Biopolymer-Based Nanocomposites

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Abstract

Agricultural, industrial, and household waste is a huge threat to environmental sustainability in recent years. Plastics that are non-biodegradable are causing serious health issues also. Hence the development of biodegradable functional materials is a necessity in the current scenario. The quality of such materials is a major environmental concern, and the production of nanocomposites may decrease the impact of the problem. Biopolymer reinforced with nanofillers is a potential solution to the issue. Functional nanomaterials can be fabricated by the effective interaction between nanofillers and eco-friendly biopolymers. This interaction also enhances physicochemical features and biological properties. These biopolymer nanocomposites act as a substitute for conventional polymers due to their relatively better properties than pure biopolymers. This chapter

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compiles the details about biopolymers and their nanocomposites. The applications of biopolymer-based nanocomposites in various fields are also summarized.

Keywords

Biopolymer · Nanocomposite · Food packaging · Biomedical · Drug delivery · Tissue engineering · Sensing

Introduction

Nanoscience and nanotechnology have developed as a flourishing field in research in recent years expanding applications in agriculture, biomedical applications, energy production, cosmetics, pharmaceuticals, and diagnostics. Large surface area to volume ratio provided by nanosized materials enhances the properties. Not only pure nanoparticles but also nanocomposites have remarkable applications. Nanocomposites are hybrid materials obtained by combining two or more nanomaterials with different physical and chemical features. Their properties are much better than microcomposites.

Nanofillers can be dispersed in polymeric matrices in various quantities to obtain polymeric nanocomposites (Bustamante-Torres et al. 2021). Such dispersion will improve the mechanical and physical properties of the matrix. The features of the nanocomposite will be much better than the individual constituents in the matrix. Combining the features of polymer matrix and nanofillers results in a synergic effect, and high performance, unique nanocomposites can be produced. Polymeric nanocomposites possess excellent thermal, magnetic, electrical, optical, and mechanical properties which pave the way for a variety of applications (de Oliveira and Beatrice 2019). Polymer matrix and nanofillers are chosen according to the requirement in properties for various fields. Polymers may be categorized into biopolymers and synthetic polymers based on their origin. Biopolymers are obtained from animals, plants, and microorganisms. Since they are generated from renewable natural sources, they can replace synthetic polymers which have an origin from petroleum resources. They are exceptional biomaterials owing to their features such as biodegradability, lack of toxicity, cost-effective production, eco-friendliness, and biocompatibility. Also, they can be conveniently degraded by the action of microorganisms or inorganic compounds, which also reduce the possibility of environmental pollution caused by synthetic polymers (Folino et al. 2020). Thus, biopolymers such as polysaccharides, proteins, and lipids find applications in pharmaceutical, biomedical, and many other applications. Biopolymer nanocomposites are composed of two or more components, in which the bulk phase is a biopolymer, and the minor phase consists of nanofillers. This chapter discusses the most recent developments in research on biopolymeric nanocomposites for a variety of applications.

Another new generation material having wide applications is nanocomposite films. Such a film is produced by the combination of a biopolymer with a nanofiller and is processed to develop a film. In nanocomposite films, the major matrix is a biopolymer and the dispersion of nanofillers in this matrix enhances the properties. Also, many limitations of biopolymers can be overcome by the addition of nanofillers. The addition of nanofillers can reinforce the matrix and create properties that are inherently absent in biopolymers. Some fillers are capable of improving the antibacterial and antimicrobial properties of the matrix which may assist in biomedical applications (Wrońska et al. 2021). It can improve the shelf life of food such as fruits, fish, vegetables, and so on in packaging applications also.

While considering food packaging applications, many synthetic polymers could satisfy all the requirements. Since these materials are non-biodegradable, they cause serious environmental pollution issues. A suitable methodology for the waste disposal of such synthetic polymers is not found till today. The increase in population always multiplies the usage of such synthetic polymers and their aftereffects happening worldwide over generations (Basavegowda and Baek 2021). Therefore, replacement of these polymers is a necessity, and current research is focusing on developing biopolymers that can reduce waste disposal. These biopolymers are degradable under biological decomposition without much affecting the sustainability of the environment. Their degradation produces harmless products which cause fewer disturbances to the earth's crust. Biopolymers are made of monomeric units combined by covalent bonds, and hence, these biopolymers may also be degraded by microorganisms via their enzymatic activities (Sorrentino et al. 2007).

Biopolymers can be derived from a variety of sources such as agricultural feedstock, industrial waste, animal and marine sources, polysaccharides, proteins, and so on. Biopolymers can be obtained from renewable and non-renewable natural sources. Natural biopolymers include polysaccharides, proteins, and lipids. Polysaccharides may be classified as wheat, pectin, chitosan, starch, and cellulose. Proteins and lipids include casein, collagen, soya, gelatin, and zein.

Even though, biopolymers act as potential candidates for food packaging, they are limited in use due to some disadvantages. They display poor mechanical and barrier properties which in turn affect their ability in processing. Industrial end-use applications are limited by the low heat distortion temperature, brittleness, and high gas permeability of biopolymers (Koh et al. 2008). These issues can be solved by the fabrication of biopolymer nanocomposites by adding nanofillers to biopolymer matrix. Mechanical, thermal, and physical properties can be enhanced by the incorporation of such nanofillers.

Earlier, major applications were completely occupied by the plastic industry. But, nowadays, bio-derived products are produced for such applications in an economical and sustainable way. Polypeptides and polysaccharides are utilized owing to their biocompatibility, biodegradability, sustainability, and minimum cytotoxicity (Wu et al. 2021). In the case of mechanical and thermal features, research is still going on to get the expected results. Industries always opt for petroleum-based polymers since they are cheap when compared to biopolymers. It exists as a threat to the sustainability of nature, and hence developing biopolymers in an economical strategy that is competitive with synthetic polymers is the future concern in this research area. Table 1 shows the source of biopolymers and their properties.

Table 1 Sources of biopolymers and their properties

No.	Source	Biopolymer	Properties	Reference
1	Crab	Chitosan	Good mechanical properties and antimicrobial properties less barrier properties	Sirisha Nallan Chakravartula et al. (2020)
2	Red algae	Agar	Good transparency and permeability, and high thermal stability	Mostafavi and Zaeim (2020)
3	Corn	Starch	Improved gas barrier features and good antimicrobial and antioxidant properties	Lu et al. (2009)
4	Fish skin	Collagen	Enhanced rheological features and high-moisture absorption	Lionetto and Corcione (2021)
5	Citrus peel	Pectin	Good chemical features, biodegradable, biocompatible, and edible	Espitia et al. (2014)
6	Milk	Casein	Nontoxic, biodegradable, and thermally stable	Chen et al. (2019a)
7	Cattle bone	Gelatin	Improved optical, mechanical, and barrier properties	Ramos et al. (2016)
8	Agricultural waste	Cellulose	Antimicrobial property, thermally and chemically stable, and crystalline	Wu et al. (2019)
9	Brown algae	Alginate	Aqueous solubility and flexibility	Katiyar and Tripathi (2019)
10	Soybean	Soy protein	Antimicrobial and gas barrier properties	Gautam et al. (2021)

Biopolymers

Biopolymers are considered as high-demand products since they can be easily degraded by microorganisms without adversely affecting the environment. Based on origin, biopolymers may be natural polymers or synthetic polymers (Muhammed Lamin Sanyang and Jawaid 2019). Natural polymers are obtained from natural renewable sources whereas synthetic polymers are obtained by polymerization or condensation reactions. Natural polymers include polysaccharides, proteins and lipids, and polymers such as polycaprolactone (PCL) and polylactic acid (PLA) are examples of synthetic biopolymers. Polymers such as polyhydroxybutyrate (PHB), polyhydroxyalkanoates (PHA), and polyhydroxybutyrate-valerate (PHBV) are produced by microorganisms like bacteria and are also considered as biopolymers (Mangaraj et al. 2019).

