also face the difficulty of achieving a sufficient shelf life for their products while retaining maximum quality and safety. This is especially true for farmers in developing nations, where infrastructure for food transportation and preservation is limited. Food safety and quality issues such as microorganism multiplication due to contamination and temperature fluctuations, nutritional qualities lost due to oxidation, and loss of nutritional qualities due to interaction with deleterious extrinsic factors (light, oxygen, and water) are just a few examples [20].

3. Scope of Nanotechnology in Food Packaging

Despite the tremendous excitement in surrounding for nanotechnology and the abundance of funding for development being poured into it, the food industry has rapidly adapted this technology. The public preference for natural food product has historically inhibited the implementation of emerging food technology and nanotechnology is not surprising and no exception. However, the public opinion about general nanotechnology applications has ranged from neutral to slightly positive [21, 22]. Nanotechnology is a very interdisciplinary field that involves the use of materials having one or more dimensions less than 100 nanometers. Typical nanomaterials are put into three categories: particulates, platelets, and fibers are the three types of particles [23]. These materials have a high surface-to-volume ratio and surface activity due to their nanoscale dimensions. When nanomaterials are mixed with compatible polymers, they can radically improve the material properties of the resulting nanocomposites, in terms of mechanical strength and thermal stability, for packaging [24]. However, the large amount of solid waste generated has become a major environmental concern [20].

The importance of nanotechnology in food and beverage packaging industry is due to enhancing food security, extending storage life, improving flavor, and nutrient delivery. Thus, nanotechnology plays a critical role in beverage and food packaging as active and intelligent packaging beyond product protection, brand presentation, and imparting functions like moisture control (e.g., pads used to absorb the drip from meat, poultry and fish in display packaging trays) and antioxidant activity to reduce exposure to oxygen (e.g., use of small sachets that scavenge or capture residual oxygen from inside the packaging as well as surrounding environment or foodstuff itself). The food product exposure to oxygen results into microbiological growth on the food, chemical changes to the food, etc. Therefore, an oxygen scavenger is helpful to reduce these effects to improve shelf life of the foodstuffs. The oxygen scavengers commonly used in packaging pasta, milk powder, biscuits, etc. Moreover, antimicrobial activity (e.g., the sachet composed of antimicrobial agent slowly released which maintain freshness and extend the product shelf life of packaged food items). Intelligent packaging signifies features that deliver information about brand protection or information for consumer on safety and food quality like smart labels (e.g., label contains time-temperature indicator and radiofrequency (RF) sensor) [3].

4. Nanomaterials

Nanomaterials are rapidly advancing with vast applications in electrical, medicine, biology, energy, etc., and other fields as multidisciplinary research progresses. Furthermore, their progress in the agriculture and food industry is strikingly similar to their modernization in the domains of medicine distribution and pharmaceuticals [25, 26]. Studies on the synthesis, characterization, applications, and assessments of nanomaterials have promoted scientific advancement to grow and alter the entire agri-food area in recent years, owing to their unique properties other than their bulk counterparts, primarily covering physical, chemical, and biological properties [27, 28]. The food industry is currently exploring use of variety of engineered nanomaterials in development of various products. For example, nanometer salt grains were developed to reduce the consumption of salt by increasing its surface area and, as a result, lower amounts of nanosalt may give the same original savory taste to humans [29]. However, moving on from just nutritional value, nowadays, a group of global food companies are currently working on including nanotechnology in their foods and food packaging [30]. Longer shelf life, improved food safety, and better diet quality have become more significant consumer demands and thus, to satisfy these needs, the emerging technologies of nanomaterials in food packaging provide innovative solutions [31, 32]. Because of their antibacterial, UV protection, and oxidation prevention properties, nanomaterials are frequently employed to improve the properties of food packaging. Due to their high antimicrobial activity, they are good for antimicrobial active packaging [33]. Silver nanoparticles (AgNPs), nanoclay, nanozinc oxide (nano-ZnO), nanotitanium dioxide (TiO_2), carbon nanotubes (CNTs), cellulose nanowhiskers, and starch nanocrystals are among the nanomaterials that have been added to food packaging as functional additions. Each nanomaterial imparts diverse capabilities to the host material due to variances in chemical structure and features, resulting in a variety of functional packaging applications [34]. For instance, when nanoclay or CNTs are composited into conventional thermoplastics, they are uniformly scattered into the polymer matrix. The nanoparticles change the molecular mobility and polymer relaxation of the plastic and, thereby, can effectively improve the thermal and mechanical properties. Moreover, the large specific surface area of the nanomaterial makes it highly active compared to its macro- and microparticle format. For example, AgNP and nano-ZnO, which are commonly used in nanoenabled food packaging, have greater activity for antimicrobial performance than particles of larger dimensions [35, 36].

