Biodegradable polymer nanocomposites for active food packaging

Soumili Roy¹, Kulwinder Singh², and Abhishek Kumar¹*
¹ Department of Physics, University Institute of Science (UIS), Chandigarh University, Punjab, India
² University Centre for Research and Development, Chandigarh University, Punjab, India

Abstract. Biodegradable polymer nanocomposites have gained attention in recent years owing to their antimicrobial activity. The article summarizes recent developments in improving antimicrobial, mechanical and barrier properties of biodegradable polymers chitosan, cellulose, gelatin and starch. ZnO, TiO₂, reduced graphene oxide and silver reinforced biodegradable polymer nanocomposites exhibit improved tensile strength due to intercalation of nanomaterials into the polymer matrices. Silver nanoparticle reinforced polymer nanocomposites have shown significant antimicrobial properties against various strains of bacteria and fungi. Although, development of antimicrobial nanomaterials embedded packaging films has helped to augment shelf-life of food, leakage of nanomaterials into the packaged food remains an area of concern.

1 Introduction

There has been considerable interest in finding novel methods for reducing plastic waste due to major environmental concerns. Being made from fossil fuels, polyethylene-based packaging materials do not biodegrade in soil causing accumulation of plastic waste in nature. Burning plastic also causes significant air pollution, releasing toxic chemicals into the environment and contributing to the climate crisis. A large number of plastic debris in the ocean is threatening marine life and this has triggered a worldwide environmental panic. Barrier properties, like the ability to resist moisture and oxygen and keep food fresh for storage, are what make plastic films the most popular and preferred form of packaging in the food industry. About 36% of globally produced plastic is used in single-use packaging materials, amongst which 85% is used in the food packaging industry alone [1]. The food packaging industry is, thus, the largest user of plastic waste contributing to an environmental crisis. To tackle this problem, a lot of focus is being directed towards developing sustainable and eco-friendly packaging materials using renewable resource [2, 3].

In this endeavour, biodegradable polymers are the materials of choice, owing to their ease of breaking down into environmentally friendly substances when exposed to natural microorganisms [4]. Biopolymers or biodegradable polymers are derived from natural sources, such as plants, animals and microorganisms [5]. Polylactic acid or PLA is one of the most popular biodegradable polymers derived from plant extracts. Polyvinyl alcohol (PVA), polycaprolactone (PCL), polyhydroxybutarate (PHB) and PVA are called synthetic biopolymers because they are not naturally occurring. They are man-made and synthesised from plant-based materials [6]. Examples of naturally occurring biopolymers include chitosan, alginites, starch, cellulose, etc. [7]. But biopolymers when used for the purpose of food packaging have drawbacks that include poor mechanical, barrier strength, insufficient thermal properties, etc. Nanomaterials, which when incorporated into these polymer matrices

*Corresponding author: abhishek.puchd@gmail.com

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).
can improve their mechanical, barrier and thermal properties [8, 9]. When nanomaterials are incorporated into the polymers, it enhances their antimicrobial, antioxidant and UV protective characteristics making them promising active packaging materials [10]. Nanobiopolymer materials are, therefore, being explored extensively as alternatives to conventional non-biodegradable packaging. Biopolymer nanocomposites are comprised of a continuous phase and a discontinuous phase. The continuous phase is the polymer matrix whereas the discontinuous phase is the nanomaterial used as filler [11]. The nanomaterials are dispersed throughout the polymer matrix. The homogeneity of the dispersion depends upon the method of synthesis of the biopolymer nanocomposite. Also, based on the homogeneity, the application of the biopolymer nanocomposite is determined. The nanomaterials that may be used as additives in the biopolymer matrices include silver nanoparticles, carbon nanotubes, nanoclay, nano-zinc oxide, cellulose nanocrystals, chitosan nanoparticles, etc. [12-17].

2 Nanomaterials as fillers for polymer nanocomposites

As the environmental threat caused by conventional non-biodegradable packaging increases, the need for alternative biodegradable packaging has increased. Biodegradable polymers are an effective alternative to conventional plastics, but their poor mechanical strength and ineffective barrier properties make them unfit for storage of food and to be used as packaging materials. Recently, however, nanomaterials being incorporated into these biodegradable polymer matrices have been shown to be effective in increasing the overall mechanical strength, barrier and thermal properties. The properties that are enhanced in the polymer matrix depend on the type of nanomaterial used. This method of incorporating nanomaterials into the biopolymer system is known as nanoreinforcement. The spaces between the polymer molecules are filled by nanofillers, thereby increasing the active and passive properties of polymer packaging [18]. In this section, various nanoparticles used in polymer nanocomposites have been discussed.