Among natural polymers, polysaccharides are produced from renewable sources, and they are made of monosaccharides linked by glycosidic bonds. Cellulose, starch, and chitosan are widely used natural polymers for different applications since they are cheap, non-toxic, and abundantly available (Sanyang et al. 2017). Among them, starch consists of two varieties of D-glucopyranose including amylose and amylopectin (Mangaraj et al. 2019). It is generated from wheat, corn, and rice. Some disadvantages of starch being used as an efficient biopolymer are its high brittleness, high hydrophilicity, and difficulty in processing. Hence surface modification is a necessity to achieve the expected properties. It can be done by the addition of plasticizers or nanofillers. Such nanocomposites were found to have good tensile strength and mechanical properties. Another natural polymer widely used in various applications is cellulose. It is a biodegradable, hydrophilic polysaccharide comprising D-glucose repeating units and are linked by glycosidic bonds. It can be extracted from plants such as wood, cereal, and cotton. It is considered as a non-toxic, renewable, and easily available cheap biomaterial for packaging applications (Walzl et al. 2019). One of the drawbacks is its low water vapor barrier features. In order to improve mechanical properties, nanocomposites are formed by incorporating nanofillers such as metal and metal oxides such as copper oxide, zinc oxide, and so on (Anastasiou et al. 2014). The enhanced tensile strength can be obtained by the addition of silver nanoparticles along with better antibacterial properties. Shells of crabs, insects, and shrimps contain enormous amount of natural polymer, chitosan (Abdul Khalil et al. 2017). As in the case of starch and cellulose, chitosan is also biocompatible and biodegradable. It is the second most available polysaccharide and is made up of D-glucosamine and *N*-acetyl D-glucosamine. It is non-toxic and displays antimicrobial activity against yeast and bacteria. Even though, pure chitosan possesses good properties and enhancement in features can be obtained by adding plasticizers or nanofillers. Another animal-originated protein gelatin also finds immense applications in various fields. Denaturation of collagen results in gelatin and the features of gelatin are affected by the type of collagen (Roy and Rhim 2021). Copolymerization with other natural polymers such as chitosan and starch as well as incorporation of nanofillers can enhance various properties of gelatin.

Polylactic acid is a synthetic aliphatic polyester obtained by the polymerization of lactic acid. It is a biodegradable polymer produced by fermentation of sources like rice, corn, and so on. It is an efficient biocompatible polymer having good mechanical strength and barrier properties. It is convenient to process to produce end use products. The brittleness of the polymer can be reduced by blending it with plasticizers or forming nanocomposites. Another commercially important synthetic biopolymer is polycaprolactone. It is a semicrystalline, linear, and hydrophobic polyester having good flexibility and elongation (Ortega-Toro et al. 2015). But poor mechanical and barrier properties limit its applications in packaging. In the case of polycaprolactone also, addition of nanofillers and formation of blends improves the properties.

Nanofillers

Novel trends and new perspectives that emerged in nanotechnology have created creative paths to facilitate the usage of nanofillers in various applications. Biopolymer nanocomposites cannot completely replace synthetic nanomaterials, but they can substitute plastic materials to a great extent (Saba et al. 2014). Nanofillers can reinforce the biopolymer matrix thereby improving mechanical properties. Nanofillers have a size below 100 nm in any one of the three dimensions. They possess different shapes such as spherical, rod-shaped, needle-shaped, etc. The size and shape of the nanofiller greatly influence the features of the polymer matrix. Nano-sized materials will have a larger surface area which enhances the interaction of polymer matrix and filler. This betterment in interaction improves mechanical, physical, electrical, barrier, and thermal properties.

There are different types of nanofillers. They are organic, inorganic, clay, and carbon-based nanofillers. Organic fillers like cellulose, chitosan, and inorganic fillers like metals and metal oxides can act as efficient nanofillers. Fullerenes, carbon nanotubes, graphene, and graphene oxide are various carbon nanostructures that act as fillers (Youssef and El-Sayed 2018). Among the above nanofillers, clay is a cost-effective fine-grained material that can reinforce the polymer matrix. It can have a sheet or platelet-like structure. Different types of clay used as nanofillers are montmorillonite, halloysite, etc. Montmorillonite contains silica sheets attached to aluminum oxide sheets whereas halloysite is aluminosilicate with nanotubes having a cylindrical shapes. Halloysite possess good antimicrobial activity in addition to mechanical properties (Shankar et al. 2018). Among natural nanofillers, cellulose, chitin, and collagen are extensively used owing to the exceptional features such as easy availability, biodegradability, mechanical strength, and biocompatibility. Surface features can be improved by the reactive hydroxyl groups on the surface in the case of nanocellulose. Nanocellulose can be classified into three on the basis of crystallinity, size, and morphology. They are nanofibrillated cellulose, bacterial nanocellulose, and nanocrystalline nanocellulose. The difference in their structure, shape, and composition is due to variations in sources and synthetic methodologies. The functional groups present on the nanofiller also depend on the source. High surface area, non-toxicity, biodegradability, and biocompatibility of chitosan make it an excellent nanofiller in the production of various nanocomposites (Marín-Silva et al. 2019). But its use is limited due to poor solubility and stability in many applications.

Among inorganic nanofillers, metals and metal oxides are an important class that act as functional agents in reinforcement. They possess antibacterial and antimicrobial activity in addition to physiochemical properties. Copper nanoparticles are excellent candidates which exhibit antimicrobial properties. Similarly, silver nanoparticles display exceptional biological properties, and many research works have reported the applications in food packaging, drug delivery, wound healing, and biomedical applications. Besides metal nanoparticles, metal oxides like titanium oxide, zinc oxide, cerium oxide, aluminum oxide, copper oxide, iron oxide, etc., can also act as functional nanofillers. When exposed to ultraviolet radiations, reactive oxygen species in titanium dioxide assist in photocatalytic activity in many reactions (Juliet and Isaac 2015). Moisture penetration into the polymer matrix is prevented by the low hydrophilicity of titanium dioxide. Zinc oxide also shows antimicrobial activity which plays a good role in biomedical applications. Small particle size, high surface area, and UV- blocking effect of copper nanoparticles provide antioxidant and antibacterial properties for copper oxide nanoparticles.

