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A Review on the Synthesis of Biodegradable Plastics Reinforced with Green-Synthesized Nanoparticles for Food Packaging Applications

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Abstract

The ecological effect of synthetic plastics is also of great concern, as they are responsible for many ecological problems, such as blockage of drains resulting in flooding, killing aquatic life, interference with soil aeration, hindrance of water uptake by plant roots, emission of microplastics to bottled water, enhanced carbon footprint, and emission of harmful gases. Green synthesis to produce biodegradable plastics is a great option to offer a solution to reduce ecological pollution. Nevertheless, the poor properties of such biodegradable materials have necessitated extensive research for their optimization. This overview emphasizes the addition of nanoparticles into various biodegradable plastic matrices, which has been found to improve mechanical characteristics, thermal stability, hydrophobicity, and water solubility. The paper discussed several nanoparticles incorporated in biodegradable plastics. These nanoparticles are antimicrobial, antioxidant, and anticancer, and their incorporation into biodegradable films provides antimicrobial properties, thus enhancing the shelf life of food items. Hence, nanoparticle-enriched films have the potential for use in active food packaging. However, the transfer of nanoparticles from the packaging material into the food is still a major issue that needs further study and addressing.

Keywords: Biodegradable plastics, nanoparticles, antimicrobial properties, green synthesis, food packaging.

1. Introduction

Plastic materials are affordable light and are unreactive. Traditionally, they have been derived from the petrochemical, which makes them non-biodegradable [1]. Non-biodegradable polymers have traditionally been widely utilized in packaging, primarily due to their superior mechanical and physical properties [2]. In addition, these materials are often improved by the addition of aluminum foil during processing, which makes them non-recyclable. The retrieval and recycling of such materials are economically and physically unfeasible as they require advanced equipment and a great deal of energy [3].

Over the past half-century, the global consumption of plastic has increased dramatically, which due to inadequate disposal and poor management practices, have created serious health and environmental problems [4]. A vast majority of plastic waste is either dumped in landfills or ends up on the beaches, oceans, and rivers, with only a little amount of it being recycled [5]. The unintended or uncontrolled release of conventional plastics into aquatic ecosystems is a major cause of marine biodiversity loss [4]. Previous studies have shown the bioaccumulation capacity of plastic contaminants in aquatic organisms like fish [6]. Apart from marine and terrestrial pollution, plastic debris also impacts the quality of air. The leaching of toxic pollutants from landfill areas is worrying, as plastic waste is often discarded near rivers, lakes, and soils [7]. Combustion of different types of synthetic plastic wastes releases dangerous gases, such as greenhouse gases, into the environment, leading to climate change and disrupting the atmospheric equilibrium of gases [8]. Another critical issue is associated with the chemical alteration of plastic discards under the influence of sunlight. When plastic waste is exposed to sunlight, it is oxidized, which results in the fragmentation of plastic into micro-particles hence, indicating the process of the degradation of the plastic. As a result, the animals in the water and on land confuse micro-plastic particles with food, which leads to their ingestion and their subsequent entering of the food chain and, in the end, to the contamination of the marine environment [9]. Therefore, reducing the consumption of plastic can solve the problem of the pollution of the ecosystem. Moreover, the fabrication of biodegradable materials that serves as an alternative to polymers based on oil can bring a number of advantages to both manufacturers and consumers [10].

Biodegradable polymers are materials that can disintegrate through the microbial enzymatic activity in a bioactive environment. Proteins, lipids, and carbohydrates are the main constituents of bio-based materials which can be produced in significant quantities by microalgae and certain species of cyanobacteria [11, 12].

In the recent years, biodegradable polymeric materials have achieved significant importance in many industries [13–15]. These materials possess a numerous merit over traditional metal-based materials, including plasticity, cost-efficiency in production on an industrial scale, light weight, durability, adaptability to any structure, and resistance to moisture [16, 17]. Research in the field of new materials and technologies, particularly biodegradable and biobased polymers, have been conducted to satisfy the constantly increasing need for new materials that are environmentally friendly. Bioplastics or biopolymers can be made from agricultural or marine resources [18, 19]. Significant steps have been taken to develop bioplastics from different resources including plants, microorganisms, and animals [20]. Although the search for new materials continues, some of the bioplastics like starch-based plastics are already available globally [21].