2.1 Silver Nanoparticles (AgNPs)

Silver has been exploited by mankind for its antimicrobial and therapeutic properties since ages [19]. In ancient times, silver helped store food, water and other beverages since it prevented spoilage [20]. Silver nanoparticles have been recognised for their high antimicrobial activity in recent times and are extensively used in the medical industry [21]. The anti-fungal, antiviral, anti-yeast and antimicrobial activity of silver nanoparticles is facilitated by their large surface area per mass which is not present in bulk or micro silver particles [22-24].

Silver nanoparticles can be used in polymer matrices to increase the antimicrobial activity of the nanocomposite polymer films. In a study by Radhakrishnan and co-workers, polyvinyl alcohol or PVA, a synthetic biopolymer, was incorporated with montmorillonite (MMT), an alumina-silicate clay, ginger extract and Ag NPs to produce PVA composite blend films (PAGM) for storing chicken sausages [25]. PVA film, PVA and MMT film, PVA and ginger extract film and PVA, ginger extract and MMT film were used as controls against PAGM film for studying the antibacterial activity of S. Typhimurium and S. aureus pathogens. PAGM film displayed strong antibacterial activity compared to commercial polyethene films. Chitosan (CS) and gelatin (GL), the two commonly used biopolymers, were used in a study by Kumar and co-workers to produce CS-GL-AgNP biocomposite films [26]. When compared to CS-GL-AgNP (0.05%) film, the 0.1% film of the same composition appeared to be more promising by extending the time period of storage of the red grapes which were used for testing purposes. AgNPs have also been seen to be effective with other nanocomposites like halloysite nanotubes (HNTs) and have been explored in combination with tannic acid (TA), a polyphenol, in a study by Majumder and co-workers [27]. A nanocomposite composed of TA-loaded HNTs with AgNPs used as nanofiller reinforcement in soy protein isolate (SPI) polymer matrix. Silver migration has been a cause of concern in silver-reinforced biodegradable packaging due to its toxicity and this study performed with
5% of the nanocomposite with SPI matrix showed acceptable migration limits along with facilitating controlled pH, lipid oxidation and microbial growth in the chicken breast fillets.

**Fig. 1.** SEM images of (A) untreated control bacterial cells and S. aureus treated with AgNPs produced from (B) A. vera, (C) P. oleracea and (D) C. dactylon [28].

AgNPs being incorporated into the matrix can also be synthesised via a biological route to make the overall production of the packaging material more ecological and cheaper. These Bio AgNPs being incorporated in polymer matrices have even shown improvement of additional properties compared to commonly synthesised AgNPs, especially in chitosan-based films [29, 30]. In such a study, by Zarrouk and co-workers, AgNPs were obtained using plant extract and incorporated along with kaolin clay and ficus carcia into a chitosan-based film [31]. This nanocomposite polymer film displayed promising results with increased tensile strength, 50% decreased light transmittance and good antioxidant, antibacterial and mechanical properties because of the synergistic effect that takes place between kaolin clay and AgNPs. SEM analysis of bacterial cells treated with AgNPs has been shown in Fig. 1 and helps us understand to what extent biosorbed AgNPs affect bacteria. Thus, packaging material reinforced with silver can be utilised for its antibacterial activity.

### 2.2 Nanoclays

Clay is the most common nanofiller that has been explored as a suitable nanofiller in polymer matrices. Clay occurs naturally and is abundant in nature resulting in cost-effectiveness as a reinforcement material. Their layered structure helps in enhancing barrier performance towards gases and vapours in addition to improving mechanical and thermal properties of polymers [32]. The impermeability of clay platelets creates a tortuous path for gases diffusing the nanocomposite resulting in enhanced barrier properties [33]. In a study by Mohsen and co-workers, the effects of nanoclay filler to polylactic acid (PLA) polymer matrix was observed [34]. After the addition of nanoclay to the polymer matrix, a major change in tensile strength was observed. This change was attributed to the hydrogen bonding taking place between PLA and nanoclay. The barrier properties of, the otherwise highly permeable, PLA also improved significantly after adding 6% nanoclay, which improved the oxygen transmission rate and water vapour transmission rate significantly.