Another class of nanofillers is carbon-based nanomaterials like fullerenes, carbon nanotubes, graphene, and graphene oxide. Significant electron mobility in carbon-based nanomaterials creates excellent mechanical properties in the nanocomposite. Among these nanofillers, graphene has a high surface area as compared to others which enable good interaction with the matrix (Gan et al. 2017). But graphene has a tendency to agglomerate, and this limitation can be overcome by graphene oxide. Hence graphene oxide is the potential nanofiller among the carbon family. Graphene oxide has low solubility, and chemical modification and surface functionalization can help in improving solubility. Carbon dots are an emerging class in the field of biomedical applications as their biodegradability, photostability, and biocompatibility make them a promising material in different fields. They are quasispherical, amorphous nanomaterials having a size of less than 10 nm. Another advantage of carbon dots is that they are simple to synthesize and sources are easily available. They find many applications in cell imaging and sensing.

While optical properties are concerned, semiconductor quantum dots are gaining much attention in recent research works. Since they are very small in size, they have a great tendency to agglomerate and oxidize (Guo et al. 2016). Optoelectronic applications always choose graphene quantum dots-based nanocomposites due to their cost-effectiveness, availability, and biodegradability. Table 2 shows the properties of nanocomposites by the incorporation of nanofillers.

Synthetic Methodologies of Biopolymer Nanocomposites

Since the use of non-biodegradable materials is increasing day by day, environmental issues are also raising. For instance, the greenhouse effect is considered a huge environmental issue. So, it is high time to develop some functional compounds which act as alternatives for these synthetic materials. But the synthesis of eco-friendly products is very costly and it cannot be compared with synthetic materials in terms of cost. It is one of the limitations to use eco-friendly materials at a commercial level. While economic sustainability is concerned, the production of biopolymer nanocomposites at a cost comparable to synthetic polymers is a hot topic under discussion. In this matter, processing methodologies play a significant role. Both the cost and quality of the product are directly influenced by the synthetic strategy. Usually, biopolymer blends or nanocomposites are developed for improving the features. Methods such as electrospinning, solution casting, ultrasonication, etc., are used to fabricate nanocomposites. Very thin nanofibers can be developed by the process of electrospinning. The spinning technique can improve both the thermal and mechanical properties. Bio nanocomposites are developed by mixing the biopolymer and nanofiller and then heating and stirring till we get a homogenous suspension. It is dried out to get nanocomposites by means of solution casting. Another method of synthesis is ultrasonication which is a more sophisticated technique to disperse the nanofiller in the polymer matrix without agglomeration.

Table 2 Properties of biopolymer-based nanocomposites

No.	Biopolymer	Nanofiller	Properties	Reference
1	Gelatin	Clay	Improved mechanical properties than the pure polymer matrix	Baab and Zude (2008)
2	Chitosan	Silver/ titanium dioxide	Excellent antibacterial properties enhanced shelf life in food storage	Lin et al. (2015)
3	Chitosan	Clay	Excellent mechanical properties, water vapor permeability is decreased	Lavorgna et al. (2010)
4	Polylactic acid	Zinc oxide	Good antibacterial property	Materials (2019)
5	Poly(butylene adipate-coterephthalate)	Silicon dioxide	Excellent antimicrobial activity, Enhancement in mechanical and barrier properties	Venkatesan and Rajeswari (2019)
6	Starch	Clay	Increased stiffness and tensile strength	Sanyang et al. (2017)
7	Gelatin	Silver	Superior antibacterial and antimicrobial properties	Kanmani and Rhim (2014)
8	Starch	Silver/zinc oxide/copper oxide	Enhancement in mechanical properties	Peighambardoust et al. (2019)
9	Polylactic acid	Zinc oxide	Better barrier and mechanical properties	Tang et al. (2020)
10	Chitosan	Curcumin	Water vapor permeability is reduced, and good antioxidant activity	Rachtanapun et al. (2021)

The uniform distribution of the nanofiller in turn improves the properties of the material also (Abral et al. 2018).

Properties of Biopolymer Nanocomposites

Many polysaccharides act as a matrix to form biopolymer nanocomposites. Among them, chitosan, starch, and hyaluronic acid are widely used. Tissue engineering is one of the major applications in which biopolymers find their use. Biodegradability, oxygen permeability, water sorption, and blood coagulation of chitosan make it an efficient material in scaffolding. When chitosan is composited with nanoclay, it was found that there was a significant improvement in mechanical properties owing to the effective interaction and uniform dispersion of nanoclay in the chitosan polymer matrix (Cano et al. 2017). Such a biodegradable nanocomposite was used as a packaging material. Similarly, biofilms can be fabricated by mixing bacterial cellulose in hyaluronic acid for healing wounds. It was found that the incorporation of cellulose improved roughness and thermal stability. These properties assist the material in tissue engineering applications (de Oliveira et al. 2017). In another work, cellulose is dispersed in alginate by means of solution casting. There was a significant improvement in tensile strength in addition to the decrease in water vapor permeability and water solubility. In another work, cellulose dispersed in starch and as a result, thermal and mechanical properties are improved when compared to pure starch matrix. Uniform dispersion and excellent interaction of cellulose in starch are found to be the reason for the enhancement in the properties (Ghanbari et al. 2018). Collagen and gelatin are also considered as a potential biopolymers which can act as an excellent matrix for the formation of nanocomposites. Polylactic acid is another renewable biopolymer which finds applications in various fields.

Applications of Biopolymers

While biopolymer acts as the raw material to produce different end use products, the features enhanced by the incorporation of nanofillers decides the design of each application (Vlăsceanu et al. 2019). For example, mechanical properties are necessary for developing biofilm for packaging applications, at the same time antimicrobial activity is essential for biological applications like drug delivery and tissue engineering. Hence, enhancements in specific properties needed to be targeted to reach the final aimed product. In the case of 3D printing thermomechanical factors play a key role. In such cases, proteins are added as plasticizers to increase the thermal stability.

Among various applications, the most important one which needs biodegradable biopolymer as a raw material is packaging. The material for such a purpose should be cost-effective, easy to decompose and recycle, biodegradable, and easy to transport. Research is still continuing to develop a raw material that can satisfy all the above features. There are inventions at the laboratory level. But the material still needs optimization to take it to commercial level. Biopolymer nanocomposites are widely used in biomedical applications also. Tissue engineering, drug delivery, and wound healing are a few biological applications. Biopolymer nanocomposites are also utilized as supercapacitors since the potential of electrode material can be improved by using nanofillers. Specific capacitance can be enhanced by the usage of biopolymers like lignin. Similarly, carbon nanomaterials like graphene, carbon nanotube, and carbon fibers find applications in the field of supercapacitors (Okonkwo et al. 2017).