Biodegradable, non-toxic polymers have withdrawn substantial attention in recent years as an alternative to the conventional plastics obtained from fossil fuel, in food packaging domain [22, 23]. A naturally occurring polysaccharide, chitosan, has been extensively used for the packaging of food due to its natural antifungal and antibacterial activities [24, 25]. Among other biodegradable plastics used in food packaging, there are cellulose [26], PHA [27], protein [28], PBAT [29], PVA [24], and others. Nevertheless, the use of such biodegradable plastics in active food packaging is limited due to various constraints, such as the lack of proper mechanical characteristics, high flexibility, high hydrophilicity, low opacity [30, 31], and thermal instability [32]. Good mechanical properties and microbial contamination prevention are among the requirements of the plastic materials to be used for packaging foods [33]. The maintenance of food freshness and quality throughout its logistics operations is crucial for increasing the shelf life of food products and decreasing the volume of food waste [34, 35]. Preservative packaging is one of the pioneering solutions for extending the expiration date of food and decreasing the quantity of food waste [36, 37]. It involves the addition of nanofillers, particularly metal nanoparticles (MNPs), into biodegradable polymer matrices. The microbicides can be divided into two: natural microbicides, including substances such as chitosan [38] and phyto-based oils [39], among others, and; synthetic microbicides, including AgNPs [40], ZnONPs [41], and TiO_2NPs [42]. The nanoparticles also present unique characteristics like large surface area and improved thermal and mechanical performance. Thus, the current work aims at giving a critical analysis of preparation, properties, and antimicrobial test of biodegradable plastics reinforced with nanoparticles.

2. Synthesis and Functionalization of Nanoparticles

Nanotechnology is a science discipline that studies the synthesis and application of nanoparticles, which are the substances whose sizes are measured in the range of 1–100 nanometers [43–46]. It is a multidisciplinary field that combines many science branches which make it one of the most promising scientific and technical advancements of recent years [47]. Over the past few decades, nanotechnology has been given much attention in the research community. It is frequently considered as the basis of the next industrial revolution with significant impacts on society, the economy, and the environment [48–50].

Nanomaterials having unique properties, including nanoscale size, surface morphology, crystallinity, solubility, and bioavailability are very attractive for diverse uses in medicine, nanobiotechnology, pharmacology, optoelectronics etc. [51 – 53]. Additionally, they have a lot of advantages over bulk materials due to their increased surface energy, spatial confinement, and fewer defects. [54]. Their multifunctionality, unique characteristics, and innovative applications are expected to lead to a substantial growth in the production of engineered nanoparticles (NPs) in the next few years, as they are now attracting interest worldwide in various industrial and scientific areas [55]. In general, the nanoparticles are produced by metals and metalloids such as platinum, silver, zinc, selenium, carbon etc. [56 – 58].

There are several ways to synthesize nanoparticles, including physical, chemical, and biological approaches, which are often divided into bottom-up and top-down approaches [59, 60]. The chemical and physical methods that are widely employed have their own limitations, chiefly being capital-intensive and time-intensive with the involvement of toxic chemicals producing ecologically harmful byproducts. To ameliorate these challenges, various approaches for green synthesis and environmentally friendly methods are being explored in order to provide a safer and sustainable alternative for medical applications [61–63].

Conversely, biological synthesis makes use of natural biomolecules [64], plant extracts [65,66], bacteria [68], algae [67], yeast, and fungi [69]. The inclusion of enzymes, proteins, lipids, carbohydrates, and other metabolites gives these biological systems considerable reductive capabilities. The production of metallic and metalloid nanoparticles through biological assisted synthesis is a one-step, top-down, bio-reductive procedure. This process involves metal ions reduction from diluted hydrous solutions under moderate conditions, atmospheric pressure, and ambient temperature [70].

Numerous plant components, including leaves, flowers, roots, fruits and rhizomes, have been effectively utilized in the synthesis of NPs [71]. The process includes carefully washing the plant material with water and sterilizing it in distilled water. The washed plant material is dried under room temperature. The dried sample is then weighed and ground for extraction. Plant extract is then dissolved in Milli-Q water and heated while stirring continuously. The resulting solution is filtered over filter paper, and then the filtrate obtained is collected in clear form to be utilized as the plant extract in synthesizing nanoparticles [72].