Phase change materials (PCM) are often employed to develop and add smart features to packaging solutions. For example, in a study by Seo and co-workers, self-steam-release films were developed by combining PLA and polyethylene glycol (PEG), a PCM, along with nanoclay [35]. In a microwave heating test, the packaging made from the nanocomposite successfully released built-up steam without bursting the package. This type of bionanocomposite film would be useful for packaging microwavable foods. To study the different effects that different nanoparticles have on polybutylene succinate (PBS), a comparative study between nanoclay and nanoCaCO₃ was conducted by Chaochanchaikul and co-workers [36]. The tensile strength was shown to be higher in 15% wt nanoclay along
with the water vapour and oxygen barrier capabilities. Nanoclay can, therefore, be established as a nanoparticle which helps in food preservation by reducing mass loss [37].

3 Synthesis of biopolymer nanocomposites

Biopolymer nanocomposites can be prepared by conjugating or blending with other materials to form composites. Several studies have explored the different methods for creating biopolymer nanocomposites. A homogenous distribution of nanofillers is sought after for benefiting from their properties.

3.1 Solution Casting

In solvent casting method, a specific solvent is used to dissolve the polymer by continuously stirring it, and the nanofiller is dissolved in the polymer solution. In solvent casting method, solvent selection is a crucial step as the polymer has to completely dissolve in the solvent and the nanostructures should be dispersed thoroughly in the polymer solution. A mould is then used to cast the mixture so that the solvent evaporates. This eventually yields thin nanocomposite polymeric films [38]. This method is suitable for polymers that are soluble in solvents and can result in a high degree of nanofiller dispersion [39].

Solution casting method was used to prepare PLA/TiO$_2$ nanocomposite by using chloroform as the solution [40]. Soy-protein isolate (SPI), persian gum (PG) and AgNP films have also been prepared by this method [41]. Distilled water was used to dissolve SPI powder to form SPI solution and similarly, distilled water was also used in PG powder to form PG solution. Both the SPI and 0.25% PG solution were mixed together and 1% and 2% AgNP solution was added to it. The films produced by this method can be seen in Fig. 2. The addition of PG to the film helped in reducing its moisture content and the addition of AgNPs helped in increasing the antimicrobial activity of the films.

![Fig. 2. SPI matrix film produced by adding PG and AgNPs [41]( role)](image)

To prepare TiO$_2$ nanoparticle-embedded polymer matrix, three biodegradable polymers, namely PLA, polycaprolactone (PCL) and cellulose acetate (CA) were used in a study by Hung and co-workers [42]. PLA and PCL were dissolved in chloroform whereas CA was dissolved in acetone. TiO$_2$ particles were dispersed into this nanocomposite by 1, 3 and 5% weight of polymer. Therefore, from the studies discussed, it can be concluded that the solvent-casting method helps in homogenous dispersion of the nanofillers in the polymer matrix [39, 43].

3.2 Melt Blending

In this method, the polymer is mixed with the nanofiller in a molten state and cooling the mixture followed by solidification leads to obtaining the nanocomposite. This method results in good nanofiller dispersion and is considered an environmentally friendly, green technique due to the absence of solvents [44]. This is a scalable technique which makes it suitable to be used on an industrial level to produce packaging materials. The physical and mechanical properties of biodegradable polymers can be improved by this method as mixing biopolymers and nanocomposites together leads to surface modification of the produced material. A layered silicate is used as a nanomaterial in this method, and if the layered surfaces are compatible enough with the polymer matrix, then the polymer can mix with the layers of the
4 Properties of Polymer Nanocomposites

Active packaging refers to a smart and intelligent system of packaging where the packaging material interacts with food components to maintain the high quality of food [46]. Where conventional, non-biodegradable polyethylene packaging only helps with food storage by providing a physical barrier, active packaging goes beyond that traditional role by interacting with food particles to maintain nutritional quality, extending shelf-life and inhibiting any external growth before consumption. Biodegradable polymers when combined with nanoparticles impart enhanced antimicrobial action which makes them suitable for applications in the food packaging sector. Nanocomposites also enhance the passive properties of the polymer matrices which includes mechanical, barrier as well as thermal properties. In this section, the properties which are enhanced by nanomaterials in biodegradable polymers are discussed.