Packaging

Efficient packaging is a necessity in the food industry. Good packaging provides expansion of the shelf life of food materials against decay via chemical, microbial, or any other hazards. It also retains safety and maintains quality (Cakmak and Sogut 2020). These packaging materials should maintain food quality and are to be convenient for processing till it reaches end-use product. Usually, materials such as glass, metal, plastic, or paper are used as packaging materials. Among plastics, petroleum-based materials are mainly used owing to their lightweight, availability, flexibility, good mechanical properties, and low cost (Wang et al. 2019). But the disadvantage of these petroleum-based packing materials is their non-biodegradability. Some of them take more than 15 years to degrade which is a severe issue while environmental sustainability is concerned. These polymers are a severe threat to nature by causing soil and water pollution. Due to this drawback, there is a high demand for eco-friendly biopolymers with good mechanical properties for the food industry. Excellent biocompatibility and biodegradability make them ideal candidates for this purpose. While using biopolymers as packaging materials, waste disposal and composting them are comparatively easy and safe since they can be degraded by microorganisms in the soil (Abdul Khalil et al. 2017). High price, low mechanical, barrier, and processing properties limit the use of biopolymers. But it is a challenge to develop biopolymers that can compete with the mechanical and barrier properties of petroleum-based polymers. Economical production cost is also a major criterion in packaging applications.

Structure modification of biopolymers via copolymerization and nanocomposite fabrication are the methodologies to attain these expected properties. In some cases, plasticizers are added to the biopolymer to enhance the properties. These plasticizers can exchange intermolecular bonds thereby strengthening the polymer chains (Mulla et al. 2021). They also provide flexibility by creating variations in conformation and hence brittleness of the polymer can be reduced. Glycerol, triacetin, sorbitol, and polyethylene glycol are used as plasticizers in the food industry. The quantity of plasticizers should be controlled since their over usage may cause health and environmental issues. Copolymerization is also a suitable method to attain properties. Compatibility, uniform dispersion, and miscibility have to be checked while copolymerization is done. Another method to improve the properties of biopolymers is nanocomposite formation by dispersing nanofiller in the biopolymer matrix (Zhong et al. 2020). It is a thrust area of research in recent years and studies prove that water and gas barrier properties can be improved along with mechanical properties by developing nanocomposites. This in turn increases the shelf life of packed foodstuff since many of the nanofillers possess antimicrobial and antibacterial properties.

For safe and secure food transport, efficient packaging of food is necessary. For this purpose, reducing microbial growth is essential. Antimicrobial packaging will inhibit the growth of microorganisms to a great extent so that shelf life can be improved (Kumar et al. 2018). Furthermore, the quality of the food can be maintained with a good appearance, and eventually it can reduce wastage. Organic materials like polymers, acids, and enzymes, and inorganic materials like metal oxides and metals can be used as antimicrobial agents. Other examples of antimicrobial agents are essential oils, peptides, and plant extracts. Metal nanoparticles like zinc, copper, and silver display antimicrobial activity. Zinc oxide, titanium oxide, and copper oxide are examples of metal oxides possessing the same property. There are research works reported for chitosan-based nanocomposites utilized in the packaging industry (Nonato et al. 2019). It is found that chitosan-based films could inhibit the multiplication of microorganisms. Like any other biopolymer, temperature, molecular weight, concentration, and type of microorganism affect the activities of microorganisms. The incorporation of metal oxides into chitosan-based films improves the antimicrobial property.

Reducing the growth of microorganisms and lipid oxidation are the ways to improve the shelf-life of food materials. By delaying the process of oxidation, better maintenance of food quality may be obtained. Prevention of food oxidation by the use of antioxidants is one of the methods to improve the same. Both synthetic antioxidants and natural antioxidants can be used to preserve food. Examples of natural antioxidants are curcumin, catechin, quercetin, mint, oregano, cinnamon, and so on (Vilela et al. 2018). In many biopolymers, these antioxidants are incorporated to get the expected results. Based on the action of antioxidants, they can again be classified as primary and secondary antioxidants. Secondary antioxidants are able to absorb ultraviolet radiation thereby preventing oxidative effects on the food products. Benzophenones, zinc oxide, titanium oxide, etc., are examples of such secondary antioxidants (Goudarzi et al. 2017).

Biopolymer-Based Nanocomposites for Drug Delivery and Wound Healing Applications

Biopolymer-based nanocomposites have been widely employed in drug delivery systems due to their biocompatible and biodegradable nature (Azmana et al. 2021; Kurakula et al. 2020). They have been used in different routes of drug delivery and have revolutionized the field of drug delivery by improvising the routes as well as vehicles for drug delivery.

Cellulose and Cellulose Derivatives

Bacterial cellulose derived from bamboo and sodium alginate was employed in developing a hydrogel nanocomposite system for controlled protein delivery by Li Ji et al. Bacterial cellulose was obtained by the inoculation of Acetobacter xylinum employing Moso Bamboo enzymatic hydrolysate as a carbon source and different weight % (0.25, 0.5, 0.75, and 1.0) of sodium alginate (SA) was added at the time of inoculation so as to obtain the nanocomposite hydrogels. The morphological analysis revealed the formation of interconnected porous structure and the pore size increased with increasing concentration of sodium alginate. The maximum pore size (50–70 nm) and uniformity in pore distribution was attained with 0.75 SA added hydrogel and at 1% SA concentration, the interconnected porous structure disappeared resulting in a structure with line-shaped nanofibrils. The drug release mechanism and pH responsiveness of two model drugs namely bovine serum albumin (BSA) and lysozyme (LYZ) entrapped in the nanocomposite hydrogel were evaluated. The results of the study indicated that LYZ has a better pH-dependent releasing ability as a result of electrostatic forces of adsorption between hydrogel and LYZ. However, due to hydrophobic adsorption between BSA and hydrogel, the drug release of BSA was poorer compared to LYZ. Overall, the study demonstrated that the hydrogel nanocomposites based on SA–BC are promising in delivering hydrophilic drugs such as proteins (Ji et al. 2021).

Nusheng Chen et al. synthesized nanocomposite hydrogels based on modified carboxy methyl cellulose (CMC) and diblock copolymer as hydrophobic micelle cores for controlled and localized release of hydrophobic drugs. The modification of CMC was done by hydrazide and aldehyde and the micelle core was based on a copolymer system which is pH-responsive, poly(ethylene oxide) (PEO) -block-poly (2-(diisopropylamino) ethyl methacrylate (PDPA). The injectable nanocomposite hydrogel was obtained by dissolving the two modified CMC precursors in a micelle solution loaded with drug and then co-extruding with the help of a double barrel syringe. The cross-linking in hydrogel composites is facilitated through a Schiff base reaction. Nile red was chosen as a model hydrophobic dye to test the efficiency of the copolymer micelle's loading ability since it will exhibit fluorescence only in hydrophobic environments. The in vitro release of doxorubicin was also evaluated in simulated body fluids having physiological conditions. The hydrogel composites based on CMC and PEO-b-PDPA micelles exhibited negligible cytotoxicity and was successful in slow and controlled drug release which can be tuned by varying the pH as well as by varying the hydrogel precursor concentrations (Chen et al. 2019b).