Synthesis of metal nanoparticles (NPs) is performed by two methods: stirring with magnetic stirrer or sonication with sonicator [73]. The stirring method is the addition of the plant extract to metal salt solutions followed by constant stirring by a magnetic stirrer [74]. The reduction of metallic ions is achieved through phytocompounds in the plant extracts such as polyols, polyphenols, and terpenoids [75]. The parameter optimization, such as time, pH, metal salt concentration, temperature, and plant extract, is carried out to get fast and maximum synthesis of metal NPs of specific size, shape, and stability [73, 76]. The process of NPs formation can be monitored by observing the color change visually or by using UV-Vis. spectroscopy, which shows a sharp peak for the surface plasmon resonance of the metal NPs [77]. After successful synthesis of the NPs, the solution is treated with high-speed centrifugation in order to separate the NPs. The isolated NPs are then washed extensively with the proper solvents and dried in a low-temperature oven [78].

Metal nanoparticles have been produced greenly by using a variety of plant species. Abul Fara *et al*. (2016) utilized aqueous leaf extract of *Adenium obesum* to synthesize AgNPs, which were spherically-shaped with 10–30 nm in size, as verified by TEM analysis. These nanoparticles also showed strong anticancer activity [79]. Also, Talabani *et al.* (2021) utilized *Petroselinum crispum* leaf extract for the synthesis of silver nanoparticles with spherical morphologies and diameters of 40-80 nm. These nanoparticles were successfully utilized in solar thermal energy conversion, which proved their use in renewable energy technologies [74]. Liaqat *et al.* (2022) synthesized AgNPs utilizing *Terminalia arjuna* and *Eucalyptus camaldulensis* leaf extracts in a combined form in another study. The formed nanoparticles, having diameter ranges of 37–80 nm and spherical morphology, proved to be antibacterial against *S. aureus* and *B. subtilis* [76]. Tesfaye *et al.* (2023) synthesized AgNPs biogenically from *Vernonia amygdalina* leaf extract, and XRD studies showed the particle diameter to range from 4.26–7.04 nm. These nanoparticles were found to have antibacterial activity against *S. pyogenes, S. aureus, P. aeruginosa*, and *E. coli* [80]. Further, Keshari *et al.* (2020) synthesized AgNPs with *Cestrum nocturnum* leaf extract that resulted in spherical particles with a mean diameter of 20 nm. The nanoparticles showed antioxidant and antibacterial activity, especially against *Escherichia coli, Enterococcus faecalis*, and *Salmonella typhi* [81].

Amaliyah *et al.* (2020) produced copper nanoparticles (CuNPs) by *Piper retrofractum* fruit extract. The synthesized CuNPs under optimized conditions are spherically-shaped with particle size of 2–10 nm, and showed antibacterial property against *E. coli* and *S. aureus* [73]. Manivannan *et al.* (2020) fabricated CuNPs by *Tecoma stans* leaf extract. The CuNPs revealed spherical shape and size of 2 – 20nm. They have antioxidant activities, antibacterial property against *Aeromonas hydrophila* and *S. pyrogenes*, anticancer activity, and antifungal property against *A. niger* [82]. Chandra and Khan (2020) synthesize copper NPs from *Anacardium occidentale* testa extract. The NPs are of size less than 20nm with an irregular spherical shape, and it is efficient in the decontamination of uranium [83]. Akhter *et al.* (2020) biosynthesized copper nanoparticles by utilizing stem extract of *Orobanche aegyptiaca*. TEM patterns have ensured the synthesis of single-phase spherical-shaped CuNPs with a mean size below 50 nm. Significant antimicrobial property of CuNPs was found against *S. aureus & E. coli,* and nematicidal activity was established against *M. incognita* in-vitro [84].

Mohammed *et al.* (2023) produced zinc oxide nanoparticles (ZnO-NPs) using *Cymbopogon citratus* essential oil extract, resulting in nanoparticles with a hexagonal rod-like morphology and a size of 20–24 nm. These ZnO-NPs showed significant antibacterial activity against *Escherichia coli* and *Staphylococcus aureus* [85]. Again, Fouda *et al.* (2023) demonstrated the biogenic synthesis of ZnO-NPs from an aqueous peel extract of *Punica granatum*. The ZnO-NPs revealed a spherical shape and size of 10–45 nm. These nanoparticles appeared to show strong antibacterial activity against *Bacillus subtilis, E. coli, P. aeruginosa*, and *S. aureus*, antifungal property against *C. albicans*, and catalytic activity with regard to the disintegration of methylene blue dye [86].