Overall, the three primary functionalities of nanocomposite materials for food packaging reported in the last three years are enhanced, smart, and active food packaging [37]. The use of nanoparticles in bionanocomposite materials increases their mechanical and barrier properties, such as elasticity, gas barrier qualities (barrier against oxygen, carbon dioxide, and flavor compound diffusion), and stability under various temperature and moisture conditions [38]. Second, smart (intelligent) packaging acts in terms of information feedback and marketing on real-time quality of packaged food products, as well as a guard against fraud and fake products and an indicator of the situation of exposure to certain adverse factors such as insufficient temperatures or high oxygen levels [39, 40]. Third, active packaging provides protection and preservation through mechanisms engaged by inherent and/or acquired elements (antimicrobial activity, biodegradable activity), resulting in a reduction in food product loss through shelf life extension [41].

4.1. Silver Nanoparticles. With an increasing demand from both customers and food processors for safe and high-quality meals, the requirement for antimicrobial composite packaging films has attracted great attention in the food industry [42]. Food packaging with antibacterial qualities is said to be capable of releasing active biocidal chemicals for improved food quality, shelf life extension, and spoiling prevention [43–45]. This is accomplished by the use of organic materials or the incorporation of inorganic elements into food packaging, the latter of which is becoming increasingly popular. For example, organic acids and enzymes when used in conjunction with organic materials [46, 47], or inorganics, such as metal nanoparticles or metal oxides, are most commonly used. [48, 49]. AgNPs with their antibacterial capabilities have been widely used in food packaging technology among existing inorganic nanomaterials for a variety of items, including fresh fruits, fresh meats, and consumer products [50].

Silver nanoparticles with a broad spectrum of antibacterial activities are fatal to many microorganisms including bacteria, algae, fungi, and possibly some viruses [51, 52]. They are synthesized from silver atom clusters for antibacterial and sterilizing applications [53]. For example, silver has proven to be a better biocide against bacterial strains including *Escherichia coli*, *Staphylococcus aureus*, *Staphylococcus epidermis*, *Leuconostoc mesenteroides*, *Bacillus subtilis*, *Klebsiella mobilis*, and *Klebsiella pneumonia* (Marambio-Jones and Hoek 2010). As AgNPs have a bigger surface area per mass than microscale silver particles or bulk silver material, they have higher potential for releasing silver ions. There are many mechanisms for the antimicrobial activity of silver that have been developed [50]. For example, AgNPs can adhere to the cell surface and degrade lipopolysaccharides, consequently forming a pit in the cell membrane [32]. A tremendous amount of research has concluded that silver salts (e.g., silver chloride) and silver-ion based materials (e.g., silver sulfide and silver nitrate) tend to have higher antimicrobial activity than nanosized silver metal materials [54].

There are several different methods that can be applied to introduce AgNPs into plastic polymers for packaging. For instance, silver ions can firstly be embedded or trapped into the porous substrate, such as zeolite, and then, these materials can be inculcated in plastics. Silver ionexchanged zeolites (Ag-zeolite) are commercially available and commonly used in active packaging film [32]. Either by embedding Ag-zeolite into a polymer matrix by extruder or by incorporation into a thin layer (3-6 mm) on the surface of the packaging where the food contacts the package, trapped silver ions can be released onto microorganisms [55]. AgNPs can be also directly scattered into the polymer matrix of the plastic [56].