In order to improve the mechanical properties of hydrogels of carboxy methyl cellulose (CMC), carboxy methyl β-cyclodextrin (cm -βCD) was cross-linked with CMC to form a hydrogel composite. The incorporation of cm -βCD has significantly improved the mechanical performance of the hydrogel as well as the storage modulus and swelling properties. The drug release study conducted using Tetracycline (TC) as a model drug revealed that the CMC- cm -βCD hydrogel was able to release TC in an effective manner both at high and low TC loading. The effective release of TC after crosslinking with cm -βCD is due to the complexation of the drug with cm -βCD. The antibacterial activity tested using S. *aureus* bacteria was also found to be better in the case of CMC- cm -βCD hydrogel loaded with 50 mg TC (Jeong et al. 2018).

J.T Orasugh et al. employed cellulose nanofibrils (CNF) isolated from jute fiber for the preparation of nanocomposite film with hydroxy propyl methyl cellulose (HPMF) and tested for transdermal drug delivery of an analgesic Ketorolac tromethamine (KT). The in vitro release studies of KT revealed that the drug was released from the composite film in a controlled manner for a prolonged time period of 8 h. The precise release of KT from the HPMF-CNF was ascribed to the three-dimensional structure and less swelling property of CNF (Orasugh et al. 2018).

Chitosan

Chitosan mainly seen in crustacean shells of marine organisms is another widely used biopolymer for developing drug delivery systems with improved biocompatibility and biodegradability. The free amino groups present in the chitosan backbone help in encapsulating hydrophobic drugs and also help in the incorporation of proteins and peptides which are negatively charged. The ability to get fabricated into various structures and shapes makes chitosan adaptable for performing different functions in drug delivery systems (Tao et al. 2021).

Deformable liposomes (DL) based on chitosan loaded with flurbiprofen was proposed by Chen et al. as an ocular delivery system for delivering flurbiprofen with a view to overcome conventional eyedrops. The coating of chitosan on DL improved the penetration as well as absorption leading to greater bioavailability of the drug in the ocular region. Moreover, the chitosan-coated DL showed reduced ocular irritation of flurbiprofen and also favored the biocompatibility of the drug in the ocular region (Chen et al. 2016).

An effective transdermal (TD) drug delivery option based on chitosan modified with glycidyl and butyl methacrylate and hyaluronic acid was developed by Anirudhan et al. for lidocaine (LD) delivery directly into the systemic circulatory system. The TD device was tested for in vitro release and in vivo skin adhesion as well as skin irritation assay. The results indicated that the transdermal patch performed controlled release of lidocaine in a sustained manner with improved antimicrobial activity and with no skin irritation (Anirudhan et al. 2016).

In another study, the inclusion complex of amlodipine besylate (APB) and β-cyclodextrin was prepared by two different methods, namely kneading method and microwave method initially, and then mixed with a nanocomposite of chitosan-graphene oxide and sodium alginate by microwave-assisted synthesis. The nanocomposite containing inclusion complex was further analyzed for drug release kinetics by varying the pH using six different kinetic models. The best-fitting kinetic model was selected on the basis of the correlation coefficient (R^2). Accordingly, the influence of relaxation and diffusion on the drug release process was explained using the Peppas-Sehlin equation (Khushbu and Jindal 2021).

A nanocomposite hydrogel based on modified chitosan (modified with methacrylated glycol-MeGC) and montmorillonite (MMT) for bone tissue engineering application was proposed by Cui Z. K et al. The MMT was introduced into MeGC hydrogel systems and was photopolymerized using a photo initiator (riboflavin) to obtain an injectable bone regeneration biomaterial with improved osteoconductive nature. The incorporation of MMT in the hydrogel helped in the formation of a microporous structure having interconnectivity and better mechanical stability. The in vitro studies showed better proliferation and differentiation of mesenchymal stem cells. The in vivo study conducted using a mouse calvarial defect model showed that the nanocomposite hydrogel can employ new cells and can also help in calvarial healing indicating its potential in tissue engineering and regenerative medicine field (Cui et al. 2019).

A piezopolymer nanocomposite system based on chitosan and hydroxylated barium titanate ($BaTiO_3$) was reported for tissue engineering by Prokhorov et al. The nanocomposite exhibited biocompatibility with fibroblast cells and also the presence of $BaTiO_3$ does not cause any cytotoxicity issues as revealed by the cell viability. Hence, the nanocomposite film can be used as a flexible platform for cell proliferation and also for skin regeneration (Prokhorov et al. 2020). A brief list of other bionanocomposites based on chitosan and the relevant application is listed in Table 3.

Table 3 List of chitosan-based bionanocomposites and applications in the biomedical field

Composite system	Synthesis method	Application	Reference
Chitosan, cellulose, and hydroxyapatite	Solvent exchange method	Bone tissue engineering	Synthesis et al. (2021)
Chitosan and iron oxide	Green synthesis	Antibacterial and antioxidant activity	Bharathi et al. (2019)
Chitosan, reduced graphene oxide, and iron oxide	One pot synthesis-solvent casting	Hyperthermia treatment	Barra et al. (2020)
Chitosan and cellulose loaded with betamethasone/silver sulfadiazine	Solvent casting	Wound dressing	Riccio et al. (2021)
Chitosan and cellulose encapsulated with 5- Fluro uracil	Ionic gelation using a crosslinking agent (sodium tripolyphosphate)	Treatment of colorectal cancer	Yusefi et al. (2021)
Chitosan and silver nanoparticles	Green synthesis	Antibacterial agent and drug delivery	(Saruchi et al. 2022)
Chitosan and graphene oxide	Gelation method	Metronidazole oral drug delivery	Kumar et al. (2021)

Silk Fibroin

Silk fibroin (SF) based nanocomposites are widely employed for tissue engineering mainly for repairing nerves, cartilage, and skin due to its superior mechanical properties, biocompatible nature, and its ability in producing lower immunogenic responses. Y. Wang et al. reported sodium alginate (SA) and silk fibroin (SF) composite hydrogel for the delivery of bovine serum albumin (BSA) and tetracycline hydrochloride. The hydrogel composites were made flexible by improving the crosslinking between SA and SF employing a carbodiimide. The composite hydrogel's swelling and mechanical properties as well as their gelation time, biodegradation, and biocompatibility were evaluated. The hydrogel composite exhibited a sustained release of micro and macromolecular drugs with no cytotoxicity and also showed appreciable biodegradation within 14 days duration (Wang et al. 2021).

A ternary nanocomposite scaffold based on silk fibroin, carboxy methyl cellulose, and magnesium hydroxide nanoparticles was envisaged for wound dressing applications by R.E. Keihan et al. The hybrid composite showed to be promising for wound healing applications as revealed by the in vivo assay results for wound healing with 82.29% healing in 12 days. The composite also showed good biocompatibility and higher bactericidal activity recommending the possibility of the compound in diverse biomedical applications (Eivazzadeh-Keihan et al. 2021).

