Bio-based polymers, their sources, and applications

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11.1 Introduction

Bio-based polymers have gained attention throughout the world recently due to the desire of discovering polymers that do not rely on fossil fuels. Biopolymers provide considerable advantages to society by reducing reliance on fossil fuels, which in turn has a positive impact on the environment in the form of reduced carbon dioxide emissions and other pollutants (Babu et al., 2013; Jane, 1995). Many biopolymers possess the potential to substitute traditional polymers and help in the resolution of some of the most pressing issues that have been caused by the excessive usage of petroleum-based polymers. Some of these issues include water and soil pollution, negative effects on human healthiness, and an increased dependence on petroleum (Klemm et al., 2005). It is possible to develop biopolymers that are biodegradable (e.g., starch and polycaprolactone) (Babu et al., 2013). As a result of initiatives such as Lead Market Initiative (European Union) and Bio Preferred (United States), the regulatory landscape is shifting toward bio-based goods (Doug, 2010). However, biopolymers still account for a very insignificant fraction (<1%) of the overall plastic market (Auras et al., 2011).

Polymers derived from renewable sources, such as lignocellulosic biomass, organic wastes, and fatty acids, are often known as bio-based polymers (Auras et al., 2011; Doug, 2010). Naturally forming biopolymers and synthetic biopolymers produced by fermentation techniques are both examples of this category. The primary group of biopolymers is referred to as natural bio-based polymers, which include compounds such as polysaccharides (hemicellulose, lignin, etc.), nucleic acids, and proteins (collagen, chitin, etc.) (Ravi Kumar, 2000). The synthetic ones

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are artificially synthesized by combining two or more compounds through fermentation and polymerization (e.g., polyethylene) to attain structural and functional similarities to conventional polymers (Rinaudo, 2006). The most fundamental types of bio-based polymers such as cellulose and starch are eminent and extensively utilized for a very long time (Catley, 1971; Sena et al., 2006). However, the usage of such natural polymers has been restricted to a few sectors, including the construction, textile, and packaging industries. Since 1990, further developments have made it possible to manufacture some novel biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoate (PHA) (Draget et al., 1997; Gómez-Guillén et al., 2011). These bio-based polymers have grabbed the attention of a broad variety of industrial stakeholders. Despite their pertinence in bio-composite formulation, further advancements are needed to boost the accessibility of biopolymers in the forthcoming eco-concerned scenario (Garlotta, 2001; Jamshidian et al., 2010; Kathiraser et al., 2007).

Quality packaging is another concern that assists in upsurging the shelf life of the packed food, maintaining the nutrients, and reducing the risk of microbial adulteration throughout the preservation period. On the other hand, environmentally friendly and sustainable packaging materials are necessary now to accomplish the complete recycling or disposal of the packaging material after utilization (Guzman, 2010; Xu & Guo, 2009). This is possible with the goal of reducing the usage of polymers from nondepletable petrochemicals and enhancing the usage of bio-based products obtained from biomass, which are both sustainable and renewable (Chen & Patel, 2012; Ebnesajjad, 2012). In this chapter, the significance of biopolymers, their sources, and their probable applications are emphasized. The categories of relevant bio-based materials, their characteristics and utilization in food packaging and other domains, and the tactics employed to increase their performances are brought into focus. The additional efforts to enhance their performances through the progress of greener methods for the implication of these biomaterials are still very much required for the continuation of imminent research.

11.2 Types of biopolymers and their sources

Biopolymers are either naturally synthesized by biomass/microorganisms or synthetically made by partially or completely renewable compounds. Biopolymers are broadly categorized into three types based on their source and synthesis: polymers derived from biomass (e.g., plants), polymers derived from microorganisms (e.g., bacteria), and polymers that are chemically manufactured from monomers (Fig. 11.1). The biomass-derived biopolymers include polysaccharides, proteins, and lipids. Bacterial cellulose, PHA, PLA, pullulan, etc. are examples of microbial-based biopolymers. The synthetic biopolymers are bio-polyethylene, polybutylene succinate, etc. (Wang, Euring, et al., 2022). Different techniques are being adopted with time to produce and use environmentally friendly, sustainable biopolymers. This section covers the sources and applications of some economically important biopolymers that could be better alternatives of petroleum-based polymers.

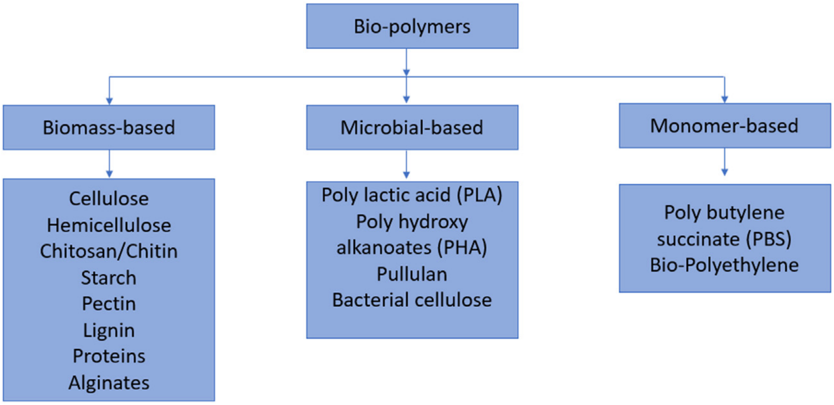

Figure 11.1 Important bio-based polymers and their sources.

11.2.1 Biopolymers derived from biomass

11.2.1.1 Cellulose

Cellulose is the constituent of the plant cell wall, which is the most plenteous polymer. Cellulose is an unbranched polymer, which is a kind of carbohydrate that has a crystalline structure and a convoluted shape. The common raw materials currently used for commercial manufacture of cellulose are cotton fibers and wood. After producing viscose from cellulosic plant fiber by dissolving it in alkali and carbon disulfide, it is subsequently treated with sulfuric acid and sodium sulfate to produce cellulose in the form of cellophane. Many cellulosic derivatives produced by chemically modifying cellulose are utilized in a wide number of applications. The most popular types of cellulose derivatives used in industries are cellulose esters, cellulose acetate, and regenerated cellulose. The most common applications of these cellulose derivatives are found in the film and fiber industries. They are extensively processed and used in molding, extrusion, and composite film production. Cellulose ethers, including carboxymethyl cellulose (CMC) and hydroxyethyl cellulose, are frequently utilized in a variety of industries such as food, beverage, cosmetics, construction, manufacturing, and pharmaceutical industries. However, regenerated cellulose dominates the market as the most important bio-based polymer produced worldwide for its use in the fiber and film industries. Regenerated cellulose fibers are used in a variety of goods, including textiles, sanitary disposables, and materials for home furnishings (Chambin et al., 2004; Chawla et al., 2009; Kennedy et al., 1993; Khatri et al., 2013; Li et al., 2011; Saxena & Ragauskas, 2009; Suwantong et al., 2008; Westermarck et al., 1999).