Cittrarasu *et al.* (2021) utilized *Ceropegia bulbosa* tuber extract to synthesize selenium nanoparticles (SeNPs) having a mean size of 55.2 nm. These SeNPs showed effective anticancer property against breast cancer cells, antibacterial property against *Bacillus subtilis* and *Escherichia coli*, larvicidal activity against *Aedes albopictus* mosquitoes, and photocatalytic activity on methylene blue degradation [87]. In a separate study, Salem *et al.* (2022) made SeNPs from *Citrus sinensis* peel waste, obtaining spherical nanoparticles of 16 to 95 nm. These nanoparticles had strong antibacterial properties against *K. pneumoniae, Pseudomonas aeruginosa, E. coli,* and *Staphylococcus aureus* [88].

Patil *et al*. (2023) synthesized gold nanoparticles (AuNPs) from *Capsicum annum* fruit extract, obtaining spherical nanoparticles of 20-30 nm. These AuNPs were shown to exhibit antiangiogenic, antioxidant, and anti-inflammatory activities, which is promising for biomedical use [89]. Bayat *et al.* (2023) used the bud extract of *Syzygium aromaticum* to prepare PtNPs, resulting in agglomerated morphology and average size of 4.55 nm nanoparticles. They have also proven anticancer and antibacterial property against *S. mutans, S. aureus, E. faecalis*, and *E. coli*, along with catalytic efficiency towards methanol in fuel production by oxidation [90].

Table 1: Shape, Size and Applications of the Biogenically Synthesized Nanoparticles.

S/N	NPs	Plants Used	Part Used	Shape	Size (nm)	Applications	Ref.
1	Silver	*Adenium obesum*	Leaves	Spherical	10 – 30	Anticancer activity	[79]
2	Silver	*Petroselinum crispum*	Leaves	Spherical	40 – 80	Solar thermal energy conversion	[74]
3	Silver	*Terminalia arjuna + E. camaldulensis*	Leaves	Spherical	37 – 80	Antibacterial property	[76]
4	Silver	*Vernonia amygdalina*	Leaves	-	4.26 – 7.04	Antibacterial property	[80]
5	Silver	*Cestrum nocturnum*	Leaves	Spherical	20	Antioxidant Antibacterial property	[81]
6	Copper	*Piper retrofractum*	Fruits	Spherical	2 – 10	Antibacterial property	[73]
7	Copper	*Tecoma stans*	Leaves	Spherical	2 – 20	Antioxidant Antifungal Antibacterial Anticancer	[82]
8	Copper	*Anacardium occidentale*	Testa	Spherical	<20	Removal of uranium	[83]
9	Copper	*Orobanche aegyptiaca*	Stem	Spherical	<50	Antibacterial activity Nematicidal property	[84]
10	Zinc	*Cymbopogon citratus*	Oils	Rod-like	20 – 24	Antibacterial activity	[85]

11	Zinc	*Punica granatum*	Peels	Spherical	10 – 45	Antibacterial property Antifungal property Catalytic property	[86]
12	Selenium	*Ceropegia bulbosa*	Tuber	Spherical	55.9	Anticancer Antibacterial activity Larvicidal activity Photocatalytic activity	[87]
13	Selenium	*Citrus sinensis*	Peels	Spherical	16 – 95	Antibacterial and antibiofilm properties	[88]
14	Gold	*Capsicum annum*	Fruits	Spherical	20 – 30	Antiangiogenic, antioxidant, and anti-inflammatory activities	[89]
15	Platinum	*Syzygium aromaticum*	Buds		4.55	Anticancer, antibacterial, and methanol oxidation for fuel production	[90]

3.0 Preparation of Biodegradable Plastics Reinforced with Nanoparticles for Active Packaging

Food contamination is a worldwide problem, leading to increased mortality rates and considerable economic losses in the food sector. Therefore, nanoparticles' usage for controlling the microbial growth in food products has been proposed. The combination of nanotechnology and materials science paves the way for creating the advanced active packaging systems. The growing interest in active packaging has been driven by the need to find sustainable substitute to the extensive use of conventional plastics. The objective of this shift is the replacement of non-degradable polymers with eco-friendly substances. But a lot of natural polymers have poor physical qualities, thus they must be combined with other biodegradable polymers. Active packaging with antimicrobial qualities is deemed beneficial in prolonging the shelf life of food products by inhibiting the proliferation of spoiling microorganisms. [91].