Another group reported chitosan nanoparticle-incorporated silk fibroin hydrogel composite for delivering dexamethasone sodium phosphate (DEX). For preparing the drug release device, the DEX was incorporated in chitosan nanoparticles by gelation (ionotropic) and then it was transferred to SF solution and sonicated to induce gelation. The in vitro drug release studies indicated that the chitosan nanoparticles helped in encapsulating the DEX for controlled release of the drug while SF acted as a matrix for prolonging the drug release (Akrami-Hasan-Kohal et al. 2021).

Biopolymer-Based Nanocomposites for Tissue Engineering Applications

Tissue engineering aims to develop functional constructs by making use of a scaffold, functional tissues, cells, and other biologically relevant molecules with a view to restore or maintain damaged tissues or whole organs (Zhao et al. 2020). Biopolymers and their nanocomposites are frequently being used as scaffolds since they can meet the prerequisites of a scaffold material such as porosity (to endorse vascularization and integration of tissues), structural resemblance with bioactive molecules, biocompatible, and controlled biodegradation (Islam et al. 2020).

Bacterial cellulose (BC) is commonly employed for tissue engineering applications compared to plant cellulose on account of the ease of production, purity, and adaptable nature. The slowly degradable nature of BC can be altered by the addition of other components. The modification can be done either at the time of synthesis of BC or post-synthesis using other biomaterials such as collagen, hydroxy apatite, hyaluronic acid, pectin, etc., Z. Keskin et al. prepared BC composite modified with keratin for tissue engineering of the skin. The main reason for the addition of keratin was to increase the bonding of fibroblasts of skin on the surface of BC. Cytotoxicity of the composites was checked using mouse fibroblast cells (L929) and also by MTT assay. The BC-keratin composites exhibited appreciable viability and biocompatibility and also showed better adhesion of fibroblasts. The group has studied both in situ and post-modified keratin–BC composites, and both composites were found to be effective for use in dermal tissue engineering applications (Keskin et al. 2017).

Conductive scaffolds based on cellulose and polypyrrole (Ppy) for nerve regeneration have been reported by R. Elashnikov et al. The surface of cellulose acetate butyrate nanofibers obtained by electrospinning was modified using polypyrrole (Ppy) and was used for the preparation of scaffolds. The coating of Ppy on cellulose helped in improving the conductivity of the scaffold for use in tissue engineering of neural tissues. The cytotoxicity of the composite fibers by LDH assay also revealed the non-toxic nature of the scaffold even after Ppy coating. The adhering of Ppy particles on the cellulose surface enhanced the roughness and subsequently helped in promoting the adhesion of human neural cells (SH-SY5Y) and also increased the viability of SH-SY5Y cells up to a period of 15 days (Lyutakov 2019).

The approach of electrical stimulation for nerve regeneration was adopted by another group (Zha et al. 2020). Cellulose and two conducting polymers (poly (N-vinyl pyrrole (PNVPY) and poly (3-hexyl thiophene (P3HT) were made into a nanofibrous mat by polymerization (in situ). The thickness as well as the porosity of the composite mats was superior to electrospun cellulose mats which helped in improving the adhesion of PC12 cells. The application of electrical stimuli augmented the proliferation of PC12 cells and the fibrous mats also showed excellent biocompatibility.

Waghmare et al. suggested the chemical alteration of carboxy methyl cellulose by the introduction of sulfate groups for constructing injectable scaffold tissue engineering cartilage. The macroporous nature of the scaffold helped in the chondrogenesis of mesenchymal stem cells as a result of the binding of growth factors through ionic interactions. The highly porous nature with and strong pore wall, the injectable scaffolds showed good resilience and were able to retain their initial shape making them suitable for engineering the load-bearing tissues (Waghmare et al. 2018).

Poly(butylene succinate) (PBS) and cellulose nanocrystals (CNC) bionanocomposites as the scaffold was prepared by electrospinning for tissue engineering application by Huang et al. Thermal and mechanical properties as well as the porosity of PBS/CNC scaffold were found to be superior at 3 wt% composition of CNC. The scaffold exhibited appreciable biodegradation compared to neat PBS and the cell viability of fibroblast cells (3 T3 cells) remained 100% even after culturing for 7 days suggesting good biocompatibility. The incorporation of CNC helped in improving cell proliferation and biodegradation of the scaffold (Huang et al. 2018).

A nanocomposite of chitosan incorporated with gold, hydroxyapatite, and graphene was prepared by hydrothermal method and was cast into a film using poly vinyl alcohol (PVA) by gel casting technique. The polymeric film showed significant differentiation and viability of osteoblasts and was also effective against both strains (gram positive and gram negative) of bacteria indicating its potential in the field of bone tissue engineering applications (Prakash et al. 2020).

The various strategies and the composition of biopolymer composites employed in tissue engineering applications are given in Table 4.

Table 4 Synthesis methods and tissue engineering applications of biopolymer nanocomposites

Components of composite	Synthesis method	Application	Reference
Carboxymethylcellulose, hydroxy apatite, and gelatin	Freeze drying followed by crosslinking	Bone tissue engineering	Karvandian et al. (2020)
Carboxymethylcellulose and polyethylene glycol	Solution casting	Skin tissue engineering	Zennifer et al. (2021)
Bacterial cellulose, β-glucan, graphene oxide (GO), and hydroxy apatite	Free radical polymerization & freeze drying	Bone tissue engineering	Umar Aslam Khan et al. (2021)
Collagen and tricalcium phosphate	3-D printing technique	Hard tissue regeneration	Kim et al. (2017)
Starch nanocrystals and gelatin	3-D printing technique	Cartilage tissue engineering	Piluso et al. (2019)

Biopolymer-Based Nanocomposites for Biosensing Applications

Biopolymer nanocomposites have also been recognized in the field of sensing especially biomolecules such as enzymes, nucleic acids, antibodies, proteins, enzymes, etc., and also other chemical species. Due to the unique biocompatible nature of biopolymers, several sensing technologies with high selectivity and specificity have been devised based on the composites of biopolymers. Biosensors are used in the detection of biomolecules and the detection is made possible by visualizing the change in optical, chemical, mechanical, or thermal properties (Subhedar et al. 2021).

The detection of purine bases such as adenine and purine employing cellulose (NC) and CNT nanohorns (SWCNHs) was reported by Ortolani et al. A thin film comprising of NC and SWCNHs with higher sensitivity and selectivity was fabricated and the detection was done using linear sweep voltammetry (LSV). The fabricated electrode demonstrated a lower detection limit (LOD) of 1.5×10^{-7} mol L^{-1} for guanine and 1.9×10^{-7} mol L^{-1} for adenine. The electrode was also successful in the real-time monitoring of purine bases in human serum and fish sperm (Ortolani et al. 2019).

An enzymatic biofuel cell was developed for the selective detection of glucose using bacterial cellulose (BC) modified with gold nanoparticles (AuNP) as the electrode material. The synergic combination of BC and AuNP in transferring the electrons from the enzyme (glucose/O_2) to the surface of the electrode helped in achieving a lower LOD value (2.874 μM) and a broader detection limit (0–50 mM). The biofuel also exhibited a higher value of power density (345.14 μW cm^{-3}) indicating its possibility to be used as a self-powered biosensor for selective detection of glucose (Lv et al. 2018).