In one of the study, Zhao et al. synthesized iturin-AgNPs, which were monodispersed and 20 nm in average size within the range of 10–30 nm. Here, a 2 mL sample of iturin A (1 mg/mL, purity of 100%) was mixed with an aqueous solution of silver nitrate (0.1 mg/mL) and then exposed to UV radiometer ($\lambda = 365$ nm) at a distance of 5 cm for 30 min. The formation of AgNPs was confirmed by the appearance of a yellowish brown color and the specific absorption at 450 nm in the reaction solution. The typical surface plasmon resonance (SPR) band at 450 nm was observed, indicating the successful formation of AgNPs. Further, electron paramagnetic resonance (EPR) spectroscopy was used to confirm the generation of superoxide during formation of the AgNPs by iturin A and chain peptide (CP). This indicated that UV irradiation is essential for the formation of AgNPs by iturin A and CP and can be deduced that the formation of AgNPs by iturin A and CP are a process of photo reduction. Additionally, to investigate the role of $O_2{\cdot}-$ in the formation of AgNPs by iturin A and CP, the changes of dissolved oxygen were measured. Hither, photo generation of AgNPs decreased significantly in the presence of N_2 due to the purge of O_2, indicating the formation of AgNPs was facilitated under UV radiation in the presence of dissolved O_2. This result illustrates that $O_2{\cdot}-$ acts as an important role in the synthesis of AgNPs. The inhibitory effects of iturin AgNPs on the Gram-positive bacterium *S. aureus* were comparatively lower than those on Gram-negative bacteria E. coli and Salmonella typhimurium. Consistent with the results obtained from well diffusion studies, iturin-AgNPs showed higher antifungal and completely inhibited all fungal growth at concentrations higher than 2.5 μg/mL. Thus, iturin-AgNPs was successfully used for the preservation of orange from fungal decay and chicken from bacterial decay with no detectable silver residue. Overall, iturin-AgNPs showed attractive potential for application in food preservation. [57]. With the increase in serious environmental requirements, biodegradable polymer-based packaging materials have also been studied extensively. Zhang et al. synthesized magnesium oxide (MgO)/silver (Ag) nanoparticles (NPs) which were prepared through O_2- reduction. Here, the UV–vis spectrum of MgO/Ag NPs showed that the 400 nm range successfully reduces Ag NPs. Since the hydration of MgO generated $Mg(OH)_2$, the surface bound electron-hole decomposed into two typical oxide catalysts, namely, surface-trapped electron and localized hole, which reacted with oxygen and formed superoxide radicals (O_2). O_2 then reduced Ag+ into Ag NPs. Further, they incorporated MgO/Ag NPs into poly(butylene succinate-co-terephthalate) (PBST) matrix to prepare PBST/MgO/Ag nanocomposite films by solvent casting. Additionally, the XPS spectrum proved the existence of Mg, O, Ag, and C elements in MgO/Ag NPs that indicated MgO/Ag NPs possess high purity and only the metallic nature of Ag other than its valence state of Ag (Ag^+) existed in the MgO/Ag NPs. FTIR spectra of PMA films indicated that only the weak physical interactions other than chemical interaction were formed between the NPs and PBST matrix. Also, here, the optimal properties were achieved by 3% (w/w) MgO/Ag NP content. The thermal decomposition for PBST was a one-stage process, whereas those for PMA films were two-stage or even three-stage processes. Overall, their initial decomposition temperature, elongation at break, tensile strength, water vapor permeability, and oxygen transmission rate were 343.3°C, 544.94%, 31.57 MPa, $1.61 \times 10 - 11$ g·m/m^2 ·s·Pa, and 4.01×10^{-11} Barrer, respectively. Furthermore, owing to the enhanced antibacterial activities of the nanofillers, PBST/MgO/Ag possessed superior antibacterial activities against Gram-positive bacteria (*S. aureus*) and Gram-negative bacteria (*E. coli* and *S. para-typhi B*). PMA-3 showed the best preservation abilities which endowed the cherry tomato with the lowest weight loss rate and highest firmness. After 7 days of preservation, the number of microorganisms on the uncovered sample was nearly five times higher than that on the sample covered with PMA-3 film. This finding was mainly attributed to the synergistic antibacterial effects of MgO and Ag NPs. Therefore, the PMA films in this work are very promising candidates for cherry tomato packing applications [58].