Metal nanoparticles are used for improving the properties of biodegradable plastics [92]. They enhance functional characteristics and impart antimicrobial properties, rendering them attractive for use in packaging [93]. Among the most widely employed metal additives in biodegradable nanocomposites are silver, zinc oxide, and titanium dioxide. Titanium dioxide has photocatalytic properties, especially under UV light, which offers protection against foodborne allergens and pathogens [94]. Likewise, nanoparticles have better UV shielding properties [95]. They are also characterized by their outstanding plasmonic and antibacterial properties, chemical stability, high electrical and thermal conductivity, and catalytic activity [96]. These properties render metal nanoparticles critical components in the production of innovative, functional, and sustainable packaging materials.

3.1 Synthesis Process of The Biodegradable Film Composites

The processing of plastic films generally encompasses two major processes: the solution casting technique and the extrusion process. In the solution casting method, the polymer and plasticizer are mixed with the nanoparticles (NPs) dispersed in a solvent. These are stirred and heated at a certain temperature, preferably between 80°C to

90°C, depending on the nature of the polymer, in a hot-plated magnetic stirrer [97, 98]. The obtained solution is poured onto glass or Teflon plates and left to dry for 2–4 days to cast the film [98, 99]. Distilled water is the most widely used solvent [97 – 100], but other solvents like chloroform [101] and glacial acetic acid [102] are also used depending on the polymer type. Commonly used plasticizers include glycerol [97 – 100] and polyethylene glycol [99]. The efficacy of film casting is critically dependent on the concentration of plasticizers incorporated into the formulation. Insufficient plasticizer content results in films that exhibit brittleness and reduced flexibility, whereas an excessive amount of plasticizer can impart a rubbery texture, compromising the mechanical properties of the films [103].

For the extrusion process, films are made by mixing the formulation mixes and processing in an extruder or mixer at fixed rotational speeds of 35 rpm [91], 100 rpm [104], or 80–120 rpm [105] to yield pellets. These pellets are then molded to make films. Extrusion temperature profiles are closely regulated and are formulation dependent, with such examples being 90/120/120/120°C [NPs 2], 80/100/110/120/130/140/140/140/130/120°C [105], or maintaining a constant temperature of 190°C [104]. The films, following synthesis, are left at room temperature inside a desiccator for 24 hours to promote stability and remove any residual moisture prior to characterization [104]. This allows the preparation of highly uniform films with consistent properties, which is ideal for large-scale applications.

3.2 Characterization of The Synthesized Biodegradable Plastic Composites

Venkatesan *et al*. (2023) blended carbon nanoparticles (CNPs) into poly(butylene adipate-co-terephthalate) (PBAT). Thermogravimetric analysis (TGA) revealed that the reinforcement of the CNPs greatly enhanced thermal stability in PBAT composites. Mechanical strength of the composites also increased with CNPs concentration, as indicated by the increase in tensile strength by 2.84 MPa. In addition, the oxygen transmission rate also showed a decrease with enhanced CNPs loading, reflecting enhanced barrier features against water vapor and oxygen. The water vapor transmission rate of the PBAT declined continuously with increasing concentration of CNPs. Water contact angle test also showed the PBAT/CNPs composites' hydrophobicity after reinforcement. The composites also showed improved antimicrobial activity against *S. aureus* and *E. coli*. The PBAT/CNPs composite film successfully maintained the freshness of carrot for 12 days, highlighting its potential to be used as an efficient material for food packaging [106].

das Neves *et al.* (2023) synthesized Starch-PBAT plastics mixed with silver nanoparticles produced from *Fusarium oxysporum*. The AgNPs were found to be very effective antimicrobials against diverse Salmonella serotypes, including drug-resistant ones, with minimum bactericidal concentrations (MBC) between 4.24 and 16.98 µg/mL. The AgNPs-based biodegradable films showed inhibitory activity against the growth of a maximum of 10^6 Salmonella isolates. However, electrothermal atomic absorption spectrophotometry analysis of the migration of silver from the films to chicken revealed that it was 12.94 mg/kg and 3.79 mg/kg, which was beyond the permissible limit of 0.05 mg/kg. These results indicate the bio-AgNPs' potential as antimicrobial packaging and the requirement to overcome silver migration to meet regulatory requirements [91].