Hemoglobin impregnated on GCE modified using a nanocomposite of cellulose microfiber and graphene (GR-CMF) was used for quantifying hydrogen peroxide (H_2O_2). The electrode showed good electrochemical behavior in the detection of H_2O_2 even in the presence of other interfering compounds with a selectivity of (0.49 μAμM^{-1} cm^{-2}). The biosensor also exhibited appreciable stability under operating conditions, lower LOD value (10 nM) and can be used for the detection of H_2O_2 in biological as well as pharmaceutical models (Velusamy et al. 2017).

Detection of glucose by in vivo (oral) and dermal monitoring was reported by C. T Tracey et al. using hybrid composite films of cellulose nanocrystals and magnetite. Both the methods of sensing (dermal and oral) displayed peroxidase-like activity and the lower level of detection of glucose was 5 mM. The sensing was based on observing the color change (colorimetry) and hence can replace the amperometry technique used in glucometers. Moreover, the sensor exhibited better selectivity in an acidic environment and hence can be employed to monitor glucose levels through saliva and sweat instead of using blood for detecting biological glucose levels (Tracey et al. 2020).

Enzymatic biosensor for detecting lactose based on molecular organic framework of Co-hemin (Co-hemin MOF) and chitosan composite was developed by Choi et al. (2020). The biosensor demonstrated a broad linear detection range (10–100 nM) and selectivity in the presence of similar interfering molecules (galactose, ascorbic acid, dopamine, glucose, and uric acid). The real-time detection of lactose in dairy products using the biosensor was compared with HPLC results and the results clearly proved the applicability of the study in the detection of lactose in commercially available dairy products.

The detection of Zidovudine (ZDV) used in the treatment of AIDS is necessary to study the adverse effects as well as the side effects caused by higher doses. Graphite electrode modified by a hybrid composite consisting of DNA, chitosan, graphene oxide, and bimetallic Au-Pt nanoparticles was reported by H.R. Akbari Hasanjani and K. Zarei (2021). The biosensor showed remarkable selectivity, a wider detection range (0.01 pM–10 nM), and a much lower LOD (0.03 pM). The real-time analysis of ZDV in human serum also produced reasonable results.

Electrospinning was employed to produce composite nanofibers of collagen, hemoglobin, and carbon nanotubes. The composite was further used for the electrochemical detection of hydrogen peroxide by amperometric and cyclic voltammetric methods. The higher surface area and porous nature of the nanofiber composites facilitated the direct transfer of electrons accelerating the electro catalysis and selective detection of H_2O_2 (Li et al. 2014).

The detection of physiological levels of dopamine using an apt sensor based on collagen (glass carp skin derived – GCSC) -graphene oxide composite system (GCSC-GO) was reported by Wei et al. (2019). The composite GCSC-GO was used as the transducer part and the biological recognition of dopamine was made possible using a label-free aptamer. The developed biosensor showed better selectivity, superior robustness, and feasibility during the amperometric determination of dopamine in human blood serum and hence can be utilized for dopamine sensing in clinical samples.

Immobilization of enzymes for optical sensing of biomolecules can be done using suitable matrix materials. Accordingly, hydrothermally grown titanium dioxide nanotubes (TNT-TiO_2) were incorporated in a polymeric matrix of alginate and then cross-linking using calcium ions (Ca^{2+}-cationic cross-linking) was done to get the nanocomposite hydrogel. The composite was initially screened for colorimetric sensing (blue color formation) of lactate and glucose in artificial sweat. The detection was very rapid in the case of TNT-alginate scaffold compared to bare alginate scaffold; 4 min and 6 min for lactate and glucose colorimetric sensing. The TNT-alginate scaffold was then impregnated on a cellulose paper strip and colorimetric detection of lactate and glucose was studied. The paper scaffold displayed homogeneity in sensing and a quicker response indicating the potential of the scaffold in devising wearable devices for real-time detection of glucose and lactate in sweat (Gunatilake et al. 2021).

A biosensor for the detection of histamine using a cryogel composite of chitosan and gold (Au) nanoparticles was reported by N. Nontipichet et al. Electrodeposition of Prussian blue (PB) was initially done on multiwalled carbon nanotubes coated on a carbon electrode (SPCE). The composite cryogel helped in the immobilization of the enzyme diamine oxidase (DAO). The method of preparation of the electrode and detection using amperometry is depicted in Fig. 1. The current generated during the

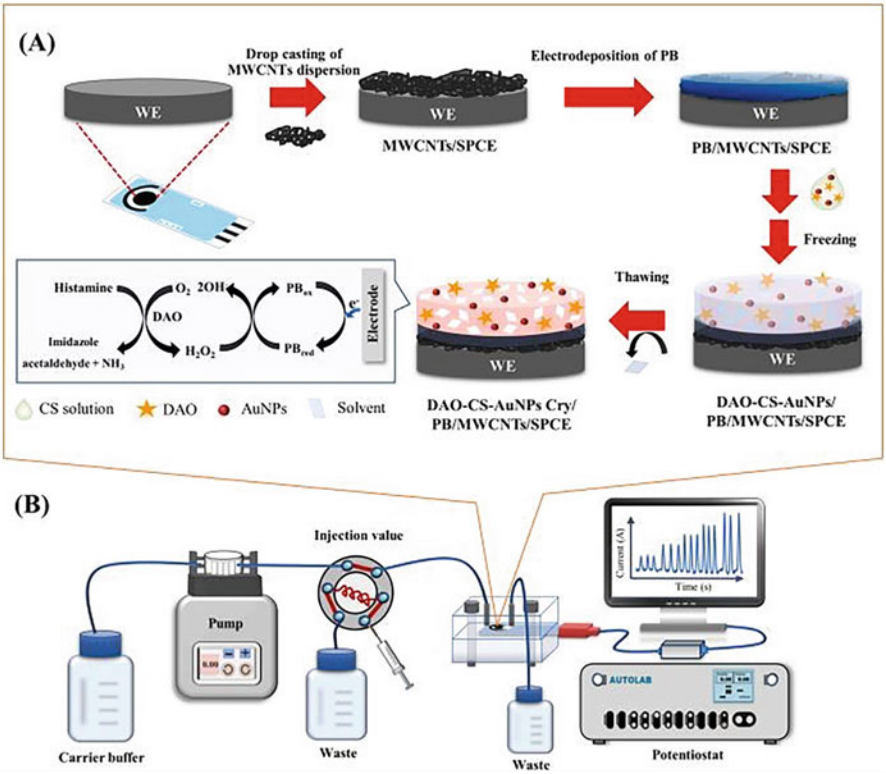

Fig. 1 Schematic representation of the preparation of modified composite electrode and the amperometric method employed for the detection of histamine

reduction of PB during enzyme catalyzed oxidation of histamine was measured. The modified electrode showed two broad linear detection ranges with exceptional stability (operational and long-term storage), selectivity, and lower detection limit (1.81 μmol L^{-1}). The sensor showed exceptional recovery during the detection of histamine in shrimp and fish samples, and the results obtained using the biosensor were consistent with that of the results using the ELISA test (Nontipichet et al. 2021).