11.2.1.2 Starch

Starch is a well-known bio-polymer produced through photosynthesis in plants, and it is stored as discrete granules. The two main components of starch are the highly branched polymer amylopectin and the linear carbohydrate amylose. Carbohydrate is naturally found in foods, including wheat, rice, corn, and potatoes. In the future, it is possible that both injection-molded items and foam loose-fill packaging coexist for "take-away" food ampoules. Modified starch has been used across different product categories, including food and nonfood sectors. The use of starch is also significant in the sectors of paints, textiles, cosmetics, and medicines. In 2002, Europeans consumed around 7.9 million tons of starch and its derivatives (Avella et al., 2005; Fuentes-Zaragoza et al., 2010; Ozdemir & Floros, 2004), with 54% of culinary applications and 46% of nonfood uses. Thirty percent of the EU's starch usage is attributed to the paper, cardboard, and corrugating industries. Thermoplastic starch films showed several applications such as packaging grocery, bakery bread, overwraps, disposable sanitary goods, fishing bait bags, and other packaging sectors. To produce biodegradable plastics, packaging, and molded items, starch is expected to play an increasingly significant role in the future (Marques & Reis, 2005; Mendes et al., 2001; Rodrigues & Emeje, 2012; Wang, 2011).

11.2.1.3 Chitin/Chitosan

Chitin is the second most found bio-polymer in nature, which is mostly derived from the exoskeletons of marine invertebrates, insects, and cell walls of some fungi. Nowadays, discarded crab meat, shrimp shells, and prawn shells are processed chemically for industrial production of chitin and chitosan. Chitosan has several uses, including pharmaceuticals and cosmetics, water purification, and plant protection. Its specific features such as good biocompatibility, less toxicity, and bioactivity have made a lot of appeal in the development of biomaterials for medical devices. Chitosan is well-suited to many physiologically vigorous chemicals used in the cosmetics and skin care industry. It is found in shampoos, permanent hair dyes, and rinses. It has the potential to compete with hyaluronic acid as a skin moisturizer due to its lower cost. However, each use of chitosan depends on the unique quality of chitosan, mainly on the factors such as the degree of acetylation and molecular weight (Bansal et al., 2011; Dodane & Vilivalam, 1998; Hafdani, 2011; Park & Kim, 2010; Ramya et al., 2012; Ravi Kumar, 2000).

11.2.1.4 Pectin

The principal cell wall expansion and development of plants are plausible by pectin, which is a complex hetero-polysaccharide present in plant cell wall. Pectin has long been a mainstay of the food packaging industry. Due to its high compatibility with other polymers, pectin has been successfully processed for food packaging. Casting and thermo-compression molding were commonly employed to produce pectin films. Pectin was employed as a direct coating material on cut vegetables and fruits due to its controlled release of active compounds. However, different combinations of polymers are used along with pectin to produce films with desired properties. Composites containing pectin, combined with maize flour and beetroot powder, have been shown to delay food spoilage by affecting the environment of the food by altering the oxygen level and preventing the production of ethylene. Such pectin film active packaging (AP) can prevent soybean oil and tomatoes from oxidizing for up to 30 days, thereby extending their shelf life. The mechanical, barrier, antibacterial, and UV-screening capabilities of food packaging were also improved by films composed of pectin and nanoparticles such as Au, Cu, Ag, and TiO_2. (Kumar et al., 2020; Mellinas et al., 2020). Moreover, pectin's mechanical, antioxidant, and antibacterial capabilities were shown to be significantly improved by the addition of tea extracts, clove, mint, and rosemary essential oils (EOs). Nowadays, aerogels have gained popularity as a food packaging material due to their low density, low heat conductivity, wide surface area, and good porosity. Pectin is also processed into aerogels, emulsions, and hydrogels for its use in food packaging, in addition to films and coatings. The antibacterial characteristics as well as the suppression of enzymatic charring were shown to be particularly promising for use in food wrapping, in case of pectin-chitosan hydrogels (Torpol et al., 2019).

11.2.1.5 Hemicellulose

Hemicellulose is a branched biopolymer that possesses many side chains and often has excellent film-forming capabilities and is extremely water-soluble. Pentosans and hexosans are the building blocks of hemicellulose. The form of hemicellulose that is found in the cell wall of hardwoods, which has the greatest abundance, is called xylan. It has been demonstrated that films made of xylan have effective barrier characteristics against oxygen and grease. However, hemicellulose films typically have the problem of being sensitive to moisture and having poor mechanical strength. These issues are solvable by either chemically modifying the hemicellulose or composing it with other polymers. Hemicellulose can be transformed into a range of different materials through chemical processing. The films prepared from galactomannan and xyloglucan were discovered to have high barrier qualities and thermal stability, which makes them viable candidates for their use as eco-friendly, decomposable food-packaging materials. A combination of quaternized hemicellulose and chitosan was found to be effective in terms of ensuring high mechanical strength and barrier qualities. Likewise, nanocellulose added to acetylated hemicellulose was shown to have improved mechanical characteristics and hydrophobicity. Such composite film could be widely utilized as a material for the AP of food products (Mugwagwa & Chimphango, 2020).

11.2.1.6 Lignin

The biopolymer lignin is a very intricate biopolymer with a networked structure, and it is widely distributed across the planet. It is mostly found in plant cell walls and usually forms ester linkages with hemicellulose. Many different types of active groups such as hydroxyl, methoxy, carbonyl, carboxyl, and benzene can be found in lignin. As a result of its antibacterial, UV-shielding, and antioxidizing qualities, lignin has found widespread usage in the packaging of food.

Lignin is highly compatible and assists in improving the antimicrobial properties of composites. This antimicrobial activity is caused by the interaction of hydroxyl groups of lignin with the microbial membrane. Besides antimicrobial property, lignin can be incorporated in polymer matrices to expand their tensile properties and wettability. Due to its antioxidant properties, low molecular weight, narrow polydispersity, and rich phenolic hydroxyl groups, it has been cast off in food packing. Conversely, the antioxidant activity and UV-shielding capabilities of lignin were shown to be greatest when syringyl groups were present in it (Guo et al., 2019).