Abdo *et al*. (2023) produced a biodegradable film for packaging purposes by utilizing a polyurethane (PU) composite filled with poly(3-hydroxybutyrate) (PHB) and different concentrations of CuO-NPs. The PHB was obtained from *Microcystis sp*. The PHB derived from algae was found to possess antimicrobial activity against *E. coli, Salmonella typhimurium, S. aureus, Listeria monocytogenes, E. faecalis, P. aeruginosa,* and *C. albicans*. Mechanical testing demonstrated that contact angle of films was enhanced from 77° to 87° with increasing CuO-NPs concentration from 2% to 4%, which represented increased hydrophobicity. X-ray diffraction analysis confirmed that there was no notable intensity change in the peaks of CuO-NPs with increasing particle loading in PHB/PU matrix. Fourier-transform infrared (FTIR) spectroscopy measured spectra in the range of 400 to 4000 cm^{-1}. The incorporation of 40 wt.% PHB greatly enhanced the tensile characteristics of the films, which were thus compatible with packaging. The work identifies the promise of PHB/PU/CuO-NPs nanocomposite films as antimicrobial and biodegradable packaging materials with improved mechanical performance [101].

Biswas *et al*. (2023) synthesized a biocomposite films by mixing taro mucilage (TM), carboxymethyl cellulose (CMC), zinc oxide (ZnO) nanoparticles, black cumin seed (BCS) oil and glycerol. Scanning electron microscopy analysis revealed that films with TM, BCS oil and ZnONPs had smoother surface morphologies. Fourier-transform infrared (FTIR) spectroscopy proved successful interactions between CMC, glycerol, BCS oil, ZnO nanoparticles, and TM. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) proved that the addition of ZnO nanoparticles, BCS oil, and TM improved the thermal stability of the CMC-based films. The addition of TM greatly enhanced the water uptake capacity, antioxidant activity, tensile strength, and elongation at break of the films, but decreased the whiteness index and water solubility. Moreover, the biocomposite films were found to have antimicrobial activity against foodborne pathogens: *S. aureus* and *E. coli*. These findings suggest that the films' enhanced mechanical, thermal, and antibacterial properties make them promising for use in food packaging [100].

Iacovone *et al*. (2023) analyzed the impact of titanium dioxide nanoparticles (TiO_2NPs) on the characteristics of cassava starch nanocomposites fabricated through extrusion with various screw velocities (80 and 120 rpm). Films extruded at 120 rpm (S120-TiO2NPs) revealed complete starch processing and well-dispersed nanoparticles, resulting in significantly more elastic nanocomposites than those fabricated at 80 rpm. The addition of TiO_2NPs increased the storage modulus in all films, and S120-TiO_2NPs also exhibited greater strain at break values. Increased relaxation time due to a decrease in the number of polymer chains involved in the relaxation process was shown by the Kohlrausch–Williams–Watts (KWW) theoretical model analysis. In addition, the S120-TiO_2NPs films were observed to provide efficient UV light protection, enhanced hydrophobicity, and enhanced biodegradation in compost. These characteristics emphasize the possibility of S120-TiO_2NPs nanocomposites as a valuable material for future sustainable food packaging applications [105].