4.1 Antibacterial Properties

The large surface area and increased surface reactivity contribute to the antimicrobial properties of nanocomposites-reinforced biodegradable polymers. These factors enable them to inactivate microorganisms effectively [47]. Silver, being one of the most commonly used nanomaterials, is used for its excellent antimicrobial properties. The antimicrobial properties of silver have long been exploited for food and beverage preservation. Biosynthesis of AgNPs using plant extracts ensures an overall green approach to making packaging materials [28]. Polyvinyl alcohol (PVA) based AgNP films and chitosan-based (CS) AgNP films were studied comparatively for antimicrobial activity by Fogliano and co-workers [48]. Different concentration of AgNPs was used to make the films and the FE-SEM of the films made by different concentrations can be observed in Fig. 3. When the growth of P. flourescens was measured in hydrogel model food, PVA/AgNPs film displayed a larger inhibition zone as compared to CS/AgNPs film. The inhibited growth of bacteria can be attributed to the positively charged Ag⁺ ions interacting with the negatively charged sulphur or phosphorus-containing bacteria. Ag⁺ ions lead to structural changes in the bacteria which ultimately lead to cell death [49]. Antimicrobial activity of AgNPs against various strains of bacteria and fungi can be observed in Fig. 4.
AgNPs are, however, known to diffuse into food material when used for packaging purposes. Thus, regulating the amount of AgNPs that diffuse into food is a major factor which validates the antimicrobial properties of the food packaging [50]. In the study by Fogliano and co-workers, the Ag$^+$ ion concentration in PVA/AgNP film in contact with the food model hydrogel was observed to be 10 times higher than that of the CS/AgNPs [48]. The enhanced release of Ag$^+$ ions may have contributed to the antibacterial impact of the PVA/AgNPs film compared to the CS/AgNPs film. This evidence confirms that while designing packaging for antimicrobial activity, along with bacterial inhibition, minimal concentration of antimicrobial compounds leaking into food should also be ensured.

![Fig. 4. Antimicrobial activity of AgNPs against different strains of bacteria and fungi namely: (A) P. aeruginosa (B) E. coli (C) Staphylococcus aureus (D) S. mutans (E) C. albicans [51]](image)

Yang and co-workers recently studied the antibacterial properties of lignin-zinc oxide (LZn) hybrid nanoparticles reinforced in glyceryl methacrylate (GMA) grafted poly (butylene adipate-co-terephthalate) (PBAT-G) matrix [52]. The PBAT/LZn composite films showed a poor bacterial adhesion rate as compared to pure PBAT. The nanocomposite films also showed UV shielding and antibacterial and antioxidant properties. Antimicrobial activity of some biodegradable nanocomposites has been shown in table 1.

### 4.2 Mechanical properties

A primary goal while creating food packaging material that can compete with contemporary non-biodegradable polyethylene packaging is providing comparable durability, stiffness, strength and toughness. Biodegradable polymer packaging materials without being reinforced by nanomaterials have shown poor mechanical properties. In a study by Puglia and co-workers, ternary polymeric films of PLA and grafted PLA (g-PLA) were reinforced with cellulose nanocrystals (CNC) and lignin nanoparticles (LNP) at two different weight percentages (1 and 3%) [66]. Comparing PLA-1LNP/3CNC and PLA-3LNP/1CNC, higher values of modulus and tensile strength in PLA-1LNP/3CNC were observed, showing that different combinations of nanofillers amounting to the same weight would have different enhancement properties. This also shows that the enhancement effect of cellulose nanocrystals is more than that of lignin nanoparticles. Combined nanofillers totalling 6% weight were also studied in g-PLA and PLA matrix and it was noticed that increasing the percentage amount of nanofillers had negative effects on the reinforcement. This was possibly due to the formation of aggregates at a higher percentage of nanofillers. Also, when compared to the binary and neat composition of PLA, ternary composition displayed higher strength and modulus showing that combination of nanofillers helps enhance properties more significantly than binary or neat ones.
Fig. 5. SEM images of tensile breakage results of PLA/nGO/starch nanocomposites for (a, a1) 10 wt%, (b, b2) 20 wt%, (c, c2) 30 wt% of starch [70].