Nanocellulose is being explored in food packaging material for its low cost, nontoxicity, biodegradability, etc. Owing to this properties, dextran-coated silver nanoparticles were loaded on cellulose nanofibrils film (CNF) (10-70 nm diameter) using the solvent casting method. The surface plasmon resonance peak was recorded at 405 nm confirming the formation of nanoparticles whereas red shift of peak at 430 nm was recorded for the hybrid film composite. The average size of AgNPs was found to be 12 nm. Interestingly, the mechanical property was enhanced by the addition of dextran-coated AgNPs to the film mainly because of positive effect on strength and reduced elongation at break from 5.5 to 2.5%. The permeability of oxygen in dextran-coated silver nanoparticles' nanocomposite film depicted highest OTR values of about 2.07 cm^3 m^{-2}d^{-1}, which is stabilized after 15 days. Further, the time-dependent antimicrobial activity of hybrid film composite showed 77% reduction in cell viability in 7 h and complete reduction in 24 h for *E. coli*. In contrast, *S. aureus* showed negligible antibacterial activity because of the slow and low release of Ag ions. Hence, the results obtained concluded that an ecofriendly hybrid film composite should be utilized in various food packaging applications [59].

4.2. Polymer Clay Nanocomposites. Among the various nanocomposites polymers, nanoclay is considered one of the most promising used material in the area of food packaging [32, 60]. It is commonly used to improve the physical properties, like water vapor permeability and gas permeability through clay composites. [61]. Polymer clay nanocomposites are a mixture of two or more materials and can be prepared by three methods, namely, in situ polymerization, solution blending, and melt blending. The cross-breed composites have led to display of huge expansions in elasticity, modulus, and hotness contortion temperature as contrasted and the flawless polymer. The composites additionally have lower water affectability, decreased penetrability to gases, and a comparative warm coefficient of development. These property enhancements can be acknowledged without a deficiency of clearness in the polymer.

Polymer nanocomposites have excellent barrier properties against gases (e.g., O_2 and CO_2) and water vapor. Studies have shown that such reduction in gas permeability of nanocomposites strongly depends on the type of clay (i.e., compatibility between clay and polymer matrix), aspect ratio of clay platelets, and structure of the nanocomposites. In general, the best gas barrier properties would be obtained in polymer nanocomposites with fully exfoliated clay minerals with large aspect ratio [62]. The enhanced gas barrier properties of nanocomposites make them attractive and useful in food packaging applications [63]. Nowadays, environmentally sustainable biopolymers such as polylactic acid (PLA), polycaprolactone (PCL), and polybutylene succinate (PBS) have become attractive materials for many packaging applications, including food. However, due to some limitations of these biopolymers such as poor barrier and weak mechanical properties, they are generally used as composite materials. Nanoclay has been recognized as a major reinforcement filler for biobased polymers. At very low clay contents, it can improve barrier property, modulus, creep resistance, and mechanical strength of biopolymer [64, 65], while biodegradability remains intact [54]. Montmorillonite (MMT) consists of an edge-shared octahedral sheet of aluminum hydroxide between two silica tetrahedral layers. It has been extensively used in polymer composites due to its excellent cation exchange capacity, large surface area, and good swelling behavior [66]. In one of the study, montmorillonite (MMT) was silylated by dispersing 10 g of dry MMT in 500 mL of distilled water at 80°C for at least 2 h while using an UltraTurrax spinning between 9000 and 11,000 rpm and further steps were conducted. Fourier transform infrared (FTIR) was conducted to determine the presence of modifiers in the clay minerals which found out two peaks at 2935 and 2880 cm^{-1} in the 3-aminopropyltriethoxysilane (APTES) modified clay mineral (Clay3), similarly the clay minerals (clay 4) modified with vinyltrimethoxysilane(VTMS) found out peaks at 1610–1630 cm^{-1} and 1410–1460 cm^{-1}, thereby confirming the modification with the organosilane. Wide-angle X-ray diffraction (WXD) revealed that the interlayer space in Clay3 is twice that of the raw clay mineral (MMT) and higher than in Clay4, thereby providing evidence that the silane APTES intercalates inside the MMT interlayer spaces, while the modifier VTMS does not increase significantly the interlayer distance. Thermogravimetric analysis (TGA) performed found that the grafted silane amount (%GSA) in the organoclay minerals, that is, Clay3 and Clay4 were 11.10 and 10.20, respectively. The cytotoxicity test performed revealed that after both exposures to Clay3 at all evaluated doses, Caco-2 and HepG2 cells were unaffected in comparison to the control cells and after 24 and 48 h of exposure, and Clay4 caused a reduction in cell viability in both cell lines. The study concludes that in comparison to the bulk material, the produced nanocomposite (PP-Clay3) exhibited better mechanical, barrier, and antibacterial properties (PP) [67].