Rizal *et al*. (2023) prepared cinnamon nanoparticle-infused biopolymer films based on red seaweed (*Kappaphycus alvarezii*) by a solvent casting technique. The incorporation of cinnamon nanoparticles substantially improved the mechanical, morphological, thermal, wettability, and antibacterial characteristics of the nanocomposite plastics. The cinnamon particles were effectively nanoscale reduced with a mean diameter in the range of 1 – 100 nm. The addition of more cinnamon nanoparticles into the seaweed matrix increased the hydrophobic character of the films. Moreover, the tensile and thermal characteristics of the plastics were significantly enhanced by incorporating cinnamon nanoparticles. The films from the biopolymer showed effective antimicrobial activity, especially at a 7% cinnamon nanoparticle loading, with inhibition zone diameters of 10.27 mm, 11.39 mm, and 12.46 mm against *S. aureus*, *E. coli,* and *Salmonella spp*. respectively. These findings present the excellent antimicrobial property of the films. In general, the functional behaviors of the biodegradable films were greatly optimized by incorporating cinnamon nanoparticles, with them being a promising material to be used for applications demanding improved mechanical strength, thermal stability, and antimicrobial activity [107].

Tran (2024) examined the effect of various concentrations of Aloe vera-synthesized AgNPs on the physical features of polyvinyl alcohol (PVA)/chitosan biodegradable films. The findings proved that AgNPs-films possessed remarkable mechanical characteristics such as elongation at break of 213.9% and tensile strength of 36.7 MPa. The films also showed potent antibacterial properties with the capability to inhibit *E. coli* growth. The introduction of the synthesized AgNPs also introduced dramatic enhancements to the hydrophobicity of the films through greater contact angles with droplets of glycerol, improved heat stability, and decreased water solubility. Such observations show the viability of the biodegradable films as an environmentally friendly option for petroleum plastics for use in food packaging and preservation [97].

According to Srisuwan et al. (2024), addition of nano-zinc oxide (nano-ZnO) in poly(L-lactide)-b-poly(ethylene glycol)-b-poly(L-lactide) (PLLA-PEG-PLLA) matrices increased the crystallization, UV-barrier function, tensile strength and antimicrobial effects of the nanocomposite films. However, for concentrations more than 2 wt%, crystallization and tensile properties became deteriorated. For concentrations under 2 wt%, ZnONPs were well-distributed in the polymer matrix, yet they agglomerated at larger concentrations. The content of nano-ZnO was also increased, which resulted in lower thermal stability and water absorption, and higher opacity in the films. Nevertheless, PLLA-PEG-PLLA/ZnO nanocomposite films revealed effective antibacterial performance against *S. aureus* & *E. coli*. Therefore, nano-ZnO is a multifunctional filler for flexible PLLA-PEG-PLLA that performs as a nucleating, reinforcing, UV-screening, and antibacterial agent. These characteristics render the nanocomposite films applicable to protecting food as well as packaging materials against transport and storage damage, indicating that they can be utilized as a multipurpose food packaging material [104].

Vasiljevic *et al.* (2024) prepared an active alginate packaging film using antioxidant Fe_2TiO_5 and antibacterial ZnO nanoparticles, which were both synthesized in a green route using citrus peel waste. The average sizes of the nanoparticles were 10 nm for ZnO and 50 nm for Fe_2TiO_5. The films were made from sodium alginate with Fe_2TiO_5 and/or ZnO nanoparticles. The incorporation of nanoparticles resulted in a color change that was observable, decreased transparency, increased protection against UV light, and enhanced the thermal stability of the films. The dry matter content of the films was around 83%, and they had low solubility in distilled water, which was mainly because of the crosslinking of alginate polymer with Ca^{2+} ions. The ZnO/Fe_2TiO_5–alginate film had the lowest swelling degree of 178%. The efficiency of these films was illustrated through their capacity to keep strawberries fresh. The research concluded that alginate packaging films with the addition of a mixture of metal oxide nanoparticles can improve food safety and have a longer shelf life for food products and thus are a viable choice for active food packaging uses [108].

Din *et al.* (2020) prepared biodegradable semolina starch-based plastics reinforced with ZnONPs that were synthesized by using *Syzygium cumini* extract, following an eco-friendly method without harmful by-products. FT-IR spectroscopy analysis identified hydrogen bonds between the starch polymer matrix and ZnONPs, reflecting robust interfacial interactions. Moisture content analysis indicated a reduction in moisture uptake with higher ZnONPs concentration, with the lowest moisture content of 9.7% reported in the 10% ZnO blend. Water solubility analysis too showed lower solubility and higher water resistance with increased ZnONPs loading. The films too showed greater antimicrobial activity. Fibroblast cell cytotoxicity tests revealed that 5% ZnO blend was cytotoxic, whereas biodegradation studies reported that the 5% ZnO blend achieved high initial rapid mineralization that slowed down slowly with time. These results prove the promise of ZnONPs-reinforced semolina starch plastics as water-resistant biodegradable materials and antimicrobial substances for use in environmentally friendly practices [98].