11.2.1.7 Proteins

Proteins are macromolecular polypeptides that are made up of one or more long chains of amino acid residues. Some proteins have excellent film-forming characteristics, making them suitable for food wrapping in the form of free-standing films. Whey, soy, wheat gluten, fish gelatin, milk protein, maize zein, and myofibrillar proteins are the few proteins that have been reported for food packaging. Collagen and gelatin are the viable proteins widely used for commercial purposes. Collagen is the prevalent and naturally occurring insoluble protein fiber found in connective tissue and the extracellular matrix of animals. The richest collagen sources include pork and cattle bones, bovine hide, and pig skin. Collagen films are commonly utilized as drug delivery systems for integrated treatments that gradually release drugs. It was also used in burn/wound sponges, tissue engineering to build artificial blood arteries, valves, and skin and bone substitutes. Gelatin is another protein, which is produced by collagen hydrolysis. Despite its ability to form gels, gelatin is used in cosmetics, medicines, food, photography, emulsification, foaming agents, colloidal stabilizers, biodegradable film-forming, and microencapsulation (Gómez-Guillén et al., 2011; Lee et al., 2001; Rubin et al., 1973). Proteins have been utilized as surface coatings of cellulose films to enhance their mechanical strength. The lesser mechanical characteristics, barrier qualities, thermal properties, and physicochemical properties of proteins limit their usefulness as food packaging materials.

However, chemical, physical, and enzymatic approaches can be used to modify proteins to create films with improved tensile strength and moisture resistance. It is found that the qualities of food packaging have been enhanced by incorporating proteins with nanofillers. For instance, the tensile and barrier possessions of protein-incorporated films used in food packaging have been improved by adding nanofillers, such as starch nanocrystals, nanocellulose, and nanochitin, and inorganic nanofillers, such as silica, zinc oxide, carbon nanotubes, layered silicates, titanium dioxide, and silver nanoparticles (Zubair & Ullah, 2020). Water barrier characteristics and microbial growth inhibition in protein-based films were found to be enhanced by using plasticizers and certain active chemical compounds.

11.2.1.8 Alginates

Brown seaweeds and soil microorganisms are the natural sources of the linear anionic polymer alginate. Sodium alginate is the most popular form of alginate, which is the primary by-product of algae processing. The industrial uses for alginates include its use in viscosifiers, stabilizers, films, ceramics, thermostable gels, welding rods, textile printing, water purification, and water-binding polymers. Alginates are frequently employed as a gelling agent in culinary and medicinal applications because of their gelling property. It is also used to thicken and stabilize a range of drinks, ice creams, emulsions, and sauces (Ertesvåg & Valla, 1998; Qin et al., 2007; Rehm, 2009; Teli & Chiplunkar, 1986; Xie et al., 2001). Alginate-containing wound dressings are frequently employed, particularly when creating hydrophilic gels that cover wounds and provide cozy, localized hydrophilic habitats for wound healing. Alginates are utilized for drug delivery in a controlled manner because the molecular weight of the alginates affects the rate of drug release. Alginates are also convenient to use in dental treatments because they quickly set at ambient temperature and are inexpensive. Alginates can effectively cure obesity, according to recent human clinical studies (Dettmar et al., 2011; Goh et al., 2012; Jensen et al., 2012). Conversely, alginate is used to enhance the barrier and oil resistance properties of paperboard by coating it with calcium chloride.

11.2.2 Biopolymers obtained from microbial sources

11.2.2.1 Polylactic acid

PLA is a polymer that can be produced from maize (starch) or sugars through bacterial fermentation. The polymerization processes such as direct polycondensation and ring-opening polymerization can be used to produce PLA from lactic acid. Corn is a great feedstock for fermentation of renewable sources to lactic acid with high purity. During the fermentation process, either l-lactic acid or d-lactic acid will be formed, which is determined by the strain of microorganism that is utilized. PLA is often used in a variety of applications on a day-to-day basis, which includes food packaging such as water bottles, candy wraps, and cups. (Auras et al., 2011). Recently, PLA with increased thermal resistance was accomplished by using kenaf and carbon fibers. In the past several years, PLA was being employed as a film material in many industries, including automotive. Although fabricated PLA fibers showed more attention in making textiles, furniture, baby wipes, landscape fabrics, and bioresorbable scaffolds. PLA and their blends are also used for a wide range of clinical applications such as drug release, degradable sutures, valve replacement, bone fixation, orthopedic claims, gene therapy, tissue regeneration, and treatments of cardio and neuro conditions (Ilyas et al., 2021; Jain, 2000; Papenburg et al., 2009).

11.2.2.2 Polyhydroxy alkenoates

Polyhydroxy alkenoates, often known as PHAs, are a kind of polyester that is produced by bacteria through the fermentation process. These polyesters are promising to replace traditional polymers that are based on hydrocarbons. PHAs are certainly present in a wide range of microbial species; however, bacteria can use a wide variety of renewable waste feedstocks to produce PHA. The steps involved in synthesizing PHA by bacterial broth fermentation include fermentation, separation, and purification. PHA and its copolymers are commonly used in the medical industry as materials for many types of implants. These include stem cell growth, tissue repair patches, meniscus repair devices, cardiovascular repair patches, bone plates, meniscus repair, and surgical mesh. Moreover, by modifying the composition of the PHA, the characteristics, such as biocompatibility and the amount of time required for polymer breakdown within the necessary time periods in particular circumstances, can be adjusted with varying PHA concentrations. Because of their controlled biodegradability and biocompatibility, PHAs are ideally suited for their use in medications (Ying et al., 2008).

11.2.2.3 Pullulan

Pullulan is a macromolecule that digests slowly and has no taste or odor, which makes it suitable for use as a meal substitute because it contains less calories. Pullulan has excellent capabilities for retaining moisture and acting as an oxygen barrier, hence it is employed as an excellent ingredient for preserving food. Therefore, the food industry makes extensive use of pullulans in food product preservation. Additionally, it inhibits the growth of fungi and other microorganisms. Pullulan has the potential for the delivery of targeted medications and genes, engineering of tissue, healing of wounds, and even as a medium for diagnostic imaging. The increasing demand for this unique biopolymer is being driven by the discovery of its novel applications in new markets such as medications, dietary supplements, and oral care products (Cheng et al., 2011).