In order to improve the barrier property of these polymeric materials plate like fillers are incorporated into the polymer, more particularly the montmorillonite (MMT). 2.5 μm thick nanocomposite layer of modified MMT/polyvinyl alcohol (PVA) was prepared by Li et al. through a gelatinous suspension of 4 wt% onto 13 μm PET film. To sandwich the nanocomposite layer, another LLDPE film with an adhesive was laminated against the PET coat. PET was used as outer layer and LLDPE as the inner layer. Pouches of 14×10.5 cm of 175 cm^3 volume were prepared and used for packaging. The RH when contacted to the LLDPE side showed that there was not much variation in the OTR (RH range of 20–50%) but increased at high RH ranges; but, the OTR of the nanocomposite layer was much lower. The hydrophilic PVA in the MMT also had the capability to adsorb water content and moisture at RH even higher than 50%, and this resulted in the increase in the mobility of the oxygen across the film and more sites for oxygen to dissolve in the layer. The oxygen permeability pace was also much slower in the MMT layer (1.44 mL/m^2 day at 20°C to 7.13 mL/m^2 day at 50°C) as compared to the control film. The MMT packaging also prolonged the retention of ascorbic acid and lycopene (hydrophilic and lipophilic antioxidants) in tomato paste and also decreased its discoloration. Hence, it is safe to conclude that MMT incorporated composite layer significantly reduced the oxygen permeability. However, low surrounding humidity condition (up to 20%) and elevated temperature of up to 50°C are recommended to get the maximum efficiency from the packaging material [68].

Tanwar et al. analyzed and evaluated the microstructure and physical characteristics of prepared films in their hunt for biodegradable and ecologically friendly packaging materials with a variety of useful applications. The extraction of the coconut shell was carried out in which 200 mL of methanol solvent was used to dissolve 20 g of coconut shell powder, and then, the mixture was continuously swirled at 25°C and 500 rpm on a magnetic plate stirrer for 24 h. The coconut shell extract was then separated from the solution using high-speed centrifugation at 5000 rpm for 10 min. In order to create active antioxidant films, 4 g of polyvinyl alcohol (PVA) and 1 g of cornstarch (ST) were mixed together in a powder state at room temperature before being dissolved in 100 mL of distilled water, and then, a hot plate magnetic stirrer was used to stir the mixture continuously for 4 h at 80°C and 500°RPM. As a plasticizer, 1.34 mL of 40 wt% sorbitol was added because the films made with sorbitol exhibit lower WVTR than films made with glycerol. To examine the interactions of different compounds of PVA/ST/SP films, Fourier-transform infrared (FTIR) spectroscopy was performed using a Perkin Elmer FTIR C91158 spectrophotometer in the wavenumber range of 4000–400 cm^{-1} with a resolution of 4 cm^{-1}, which indicated that the hydrogen bonds between PVA and ST molecules were partially broken, and new hydrogen bonds were formed between the silanol groups (-SiOH) of sepiolite and PVA/ST as a result, which caused the stretching -OH vibration to move to a lower wave number of 3254 cm^{-1}. In order to analyze the thermal behavior of the films, Thermogravimetric analysis (TGA) analysis was performed by taking a test sample that was heated from room temperature (25°C) to 800°C at a heating rate of 20°C/min in a nitrogen gas atmosphere, which indicated that the thermal degradation of all the samples was predominated by three distinct regions and the maximum degradation (65%) took place at 200–400°C (T_{max} = 330°C). Using a scanning electron microscope with a 5 kV accelerating voltage, the morphological structure of produced PVA/ST/SP/CSE films was examined and they found that the addition of TP results in irregularities in the films because of aggregation and nonuniform dispersion of tea polyphenols in the matrix. X-ray diffraction (XRD) examination using Cu Kα radiation on an X-ray diffractometer at a voltage of 40 kV and 40 mA was used to determine the crystal structure where each test sample was scanned twice at a speed of two times per minute, ranging from three to forty times, this found out a strong signal at $2\theta = 19.70°$ and an intensity of about 51,035 counts for PVA/ST film. For PVA/ST and PVA/ST/SP/CSE-20% films, the addition of CSE and SP clay dramatically reduced the tensile strength (TS) from 32.77 MPa to 10.86 MPa. The study concludes that CSE has great antioxidant qualities and had an impact on the PVA-atarch films' physical characteristics when used to produce biocomposite films. Additionally, it enhanced the mechanical characteristics of films (elongation at break). The findings of this study suggest that CSE has excellent potential as an antioxidant agent and the findings of this study pave the way for the efficient and economical use of discarded coconut shells in the production of biocomposites for uses in food packaging [69].