Table 2: Mechanical properties and water contact angle of The Biodegradable Plastics-NPs.

S/N	Plastic's Type	NPs Used	Tensile Strength (MPa)	Elongation at Break (%)	Water Contact Angle (◦)	Ref.
1	PBAT	CNPs	7.5 – 9.9	306.25 – 368.75	72.7–102.5	[106]
2	PHB/PU	CuO-NPs	7.04±0.42–13.27±2.59	308.74 – 412.69	74 – 87	[101]
3	CMC/TM/BCS Oil	ZnO-NPs	6.29±0.64 – 14.41±0.65	31.54±6.25 – 65.64±4.86	-	[100]
4	Cassava Starch	TiO_2-NPs	2.5±0.3 – 3.4±0.3	-	64±4 – 77±3	[105]
5	Seaweed	Cinnamon NPs	39.25 – 53.06	27.5 – 40.05	61.74 – 88.92	[107]
6	PVA/Chitosan	AgNPs	36.7 – 40.03	213.9 – 238.4	60.86 – 77.54	[97]
7	PLLA/PEG/PLLA	ZnO-NPs	14.7±4.7 – 21.3±4.1	29±6 – 57±6	-	[104]

Table 3: Thermal Decomposition Temperature and Antimicrobial Properties of The Biodegradable Plastics-NPs.

S/N	Plastic's Type	NPs Used	Thermal Decomposition(°C)	Antimicrobial Activity Against	Ref.
1	PBAT	CNPs	364 – 434	*S. aureus* and *E. coli*	[106]

2	Starch/PBAT	AgNPs	-	*S. aureus, E. coli, Salmonella typhimurium UK-1, Salmonella typhimurium ATCC*, and *Salmonella enteritidis*	[91]
3	PHB/PU	CuO-NPs	-	Bacteria *(E. coli, Salmonella typhimurium, P. aeruginosa, S. aureus, Listeria monocytogenes, and E. faecalis).* Fungi *(C. albicans)*	[101]
4	CMC/TM/BCS Oil	ZnO-NPs	450	*S. aureus* and *E. coli*	[100]
5	Seaweed	Cinnamon NPs	360 – 410	*E. coli, S. aureus*, and *Salmonella spp.*	[107]
6	PVA/Chitosan	AgNPs	250 – 500	*E. coli*	[97]
7	PLLA/PEG/PLLA	ZnO-NPs	250	*E. coli* and *S. aureus*	[104]
8	Alginate	ZnO/Fe_2TiO_5-NPs	800	*S. enteritidis*, *E. faecalis, E. coli* and *S. aureus*	[108]

Conclusion and Future Direction

As a result of growing environmental concerns about traditional plastics, biodegradable plastics have emerged as an eco-friendlier option. However, biodegradable plastics' barrier, thermal, and mechanical properties are generally inferior compared to that of petroleum-based plastics. In order to surpass these limitations, the incorporation of nanoparticles (NPs) in biodegradable polymers has been identified as a promising direction. This review presents a detailed description of preparation techniques, properties, and applications of metal nanoparticle-reinforced biodegradable plastics. The paper explains the synthesis and functionalization of MNPs, dispersion of MNPs in polymer matrices, and improvements in mechanical strength, thermal resistance, and antimicrobial property. This study targets a number of nanoparticles including silver nanoparticles (AgNPs), zinc oxide nanoparticles (ZnO-NPs), copper oxide nanoparticles (CuO-NPs), carbon nanoparticles (CNPs), cinnamon nanoparticles (Cinnamon NPs), and titanium dioxide nanoparticles (TiO2-NPs). These nanoparticles are found to have high antioxidant, and anticancer activities. When used in biodegradable films, they impart antimicrobial activity, which can increase the shelf life of food items. Consequently, films enhanced with nanoparticles have potential for application in active food packaging systems. The critical challenge that should be addressed for safety and efficacy purposes is the possibility of nanoparticles migrating from the packaging material into the food, raising a fundamental issue that calls for further studies.

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