11.2.2.4 Bacterial cellulose

Certain species of bacteria, rather than plants, are responsible for the production of cellulose. Bacterial cellulose is distinguished by its qualities such as a high degree of polymerization, purity, strength, and capacity for storing water. Bacterial cellulose has a high demand because it is chemically pure with high strength compared with plant cellulose alone. Due to its overwhelming properties, it is possible to utilize it in the production of goods that have a decent level of strength. Bacterial cellulose assorted with starch and chitosan led to the development of environmentally safe, eatable food packaging materials that have excellent mechanical and antibacterial qualities. Composite films made of corn starch and bacterial cellulose nanowhiskers (CNWs), coated with electro-spun PHAs, were investigated for their use in food packaging applications to enhance the tensile properties of films, as well as barrier assets. In fact, the antimicrobial properties of such cellulose nanofibers (CNFs) make them a suitable candidate for medical applications (Abral et al., 2021). Outside of the culinary, bacterial cellulose has only a limited number of applications due to its prohibitively expensive price. Additional applications of bacterial cellulose are found in acoustic diaphragms, mining, paints, adhesives, and oil gas recovery.

11.2.3 Biopolymers made from monomers

11.2.3.1 Polybutylene succinate (PBS)

The production of the aliphatic polyester, known as polybutylene succinate or PBS, involves the combination and condensation of succinic acid with 1,4-butanediol. Either monomers originating from fossil fuels or produced by bacterial fermentation can be used in the production of PBS. Different approaches are used for turning fossil fuels into succinic acid, where electrochemical synthesis pays more attention due to low cost and high yield. Feedstocks derived from fossil fuels such as formaldehyde and acetylene are utilized in the production of 1,4-butanediol by using conventional techniques. The biological process includes the production of glucose, conversion to succinic acid, and chemical reduction of succinic acid to butanediol. On the other hand, the fermentation method of producing succinic acid provides several benefits such as using nonconventional or renewable sources and consuming significantly less overall energy, which are substantial in contrast to the chemical method. The applications of goods that are entirely composed of PBS are restricted because of their low mechanical flexibility. However, the commercial uses of PBS blends with PLA or starch derivatives have been recognized in a variety of industrial sectors, including agriculture, fishing, forestry, and construction. In addition to that, it finds application in the foaming and food packaging industries. Specifically, it is employed as a non-migrant plasticizer for packaging film applications (Xu & Guo, 2010).

11.2.3.2 Bio-polyethylene

Bio-polyethylene is a synthetic polymer made by converting ethylene to polyethylene by a process known as polymerization, which takes place at high temperatures and pressures in the presence of a catalyst. For this purpose, ethylene is often formed by steam splitting of heavy oils or by dehydrating ethanol. Nowadays, polyethylene is also synthesized by dehydrating ethanol obtained from microbial/biomass fermentation, which is referred to as green polyethylene. Currently, sugarcane is used as the primary feedstock to produce bioethanol, which is further used in the commercial production of bio-polyethylene. Bioethanol may also be produced from bio-renewable feedstocks, such as sugar beets, starch crops, wheat, wood, and other plant waste products, by using a specific strain of microbes through the biological fermentation process. Bio-polyethylene has greater application in engineering and agriculture, as well as in the packaging industry. Plastic bags, toys, food packaging films, milk and water bottles, and agricultural mulch films are just some of the applications that make use of this material because of its inexpensiveness and high level of performance (Kasirajan & Ngouajio, 2012). The different bio-based polymers, their sources, and their production methods are briefly tabulated in Table 11.1.

Table 11.1 List of important bio-based polymers along with their sources and production strategies.

Occurrence/production of polymers	Polymer name	Sources	References
Natural bio-based polymers	Starch	Wheat, rice, corn, and potato	Jane (1995)
Bio-based polymers produced by bacterial fermentation	Cellulose	Cotton fibers, wood	Chawla et al. (2009), Klemm et al. (2005)
Natural bio-based polymers	Chitin and Chitosan	Shells of prawns and crabs	Ravi Kumar (2000), Rinaudo (2006)
Biopolymers obtained by fermentation broth of fungus	Populan	*Aureobasidium pullulans*	Catley (1971), Sena et al. (2006)
Natural bio-based polymers	Collagen and Gelatin	Bovine hide, and cattle bones, pig skin, and pork	Gómez-Guillén et al. (2011)
Natural bio-based polymer	Alginates	Seaweeds and soil bacteria	Draget et al. (1997)
Biopolymers obtained by bacterial fermentation of renewable sources	Polylactic acid	Corn (starch) and sugars	Garlotta (2001), Jamshidian et al. (2010)
Biopolymers obtained by bacterial fermentation of renewable sources	Polyhydroxy alkenoates	*Pseudomonas putida*	Kathiraser et al. (2007)
Biopolymers obtained by fermentation of renewable sources/ petroleum-based chemical processing	Polybutylene succinate	Fossils	Xu and Guo (2009)
Biopolymers obtained by microbial fermentation of renewable sources	Bio-polyethylene	Microorganisms	Ebnesajjad (2012), Guzman (2010)

11.3 Implication of biopolymers as bio-fillers

Bio-fillers are polymeric materials obtained from biomass, which are paid much attention nowadays due to their specific properties and wide range of applications. These materials can be incorporated with a wide variety of matrices to form bio-films or composites. Bio-fillers could be attained from diverse sources such as animals, plants, and algae, of which plants are widely utilized for this purpose due to their wide distribution and availability. Fig. 11.2 illustrates diverse biomass sources that are utilized for the extraction of bio-fillers. The most popular cellulosic bio-filler forms obtained from plant biomass include natural fibers, CNFs, cellulose nanocrystals (CNCs), and cellulose microcrystals. Besides cellulose, starch, soy protein isolate, and soybean straw were also tried as bio-fillers to analyze their ability to form composite films (Gupta et al., 2022; Vinod et al., 2020). Of which, starch-based films showed low impact in terms of poor mechanical properties, while offering cost-effectiveness and renewability. Because of the noncellulosic components and proteinaceous nature, soybean straw and soy protein isolate also resulted in low impact in contrast to pure cellulosic fillers.