Nanoclays are known for their large aspect ratio which favours enhancement in mechanical strength of the nanocomposite [67]. Additionally, the intercalation process that clay undergoes when mixed with a polymer matrix also helps strengthen the mechanical properties of the nanocomposites as shown in a study by Naidu and co-workers [68]. When 5% bentonite nanoclay was reinforced in xylan-alginate based films, an increase in tensile strength was noticed which was attributed to the result of intercalation in the polymer film. Increasing the concentration of the nanofiller clay in the polymer matrix does not always ensure the increase in tensile strength as was reported in a study by Hosseini and co-workers [69]. At 5% and above concentration of nanoclay concentration, the tensile strength was reported to significantly decrease owing to the agglomeration of nanoparticles. In a recent study reported by Wu and co-workers, the tensile strength of PLA-based starch and nanographene oxide (nGO) incorporated nanocomposite structures was studied [70]. Starch was added in 10, 20 and 30 wt% concentration in PLA polymer. However, starch is known to reduce the mechanical properties in blended polymers. To overcome this, nGO, an amphiphile, was added to enhance the barrier properties of the nanocomposites. In fig. 5., the SEM images show the tensile breakage results in the different nanocomposite concentrations. The nGO promoted composting of starch and PLA as addition of nGO induced a crystallisation reaction in PLA and adhesion between the surface of starch and the PLA surface increased. PLA/starch/nGO nanocomposite having 20 wt% of starch had the highest stress value and lowest elongation value making it the nanocomposite with the most enhanced mechanical property. Adhesion between the nanoparticle and polymer is, thus, an important factor for better dispersion of the nanoparticles in the polymer matrices which results in a high tensile strength [71].

4.3 Barrier properties

Although, biodegradable polymers, such as PLA, polyhydroxyalkanoates (PHA), polycaprolactone (PCL), are environmentally friendly, their poor barrier properties make them unfit to be used as packaging materials. Their intrinsic structure leads to permeability of small molecules and gases. However, when biodegradable polymers are reinforced with nanomaterials or nanofillers, their barrier properties are enhanced. Nanocomposites enhance the barrier properties by creating a tortuous path for escape of gases. Low permeability to gases leads to retardation in oxidation and extends shelf life [72]. In a study by, Ali and co-workers, PLA/TiO2 films were observed for oxygen permeability which helped in determining the barrier properties of the nanocomposite films [40]. It was observed that the
oxygen permeability of PLA/TiO₂ films improves significantly as compared to pure PLA films. A decrease in oxygen transmission rate with an increase in TiO₂ composition quantified the observed results.

PBS or polybutylene succinate and graphene nanoplatelet (GnP) nanocomposites prepared by melt process were studied for water and dioxygen permeability by Cosquer and co-workers [73]. The study determined that an increase in barrier properties was observed which is evident by the depletion in water and oxygen permeability because of the tortuous path created by the GnP integration. Interestingly, it was also observed that the plasticization effect due to the high-water activity was not sufficient to counteract the contribution of GnP and PBS matrix in affecting barrier properties. Thus, choosing the right nanofiller can help with strengthening barrier properties.