One more example of commercial nanoclay composites is Durethan® KU2-2601, which is the trade name of a nanoclay engineered polyamide 6 film developed by Bayer 68–70 and commercialized under Lanxess Deutschland GmbH.7 [70]. It is used in a variety of markets and applications including medical and food packaging film. Durethan KU2-2601 is composed of clay platelets distributed throughout the polymer matrix that perform as a barrier. The composited film can prevent oxygen (O_2) and carbon dioxide (CO_2) penetration from the outside, while retaining the moisture of the food on the inside [71].

4.3. Zinc Nanoparticles. The food industry uses ZnO as a source of zinc, an essential micronutrient and serves important and critical roles in growth and development and safely recognized as GRAS material by Food and Drug Administration. [72]. Recently, researchers have tested the *in vitro* antibacterial activity of ZnO and also potential application in food preservation. [73]. Antimicrobial active packaging based on metal nanocomposites are made by incorporating ZnO NPs are embedded into polymeric matrix to provide antimicrobial active packaging-based material. ZnO nanoparticles exhibit high surface to volume ratio, optical transparency, electrical conductivity, and direct contact with bacterial cell wall thus enabling destruction to bacterial cell in better manner than their micro- or macroscale equivalents [73]. ZnO nanoparticles have been evaluated for antibacterial effectiveness against Gram-positive bacteria like *Bacillus subtilis* and *Staphylococcus aureus*, which have shown sensitivity to these nanoparticles [74, 75]. ZnO is particularly appealing for packaging applications when compared to AgNP since it is less expensive and less hazardous to animals and people [76]. Glass, low-density polyethylene (LDPE), polypropylene (PP), polyurethane (PU), paper, and chitosan have all been mixed with ZnO nanoparticles utilizing various incorporation methods [36].

The mechanism behind antimicrobial activity of ZnO is not fully understood. Under UV irradiation, ZnO can produce a great amount of hydrogen peroxide, which can cause oxidative stress in bacterial cells. Some studies present that zinc ions play a key role in inhibiting bacteria proliferation (i.e., bacteriostatic), rather than killing bacteria (i.e., bactericidal) [42]. A plastic wrap containing nano-ZnO from Song Sing Nano Technology Co., Ltd. (Taiwan) is designed for beverage and food packaging. In addition, many researchers are studying the feasibility of nano-ZnO for applications in food packaging. For example, Akbar and Anal [77], investigated the antibacterial activity of ZnO on *Salmonella typhimurium* and *Staphylococcus aureus* in ready-to-eat poultry meat. Also, Tankhiwale and Bajpai [78] prepared and characterized a nano-ZnO composite film with polyethylene and reported the potential to protect food from bacterial contamination [61].

In another interesting study sulphate-containing polysaccharide carrageenan, which is derived from red algae (Eucheuma denticulatum) have also been used in combination with ZnO for food packaging. In this study, SiO_2-ZnO nanoparticles were added to semirefined iota carrageenan-based (SRIC) films as active food packaging. The nanoparticles were dispersed using a bead milling technique, and the films were made using the solution casting technique. The findings from the study on the effects of the addition of SiO_2 and ZnO nanoparticles, and mixtures of SiO_2-ZnO nanoparticles varied in SiO_2/ZnO ratios (SiO_2-ZnO 1 : 1, 1 : 2, and 1 : 3) showed that the SRIC film's tensile strength (8.52–11.68 MPa), water solubility (85.88%) water vapor barrier performance, UV screening, and antimicrobial activity (*E. coli* was shown to have higher inhibitory action than *S. aureus*) were improved. Additionally, it did not entirely result in the loss of the film's other beneficial qualities, including transparency, water solubility, degradability, and thermal stability. A well-scattered filler suspension that was uniformly dispersed throughout the matrix is thought to have had an impact on the improvement in film characteristics by strongly interacting with the film matrix. It was determined that the SiO_2-ZnO 1 : 3 film showed the best performance among the active packaging films. The film surfaces in this study are described as being hydrophobic because the surface energy ranges from 18.603 to 22.137 mN/m [79].