Chitosan was employed to increase the stability of carbon nanotubes in an aqueous solution to form a well-dispersed composite for the detection of the hormone leptin in blood serum. The single-walled carbon nanotubes (SWNTs) were functionalized using a cross-linking agent for 30 min in order to activate the functional group (carboxyl group) and dispersed in a chitosan matrix followed by the addition of leptin (with the non-specific sites of binding blocked using bovine serum albumin) to obtain the biosensor. The sensor exhibited an appreciable recovery rate and the study can be extended for real-time detection of leptin in clinical samples (Zhang et al. 2018).

Miscellaneous Applications of Biopolymer-Based Nanocomposites

Biopolymers are used in developing hybrid composites with improved properties because of their biocompatible and biodegradable nature. In addition, the presence of multiple functional groups present in biopolymers helps in controlling the properties when combined with other nanomaterials. Biopolymer composites of cellulose, collagen, gelatin, proteins, alginate along with metal nanoparticles, metal oxides, carbon nanomaterials, etc., have received more consideration in the field of optics and electronics (Colusso and Martucci 2021).

Conducting a biopolymer composite film of collagen and copper nanoparticles has been reported by K. Cheirmadurai et al. The copper nanoparticles were prepared following a green procedure using henna leaf extract and discarded collagen was utilized to develop the conducting film. The improved electrical conductivity of the films suggests the potential of the composite for various electronic applications. The film when introduced between batteries was capable of illuminating a LED lamp demonstrating its excellent electrical conductivity (Cheirmadurai et al. 2014).

Bacterial cellulose (BNC) possessing high purity has been used in combination with gold nanorods for developing Surface Enhanced Raman scattering (SERS) composite for the detection of bacteria, and lower concentrations of rhodamine have been reported by Tian et al. The porous and 3D structure of BNC helped in enhancing SERS making the composite beneficial for catalysis as well as energy storage applications (Tian et al. 2016).

Cellulose was employed as the template for developing a hierarchical nanocomposite consisting of phosphotungstic acid (HPW) and TiO_2 for photocatalysis applications. The composite was further evaluated as a photocatalyst for the degradation of methylene blue (Lin and Huang 2021). Another group reported the use of cellulose to properly disperse silver nanoparticles and zinc oxide nanoparticles for fabricating a composite for photocatalysis. The composite displayed better degradation of methyl orange (92% in 2 h) under sunlight as well as UV light (Shi et al. 2021).

A photocatalyst (TFCM) employing chitosan microspheres as a matrix for the effective dispersion of ferrite nanoparticles was reported by Nawaz et al. The degradation of methylene blue was investigated and the results obtained indicated the efficiency of TFCM as a photocatalyst in degrading 93% of the dye in 150 min (Nawaz et al. 2020). The relevant biopolymer-based nanocomposites reported for photocatalytic applications are given in Table 5.

Biopolymer-based supercapacitor electrodes have been reported because of their natural abundance, the easiest way of extraction, multifunctional nature, etc. (Pandiselvi and Thambidurai 2014). Cellulose and chitosan are the most exploited biopolymers for supercapacitor applications (Roy et al. 2021). They are either used in the form of composites with conductive materials or as a renewable source of carbon precursor.

Active electrode material based on chitosan and polyorthoamino phenol (POAP) for developing supercapacitors was reported by Ehsani et al. The electrode material exhibited superior mechanical stability due to the incorporation of chitosan and

Table 5 Photocatalytic applications of biopolymer nanocomposites

Photocatalyst	Pollutant	Degradation efficiency and time	Reference
Chitosan loaded with Zr/ZnO	Hexavalent chromium	94.6% in 60 min	Preethi et al. (2020)
Carboxy methyl cellulose with Zinc ferrite ($ZnFe_2O_4$)	Ciprofloxacin	87% in 100 min	Malakootian et al. (2019)
Starch, bismuth tungstate, and graphene oxide	Ethylene	88.4% in 200 min	Xie et al. (2020)
Sodium alginate and TiO_2	Tartrazine	89% in 180 min	Dalponte et al. (2019)
Bacterial cellulose, SiO_2, and TiO_2	Crystal violet	97% in 50 min	Rahman et al. (2021)

demonstrated a higher value of specific capacitance (345 F/g at 100 mVs^{-1}) and retention of initial capacitance after 1000 cycles (Ehsani et al. 2019). Another study reported on chitosan and polyvinyl alcohol incorporated hydrogel electrodes with remarkable energy density (10.03 Wh kg^{-1}) and cycling stability (up to 5000 cycles) (Li et al. 2022). Cellulose aerogel and carbon composite were employed in developing an asymmetrical supercapacitor. The 3D porous hierarchical percolation of cellulose aided in electrolyte penetration, faster electron, and ion transport resulting in higher power (23 WL^{-1}), and energy densities (3.4 Wh L^{-1}) (Lei et al. 2021). Another group reported on cellulose nanofiber and graphene oxide fabricated as composite foam with improved electrochemical activity as an electrode for the supercapacitor. The foam electrode showed a higher specific capacitance (398.47 F/g at 0.5 A/g current density) and outstanding cycling stability even up to 10,000 cycles (Liu et al. 2021).

Future Outlook

Biopolymers have a significant role in various fields of applications owing to their good mechanical, thermal, and barrier properties. The development of biopolymers is necessary to reduce atmospheric pollution caused by synthetic polymers. But the cost of biopolymers is a factor that has to be addressed in further research. It is essential that biopolymers should be produced at a commercial level at a price comparable to synthetic polymers. The properties of biopolymers can be manipulated by the incorporation of various nanofillers in different compositions. In this respect, nanotechnology has a prominent role in improving the existing features of a biopolymer. The replacement of plastic materials that are used today has to be completely substituted with biodegradable polymers. Reusability of these plastics is not a final solution for the environmental issues. An ultimate solution will be possible only by the complete substitution of plastics for biopolymers. Such a process will assist in reducing pollution issues and leads to a sustainable future.

Conclusions

When environmental issues are concerned, recent research focuses on biopolymer-based nanocomposites for a variety of applications. However, many limitations in the processing and production of biopolymer-based nanocomposites have to be nullified in order to reach a commercial level. In this regard, a thorough study of natural biopolymers indicating the challenges faced in this area. This chapter summarizes the properties of biopolymers, the introduction of nanofillers to form bio nanocomposites, and their properties and applications in food packaging, drug delivery, wound healing, tissue engineering, and sensing. From recent studies, it is clear that blending of biopolymers and fabrication of nanocomposites are effective ways to get the desired results. The incorporation of nanofillers can optimize the properties of the matrix along with the reinforcement provided. The chapter recommends novel, economic synthetic strategies of bio nanocomposites that can pave a new way in the field of polymers and can contribute new opportunities in various applications.

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