11.3.1 Natural fibers

The fiber-like structures obtained from diverse biological sources are collectively called natural fibers. Based on their origin, natural fibers are classified into animal-based (e.g., silk and wool), plant-based (flax, hemp, cotton lint, sisal, etc.), and geological-process-based (e.g., asbestos) fibers. Natural fibers derived from lignocellulosic materials or biomass are extensively employed as reinforcing fillers in bio-composites due to their high cellulose content. Because cellulose content

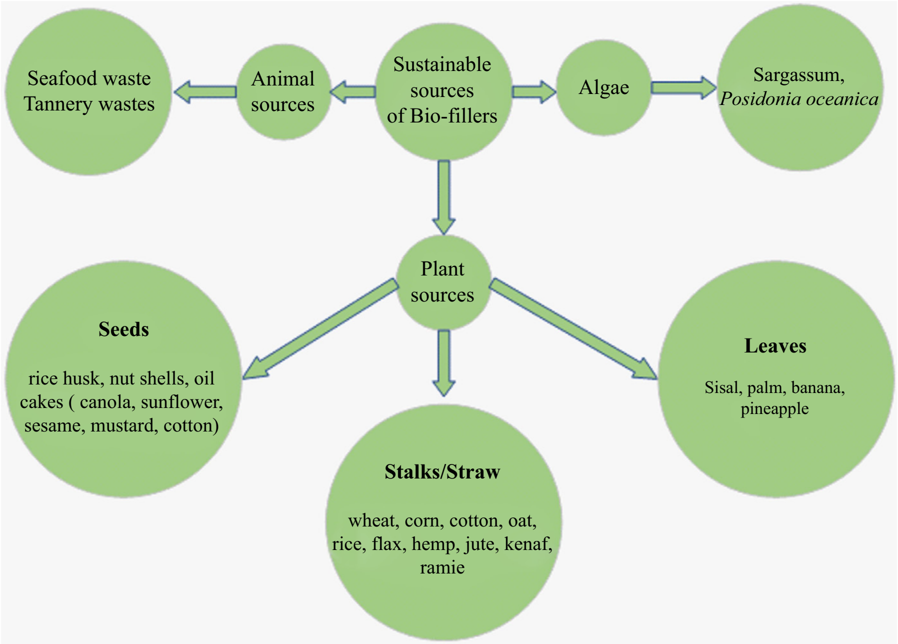

Figure 11.2 Probable sources of bio-fillers.

provides more strength than proteinaceous animal fiber, natural plant fibers could be reinforced with matrices to form bio-composites in the best possible ways through extrusion, resin transfer molding, and injection or compression molding techniques (Faruk et al., 2012). Such composites offer renewability, degradability, easy processibility, and cost-effectiveness. These composites are suitable for structural applications in diverse sectors such as aircraft/automotive industry, packaging sector, and food industries. Moreover, low density of most of the fibers makes them suitable for light-weight structural applications. On the other hand, the hydrophilic nature of certain plant fiber composites reported a significant issue due to their relatively high lignin and hemicellulose content rather than high cellulose content. Despite this, high-water permeability, less strength, high degradation rate, and shorter lifespan are reported for such composites (Chong et al., 2021).

11.3.2 Cellulose nanofibers

The nano-sized fillers made from biomass, plant fibers, or cellulose are referred to as CNFs. These are the significant class of fillers used to fabricate bio-films with high specific strength. Due to their high cellulose content and low lignin/hemicellulose content, compared to natural plant fibers, CNFs possess good mechanical, thermal, and compatibility features. The CNFs were combined with polymers, including PLA and polyethylene glycol, to attain reinforced composite films for packaging. However, a failure in water vapor barrier properties and compatibility was noted earlier in some studies conducted with CNF-incorporated films. To accomplish the remarkable compatibility with PLA, CNFs were chemically treated to ensure hydrophobic characteristics. CNF film's water vapor barrier properties have also been enhanced by the use of the sol-gel process, layer-by-layer assembly, electrospinning, and composite extrusion. Another examination showed that coating packing paper with a biodegradable composite reduces its water vapor permeability. Likewise, few investigations were made with coupling clay minerals with CNF to accomplish good tensile strength and fire, water, and air resistance, as well as cost reduction. In addition, antibacterial and cushioning aerogels for food packaging were generated by employing CMC nanofibers and chitosan/silver nanoparticles through 3D printing (Wang, Euring, et al., 2022).

11.3.3 Cellulose nano/micro crystals

Apart from CNF, CNCs and microcrystalline cellulose (MCC) are the other different forms of cellulosic fillers that are widely accepted for the fabrication of light-weight polymer composites or bio-films due to their contending biocompatible properties. These are used in the best possible ways to replace synthetic reinforcements, and thereby to assure better performance and sustainability due to their good specific strength and eco-friendly nature. The utilization of CNC and MCC ensures more durability and compatibility in contrast to lignocellulosic plant fibers due to their high cellulosic but low noncellulosic content. CNCs can be extracted from a wide variety of sources and are extensively used as a reinforcing agent for a broad variety of materials because CNCs occasionally undergo chemical changes to increase their compatibility with other substances. To make food packaging materials, it is combined with PLA, PA, polyethylene, polypropylene, polyethylene terephthalate, and CMC. It is found that films made from PVA/CMC/CNC were proven to be improved in their specific characteristics, including transparency (Wang, Euring et al., 2022; Yu et al., 2020). Moreover, PLA/nanocellulose composite materials also possess antibacterial capabilities if certain antimicrobial ingredients are included in the composite material. Both organic and inorganic materials could be included as antimicrobial substances. Organic antimicrobial agents include polymers, organic acids, or enzymes, whereas inorganic antimicrobial agents include nanoparticles of metal or metal oxides. Conversely, MCC is an extensively acknowledged micro-sized filler for bio-film claims, due to its superior thermal, mechanical, and physical properties. MCC united composites resulted in enhanced properties such as high tensile properties and water vapor barricade abilities. For instance, MCC extracted from diverse agricultural sources showed low density, better thermal stability, antimicrobial properties, and crystallinity compared with fibrous cellulosic materials. In fact, of these optimistic features, the demand for MCC is elevating expansively nowadays for the preparation of light-weight films for food packaging requests (Chawla et al., 2009; Khatri et al., 2013; Wang, Euring et al., 2022).

11.4 Bio-plasticizers: an emerging trend

Bio-plasticizers are environmentally friendly materials/biopolymers that can be incorporated with other materials to improve their flexibility, workability, and distensibility. When a bio-plasticizer is introduced to the polymer system, plasticizers could upsurge the distance between its polymer chains. This makes it simpler for chain segments to move and rotate, which in turn allows polymer chains to wind around one another. In addition, bio-plasticizers possess biocompatibility and film-forming ability and partake unique physical, chemical, thermal, and surface properties. Bio-plasticizers can be employed in the best possible ways through copolymerization and by incorporating it with other polymers as blends. Moreover, more than 60% of the total plastic yield comes from polyvinyl chloride (PVC) and plasticizers, making them one of the significant additives in the production of polymer components. Bio-plasticizers have been utilized extensively to make PVC plastics because they are a cheap and raw source, and their utilization has improved waste management through the recycling of wastes and eco-friendly biodegradable materials. The interest in polymers derived from biomass has increased in response to rising worries about the environment and diminishing petrochemical resources. Although all biopolymers obtained from biomass do not possess plasticizing properties, only a few polymers are known for their plasticizing effect (Jia et al., 2018).