One of the most promising biobased and biodegradable polymers used for food packaging is polylactic acid or PLA, which is a linear aliphatic thermoplastic polyester derived from renewable sources such as corn starch, rice, and sugar cane. Due to its superior transparency, simple processing, and comparable mechanical properties, PLA is one of the most promising biobased and biodegradable polymers used for food packaging. An investigation was carried out on composite films made of PLA and reinforced with acetylated cellulose nanocrystals (ACNC) (1 wt percent) and ZnO nanoparticles (1, 3, 5, and 7 wt percent), which were made using the solution-casting process. The cellulose nanocrystals' surface acetylation enhanced its dispersion in the PLA matrix. Excellent antibacterial activity was also shown by this ternary composite against *S. aureus* and *E. coli* (when the additional content of ZnO is less than 5 weight percent, the rate of bacterial growth inhibition can reach up to 99.9%). Zn^{2+} migrated from PLA/ACNC/ZnO composite film to food mimics at rates that were less than the required migration limit (5 mg/kg). The SEM, FTIR, and XRD analyses demonstrated strong intermolecular compatibility. The tensile strength of the PLA/ACNC/5 percent ZnO composite film increased by 40.5 percent when compared to pure PLA, while the oxygen barrier improved by 43.6 percent and the water vapor barrier climbed by 26.3 percent [80].

ZnO nanoparticles have also been explored as fillers in organic or inorganic composites to improve the structural, optical, and electrical properties of sodium alginate/polyethylene oxide. The goal of this study was to create a reinforcing and antibacterial nickel and zinc oxide nanoparticle- (Ni/ZnO NP-) loaded sodium alginate/polyethylene oxide (50 percent NaAlg/50 percent PEO) blend-based film. The sol-gel method was used to create the Ni/ZnO nanoparticles as a nanohybrid at various concentrations (0.0, 5.0, 10.0, 15.0, and 20.0 wt%) using the solution cast method. The NaAlg/PEO-Ni/ZnO nanocomposite's crystallinity level was reduced from 47 to 25 percent, while the dielectric and AC conductivity properties of the nanocomposites increased with the addition of Ni/ZnO nanoparticles as their concentrations rose. Ni/ZnO nanoparticle loading improved the nanocomposite's mechanical properties, such as its tensile strength, which went from 30.18 to 72.34, stiffness, increasing from 18.78 to 38.42, and Young's modulus, raising from 8.24 to 29.76. With an increase in Ni/ZnO nanoparticle concentration, the water solubility of nanocomposites films decreased from 65.5 percent to 9.81 percent, and the polymer nanocomposites films had remarkable antibacterial activity against *E. coli*, *S. aureus*, *A. niger*, and *C. albicans*. The produced polymer nanocomposite films were found to be amorphous according to an XRD analysis, with two distinctive peaks appearing at about $2\theta = 18.97^\circ$ and 23.06°. The interactions/complexation between the NaAlg/PEO and the Ni/ZnO nanoparticles have been demonstrated by the FTIR data [81].

5. Societal Concerns regarding Nanotechnology in Food

Nanotechnology has a very high potential to help society through applications in food bundling. It can make the items less expensive and the creation more effective by delivering less waste and utilizing less energy. Nonetheless, any new innovation conveys a moral obligation regarding shrewd application and the acknowledgment that there are potential unanticipated dangers that might accompany colossal positive potential. In corresponding to the specialized development of nanotechnologies, it is normal that there will be new administrative orders and rules to oblige nanotechnology-based items. In general, the benefits of nanocomposite materials are widely understood, whereas the possible (eco)toxicological consequences and effects of nanoparticles on human health have received less attention. Concerns about human and animal health arise as an outcome of their interactions with the food system. The use of nanomaterials in nanosensing or food packaging applications may result in nanomaterial migration into the human body. This can happen by inhalation, skin penetration, or ingestion as a repercussion of nanocomponents from packaging or sensing elements leaching into food, or by storing packaging and nanosensors in landfills with the potential for release into the environment, air, water, and soil [82–84]. Nanoparticles have been demonstrated to have toxicological effects on biological systems in several investigations [83, 84]. The toxicity, however, appears to be dependent on the kind and size of nanoparticles [85]. The migration of nanomaterials from the container or the sensing element inside the package into the food is capable of being a possible source of worry. Ingestion is the most obvious route for nanoparticles to come into contact with the human body in food applications. As a result, gastrointestinal tract features such as pH, the presence of various surface-active chemicals, electrolytes, digestive enzymes, gut bacteria, and mechanical forces alter nanomaterial absorption, potentially causing changes in nanoparticle properties and agglomeration state [86]. Echegoyer and colleagues evaluated Ag migration from several types of nanocomposites (plastic food containers) into food, concluding that the highest level of Ag migration was seen in acidic meals. Furthermore, microwave cooking promoted Ag nanoparticle migration more than a regular oven [87]. Metal and metal oxide nanoparticles are frequently referred to as biocompatible materials that have no notable harmful effects *in vivo* or *in vitro*; nonetheless, proinflammatory reactions and oxidative stress have been reported as a consequence of their presence [88–90]. The migration of metal oxides such TiO_2, ZnO, SiO_2, and aluminium oxide, which were utilized in food packaging to increase mechanical, antibacterial, light-blocking, and gas barrier properties of polymers, was studied. There was no evidence of nanomaterial migration from packaging to food [63].