Table 1. Antimicrobial activity of some biodegradable polymer nanocomposites

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Polymer Matrix</th>
<th>Nanomaterial used</th>
<th>Strain of bacteria/ fungi tested</th>
<th>Conc. of nanomaterial</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Poly (vinyl alcohol) or PVA</td>
<td>Ag</td>
<td>P. fluorescens</td>
<td>5 wt%</td>
<td>[48]</td>
</tr>
<tr>
<td>2</td>
<td>Agar / banana powder blend</td>
<td>Ag</td>
<td>L. monocytogenes, E. coli</td>
<td>1 mM</td>
<td>[53]</td>
</tr>
<tr>
<td>3</td>
<td>Chitosan-Fucoidan</td>
<td>Ag</td>
<td>S. aureus, E. coli</td>
<td>100 µg/mL</td>
<td>[54]</td>
</tr>
<tr>
<td>4</td>
<td>Chitosan</td>
<td>Ag-TiO₂</td>
<td>E. coli</td>
<td>10 mg/mL</td>
<td>[55]</td>
</tr>
<tr>
<td>5</td>
<td>Guar Gum</td>
<td>Ag-Cu</td>
<td>L. monocytogenes and S. Typhimurium</td>
<td>(a) 7.5 mg (b) 15 mg (c) 30 mg</td>
<td>[56]</td>
</tr>
<tr>
<td>6</td>
<td>Gelatin</td>
<td>Ag-Cu</td>
<td>L. monocytogenes and S. Typhimurium</td>
<td>AgNPs: (a) 0.5% (b) 1.0% (c) 2.0% (d) 4.0%</td>
<td>[57]</td>
</tr>
<tr>
<td>7</td>
<td>Chitosan/ Purple corn extract</td>
<td>Ag</td>
<td>E. coli, Salmonella, S. aureus, L. monocytogenes</td>
<td>2 wt%</td>
<td>[58]</td>
</tr>
<tr>
<td>8</td>
<td>Agar</td>
<td>Cu-S</td>
<td>E. coli and L. monocytogenes</td>
<td>0.5 wt%</td>
<td>[59]</td>
</tr>
<tr>
<td>9</td>
<td>PCL</td>
<td>ZnO</td>
<td>E. coli</td>
<td>3 wt%</td>
<td>[60]</td>
</tr>
<tr>
<td>10</td>
<td>PVA/Pluronic</td>
<td>ZnO</td>
<td>B. subtilis, S. aureus, E. coli, P. aeruginosa, C. albicans</td>
<td>5, 10, 15, 20, and 25 wt%</td>
<td>[61]</td>
</tr>
<tr>
<td>11</td>
<td>Poly(3hydroxybutyrate-co-hydroxyvalerate)</td>
<td>TiO₂-humic substance</td>
<td>S. aureus, E. coli</td>
<td>1, 3, 6, 10 wt %</td>
<td>[62]</td>
</tr>
<tr>
<td>12</td>
<td>PLA/PBAT</td>
<td>TiO₂</td>
<td>S. aureus and E. coli</td>
<td>7 wt%</td>
<td>[63]</td>
</tr>
<tr>
<td>13</td>
<td>PHB/PEG poly (ethylene glycol)</td>
<td>Nano-silica (n-Si)-clove essential oil (CEO)</td>
<td>S. aureus, E. coli and A. niger</td>
<td>0.5, 1, 1.5, 2 wt% of n-Si, 30 wt% of CEO</td>
<td>[64]</td>
</tr>
<tr>
<td>14</td>
<td>Chitosan/gelatin</td>
<td>Green tea-derived carbon dots</td>
<td>E. coli and L. monocytogenes</td>
<td>3 wt%</td>
<td>[65]</td>
</tr>
</tbody>
</table>
5 Conclusion and Future Trends

The looming environmental crisis has caused human beings to look for more sustainable and biodegradable technologies in every sector. Plastic packaging, made from polyethylene, after being dumped on land, is carried away by rainwater and sewer systems into oceans or ends up in landfills. Extinction and threat to marine life have become a major cause of concern among scientists and wildlife enthusiasts. Not only are plastics harming the environment, they are also contributing directly to the climate crisis as they are produced from fossil fuels. The food packaging industry which is one of the largest users of single-use plastic is a major contributor to these problems. Novel methods of producing biodegradable packaging materials are, thus, being developed rigorously to minimise the effect on the environment and compete with the widespread popularity of synthetically synthesised polymers which are easier and cheaper to produce on a large scale.

Incorporation of nanomaterials into biodegradable polymer materials has shown promising results towards the advancement of active packaging material technology. Although these materials are superior to conventional, non-biodegradable packaging owing to their active packaging features, the toxicity of these materials towards humans in long term is also a major cause of concern. Development of antimicrobial packaging has helped with prolonging shelf-life of food, but antimicrobial compounds in the packaging films leaking into food matrices have also been reported. The leaking of nanoparticles into the food matrix has been a cause of concern for using nanomaterials in packaging materials. Because the nanoparticle reinforcement into polymer matrices is relatively new, the effects of nanomaterials on humans have not been well-researched. Toxic limits for the presence of nanoparticles in food have, however, been set by food regulation authorities. Innovative technologies need to be developed to overcome this drawback which limits us from using active food packaging materials on a large scale.

References

19. J. L. Clement and P. S. Jarrett, Met Based Drugs 1, 467 (1994)
20. T. V. Duncan, J Colloid Interface Sci 363, 1 (2011)
27. S. Majumder, S. Huang, J. Zhou, Y. Wang, and S. George, Food Packag Shelf Life 39, 101142 (2023)
35. H. Shin, S. Thanakkasaranee, S. Kambiz, and J. Seo, Food Packag Shelf Life 40, 101188 (2023)
37. Y. Balçık Tamer, Polymer-Plastics Technology and Materials 62, 1138 (2023)
40. N. Abbas Ali and F. Tariq Mohammed Noori, (n.d.)
42. J. Xie and Y.-C. Hung, LWT 96, 307 (2018)


73. R. Cosquer, S. Pruvost, and F. Gouanvé, Membranes (Basel) 11, 151 (2021).