Bioplastics are plastics that are bio-based, biodegradable, or have both characteristics. The ultimate makeup of bioplastics must contain at least half of the bio-plasticizer share. Under accelerated composting conditions, it should biodegrade by at least 90% of its total weight per volume in 6 months. Biodegradable bioplastic materials should not pose a risk to the environment and plant growth even after 6 months. Under monitored composting conditions, the minute particles of bioplastic components should become undetectable after 2 months. There are four broad categories of bioplastics (both biodegradable and nonbiodegradable), which include bioplastics synthesized from petrochemicals, bioplastics from bio-based monomer, microbial-based bioplastics, and bioplastics directly derived from biomass. Each of the categories possesses its own unique features and uses, and is increasingly used as an environmentally preferable substitute for traditional plastics. Nevertheless, most petroleum-based plastics are quite stable in the wild, often lasting hundreds of years without being degraded (Venkatachalam & Palaniswamy, 2020). According to the most recent market statistics published by European Bioplastics, the worldwide production capacity of bioplastics is expected to expand from 2.11 to about 2.87 million tons from 2020 to 2025.

The utilization of agro-wastes or biomass for bio-plasticizer extraction is an overwhelming strategy that would assist in reducing major environmental problems such as global warming, waste recycling, and toxic release. Research on biomass-based plasticizers (e.g., vegetable oils, glycerol, and citric acid) is essential to identify potential alternatives to o-phthalate plasticizers. Common examples of bio-based plasticizers include polyester plasticizers, epoxidized plasticizers, flame-retardant plasticizers, citric acid esters plasticizers, macromolecular plasticizers, and glyceryl ester plasticizers (Fig. 11.3). Renewability, degradability, low toxicity, improved solvent impervious isolation, and plasticizing features of bio-based plasticizers make them a

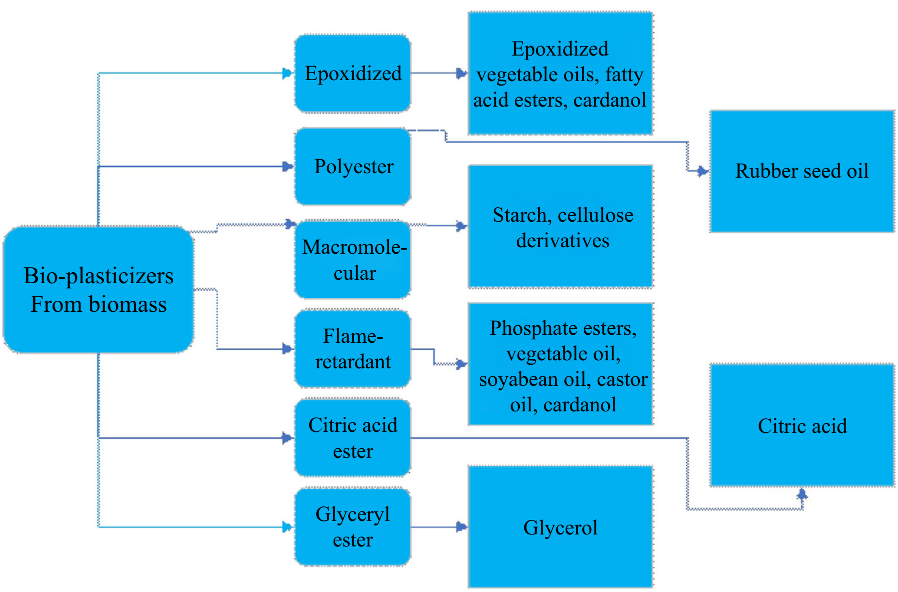

Figure 11.3 Types and sources of typical bio-plasticizers.

viable alternative to o-phthalate plasticizers. The following are some instances of the many types of bio-based plasticizers that have recently achieved advancements in their multifunctional uses in PVC products (Chu et al., 2022).

Epoxidized plasticizer is an ecologically friendly plasticizer that is employed in the plastic, rubber, and coatings industries. This embraces epoxidized fatty acid esters, vegetable oils, and epoxy groups as cardanol derivatives. Nowadays, epoxidized fatty acid esters and vegetable oils are the most typical plasticizers possessing high market value. Polyester plasticizer is typically made by the polycondensation reaction of dibasic acid and diol. It is referred to as an enduring plasticizer due to its extended service life, high molecular weight, and ease of oil and solvent extraction. Renewable, biodegradable polyester plasticizers obtained from rubber seed oil have attracted researchers' attention due to their optimistic future in research and practical applications. In addition, polyester plasticizers still have the limitations such as low-temperature performance, poor processability, and inefficient plasticizing compared to other bio-plasticizers. Macromolecular plasticizers, including starch and cellulose plasticizers, provide excellent properties and a wide range of applicability compared to other bio-plasticizers.

Phosphate plasticizer is another type of multipurpose plasticizer used in PVC products due to its plasticizing and flame-retardant qualities. Phosphate esters can be used in conjunction with many different types of resins and synthetic rubbers (PS). Rubber, textiles, military goods, plastics, conveyor belts, electrical appliances, and a wide range of construction materials are fabricated with fireproof and nonflammable properties, using phosphate ester plasticizers. Vegetable oil, soybean oil, castor oil, and cardanol are processed to produce the aforementioned plasticizer type. Glycerol is a byproduct of biodiesel synthesis, and it has several applications beyond the oil and gas industry, including in the fields of medicine, plastics, and microbiology. Glycerol-based plasticizers were developed by Palacios et al. and employed as a phthalate replacement. Glycerol triesters were synthesized from propanoic, butanoic, isovaleric, isobutanoic, and benzoic acids. A combination of starch plasticizer and glyceryl ester plasticizer was found to be more effective. Citric acid ester plasticizers are widely considered to be among the safest and most nontoxic plasticizers available. In fact, for safety concerns, it is used for packaging of food, toys, and medical and hygiene supplies. Because citric acid is produced cheaply by the fermentation process, it is considered a cheap plasticizer for the synthesis of PLA, PVC, and other polymers (Jia et al., 2018).

11.5 Mode of processing and application of biopolymers

The biopolymers, extracted from various sources, are processed with matrices through diverse processing techniques to obtain polymer composites, composite films, and composite foams (Fig. 11.4). The composite films are generally fabricated through solution casting, tape-casting, extrusion, and blowing techniques. Polymer composites are made by compression molding, filament winding, resin transfer molding, pultrusion, injection molding, hand lay-up, and vacuum-bag molding techniques.