Although several studies reported that migration of nanoparticles from food packaging is negligible, a food safety concern exists in the mind of the consumer. Because there are no specific regulations for some nanomaterial migrations limits (e.g., nanoclay, AgNP, and nanosilica), the government has asked the public for this authorization. Several media outlets and non-governmental organizations (NGOs) have brought up this issue via their communication channels. They have two aims: (a) to warn people that nanomaterials have been introduced into our daily lives with an uncertainty of safety and (b) to provoke governmental agencies to regulate nanofood packaging [61].

To address the present uncertainties and data limitations of nanomaterials' usage in food applications, more research and studies focused on physicochemical characterization, exposure assessment, toxicokinetic, and toxicity are needed. The research should look into the interactions and stability of nanomaterials in food and feed, along with gastrointestinal systems and biological tissues. In addition, systematic procedures for detecting, characterizing, and quantifying nanomaterials in food raw materials and feed, as well as approaches for assessing toxicity of nanomaterials, including chronic exposure and carcinogenicity, should be established [86].

6. Conclusion

Nanomaterials are increasingly being used in the broad-spectrum of applications. According to current food packaging research, nanotechnology is capable of offering a variety of alternatives for improving food packaging based on nanomaterial functionality, ranging from biobased packaging to intelligent/active packaging. The concept of food packaging will become increasingly sophisticated in the industry in the future as a result of the growing demand for types and varieties of exotic foods and the resulting provision of safer packaging of goods. Nanotechnology, which is used to process food packaging, allows for significant improvements in packaging material properties, but more research and development is required to understand in detail the role of nanotechnology in food packaging materials, particularly in terms of the benefits and drawbacks. It is being explored to improve the food quality and safety by incorporating nanoparticles into foods and packaging materials thus making it possible to improve the qualities of food, such as making it healthier, tastier, and more nutritious. Furthermore, by including appropriate nanomaterials, the mechanical, barrier, and thermal properties of packaging materials could be improved significantly, extending the shelf life and safety of food. Surface-modified antimicrobial films made of nanocellulose with inorganic or organic antimicrobial agents integrated have extraordinarily strong antibacterial activity against Gram-positive and Gram-negative bacteria. The outcome of the research possesses great antioxidant activity thus making it a promising candidate for food packaging industry. The research on nanomaterials in food packaging industry will pave a new direction of efficient, cost-effective, and durable nanocomposite material for improved food packaging applications.

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declared that there are no conflicts of interest.

Authors' Contributions

S.B., J.L., and A.R. were responsible for the conceptualization of the work. A.S., S.B., and J.L. were responsible for the data curation. A.S., S.B., A.R., J.L., S.A., M.A., M.J.H., M.A., and O.A. were responsible for the resources. A.S., S.B., A.R., J.L., and M.J.H. were responsible for writing—original draft preparation. A.S., S.B., A.R., J.L., S.A., M.A., M.J.H., M.A., and O.A were responsible for writing—original draft preparation. A.R., J.L., and S.B. were responsible for the supervision. S.B., A.R., J.L., S.A., M.A., M.J.H., M.A., and O.A. were responsible for the project administration. S.B., A.R., J.L., and S.A. were responsible for the validation. All authors have read and agreed to the published version of the manuscript.

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