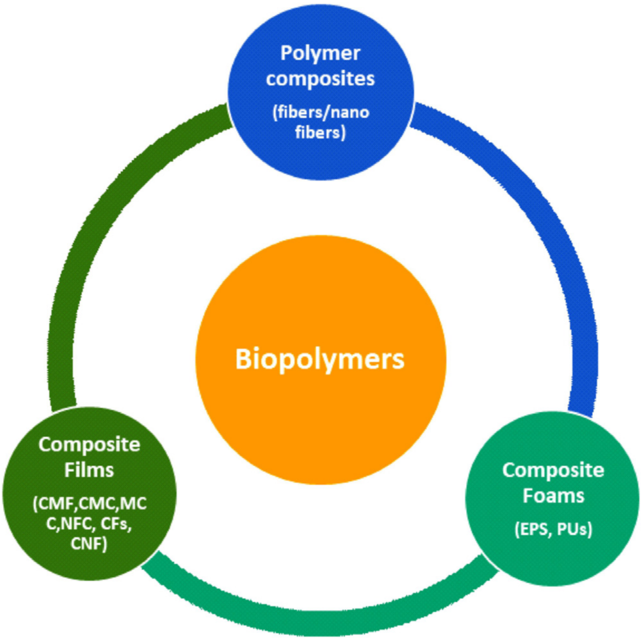

Figure 11.4 Processing forms of biopolymers.

11.5.1 Polymer composites and nanocomposites

In the past few decades, structural applications have mostly made use of synthetic fiber-based materials. Nowadays, bio-based fibers are widely utilized for structural composite formulation because of their low cost, biodegradability, renewability, and lightweight nature. Natural plant fibers are potential materials for fiber-reinforced polymer composites (Divya et al., 2022). Reinforcing two or more materials together to create a polymer-reinforced composite is a common practice today. This process often results in a composite with desirable properties that are derived from the original elements. One or more discontinuous phase (reinforcing phase) components will often be inserted into a material with a continuous phase. Generally, the reinforcing material is reinforced into the matrix in a distributed way to produce the discontinuous phase of composites. Such composites can be made via injection molding, compression molding, melt-extrusion, filament winding, resin transfer molding, vacuum-bag molding technique, pultrusion, or hand lay-up technique with a thermoset or thermoplastic polymer matrix as the continuous phase. Sometimes, bio-based polymers can be employed as matrices to obtain completely biodegradable green composites. Because the matrix maintains the reinforcement in its intended location, a significant share of mechanical characteristics could be imparted to the composite. Furthermore, the interfacial bonding between the reinforcement and matrix is significantly affected by the roughness of the reinforcement surface (Indran et al., 2022; Manimekalai et al., 2021). However, the ultimate strength of a composite depends on the reinforcements employed in its construction, including their quality, distribution, interactions, and percentage by weight or volume. Where shape, size, and distribution of the reinforcing phase have a significant impact on composite qualities.

The composites made of low-density reinforcements and moderate-density reinforcements are suitable for structural applications in diverse sectors such as automobile, aerospace, marine, packaging, and biomedical (Indran et al., 2018). Bio-composites made of nanoparticles have also been investigated for their use in lightweight goods. Such nanocomposites are suitable for wound dressing and active food packaging due to their lightweight and antibacterial features, as investigated earlier, because they successfully strengthen the biopolymer matrices and offer protection against a broad spectrum of bacteria, viruses, and fungi (Viswanathan et al., 2006). Silver nanoparticles are most utilized for food packaging applications. Although many nanocomposites and active systems that have been investigated were made using solvent evaporation, for such systems to be widely used in industry, biodegradable nanocomposite creation via scalable methods is required. Extrusion is a continuous and scalable processing method; however, it has not yet been fully investigated for its impact on nanoparticles or bioactive compounds. The manufacturing process can degrade the additives, so it is important to study how the components mix and distribute within the matrix, how they interact, and what influence they have on the quality of the material. Bio-composites consisting of thermoplastic starch and nanoparticles have effectively been extruded in recent research. Most of the research has focused on starch-based and nano clay bio-composites. Besides, titanium oxide and zinc oxide nanoparticles are also used to improve composite properties (Song et al., 2014).

11.5.2 Bio-composite films

The thin composite films made of biopolymer reinforcement and matrix are referred to as bio-composite films. A wide variety of processing techniques may be employed to create bio-composite films using various biopolymer matrices and fillers. Many such films have been examined to date to identify their specific properties and probable applications. Different cellulose derivatives or cellulosic fillers such as cellulose microfibers (CMF), nano fibrillated cellulose (NFC), CMC, MCC, cellulose fibrils (CFs), and cellulose nanofibrils (CNF) are mainly employed for this purpose (Balavairavan et al., 2023; Divakaran et al., 2024). Dilute cellulose suspensions can be refined under high pressure and then treating the resulting material with chemicals or enzymes to produce CMF. MCC is another filler form that results from removing the amorphous portions of cellulose. This process leaves pure cellulose crystals in a stable colloidal solution. This polysaccharide has several potential applications as a biopolymeric matrix or bio-composite filler, depending on the cellulose structure and the material's desired qualities. Despite this, Kumar et al. (Ortega et al., 2022; Senthil Muthu Kumar et al., 2018) used CFs isolated from Napier (*Pennisetum purpureum schum)* grass in bio-films by combining them with some matrices. There is a great promise for the edible coating or packaging films, made from CMC and crystalline CNFs, to prolong the shelf life of unprocessed and slightly processed produce. In addition, starch-based composite films have used CNFs as fillers as well. In case of such fillers, the reinforcement concentration adversely affects the bio-film properties. Generally, the lowest concentration (<10%) is preferred for cellulosic fillers because highest concentration leads to the brittle nature of films. In addition, starch and nanomaterial-based polymeric films showed a positive impact on various film properties. Solution casting, tape-casting, extrusion, and blowing techniques are employed for bio-film preparation; of which, solution casting is most preferred (Vinod et al., 2020).

11.5.3 Composite foams

Lightweight and insulating foam-like polymer compounds are in high demand today, which includes expanded polystyrene (EPS) and polyurethanes (PUs) (Kausar, 2018). Bio-based tannins, polyols, recycled polymers recovered from wood, and other bio polyols produced from agri-food wastes, crop straws, and citric peels have been used to generate novel and more sustainable PU foams earlier. Scaffolds for tissue regeneration made from PUs are appealing because of their technical performance, ease of endorsement, and biocompatibility. However, PUs are very resistant to biodegradation due to the heterogeneous assembly and the feasibility of their building blocks. Therefore, completely biodegradable scaffolds are being designed for biomedical applications. In addition, alternatives to EPS, such as biodegradable foams, are presently being researched, particularly for their use in throwaway packaging. Thermoforming for the construction of containers and extrusion-cooking for cushioning materials are just two of the methods researched to create bio-based foams. A variety of methods, including extrusion, microwave, baking (thermoforming), freeze-drying/solvent exchange, and supercritical fluid extrusion, were compiled by Soykeabkaew et al. for processing starch-based foams (Kausar, 2018; Soykeabkaew et al., 2015). The porous foam is shaped during thermoforming by insufflating the molten polymer mix with gas, which expands when pressure is lowered, or by using blowing components that create gas through thermal breakdown or chemical response. In fact of less toxicity, excellent constancy, and cheap cost, carbon dioxide has surpassed hydrochlorofluorocarbons as the gas of choice for the blowing of such polymer foams.

11.6 Applications of biopolymer-based composites

Biopolymer-reinforced composites are extensively used for diverse purposes in different sectors such as packaging, biomedical, fertilizer delivery, and wastewater treatment applications (Table 11.2 and Fig. 11.5). The specific applications of diverse biopolymer-based composites are discussed below.

Table 11.2 Processing methods and applications of certain biopolymers.

Applied sectors	Biopolymers	Processing methods	Applications
Packaging	Chitosan	Casting	Mushroom preservation
	Chitosan-cassava TPS	Compression molding	Pork meat preservation
	Chitosan-CMC-oleic acid	Casting	Preserve bread to improve shelf life
	Chitosan-corn starch	Solution casting and heat sealing	Fruit preservation and transport
	Whey, corn starch	Solution casting followed by heat sealing	Cheese conservation
	Starch	Electrospinning	Waterproof food packaging
	Cassava starch	Thermoforming foaming	Food packaging
	Tapioca starch	Solution casting	Ready-to-eat meat preservation
	Gelatin/gellan gum	Casting	Fish and milk preservation
	Zein	Electrospinning	Cheese preservation
	Curdlan-PVA	Solution casting	Chilled pork preservation
	PLA	Casting and drying at vacuum oven	Cheese preservation
Biomedical	Chitosan	Casting	In vitro drug release
	Chitosan-PVA	Electrospinning	Wound dressings
	Chitosan-PVA	Casting-freezing-lyophilization	Scaffolds formation
	Collagen	Electrospinning	Bone tissue engineering
	Collagen and gelatin	Casting-freezing-lyophilization	Bi-porous scaffolds generation
	Hyaluronan-PVA	Electrospinning	Wound dressing mats
	PLA	3D printing	Tissue engineering
	Soy protein isolate-agar	Casting	Wound dressing with drug release
Agro-industrial	Cassava starch	Casting	Controlled fertilizer release
	Protein hydrolysate-PEG	Spraying	Spray coated mulch
	Protein hydrolysate-PEG	Melt mixing followed by hot pressing	Production of nursery containers
Waste treatment/Pollutant removal	Chitosan	Precipitation by alkaline solution	Cadmium removal
	Alginate	Cross-linking with calcium chloride	Removal of dye
	PLA	Electrospinning	Antifouling membrane

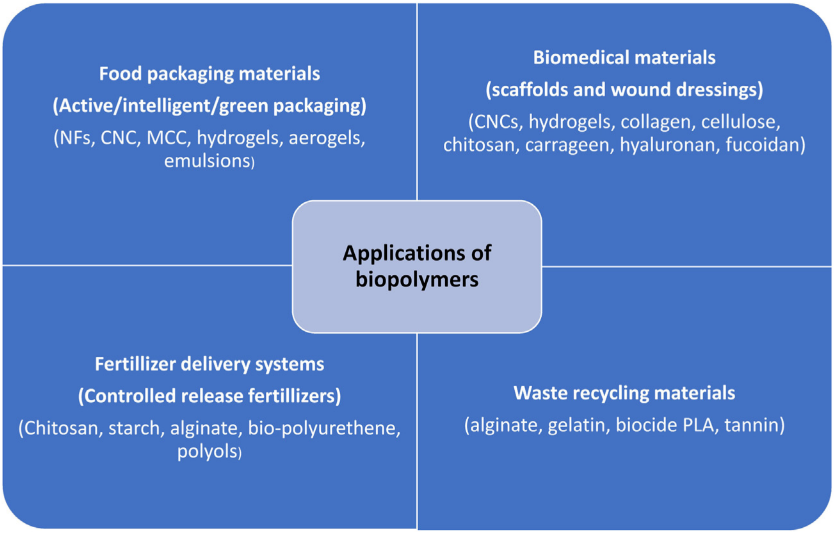

Figure 11.5 Applications of biopolymers in diverse sectors.

11.6.1 Biopolymers for food packaging

Food materials need to be packaged properly to prevent spoilage and assure safety, loss of freshness, and contamination during their transportation and storage. For that, it is imperative to recognize the specific requirements of the foods that are being transported or stored. For instance, in case of vegetables, their respiration and transpiration rates should be lowered, which could be done by organizing environmental factors such as light, humidity, gas (O_2, CO_2, and ethylene), and temperature. Milk, cheese, and cream are perishable goods that need to be shielded from the effects of oxygen, light, and moisture to prevent spoilage. Discoloration is common in meat products, although it may be prevented by vacuum packaging or modified environment packaging. Eco-friendly biopolymer packaging has been widely utilized nowadays to defend the eminence and protection of foodstuffs. Sustainable and green packaging is in great demand as people are becoming more aware of the harmfulness of packaging material to the environment. Currently, bio-based products are not only produced from exhaustible petrochemicals but also from renewable and sustainable biomass (Chen et al., 2019).

Diverse kinds of food packing technologies, such as intelligent or smart packaging (IOSP), passive packaging, sustainable or green packaging (SOGP), and AP, have been created per the goals and procedures of food packing. Mechanical durability, barrier performance, and thermal stabilities were given more weight in passive packaging. Indicators of time and temperature, gases, microwavable doneness, radio frequency identification, etc. have been used to successfully implement the IOSP. The SOGP seeks to produce environmentally friendly materials for food packaging. Because of the concerns about the possessions of such packaging wastes to the environment, the SOGP has got much attention today. Its effectiveness is often determined by the construction and dealing methods used, as well as the destination of the packing material. SOGP offers renewable resources or recycled material packaging to lessen the usage of petrochemicals, abolish CO_2 emissions, and provide economically feasible light-weight safe packaging (Majid et al., 2018; Pal et al., 2019).

Nanomaterials, fibers, other biopolymers, and their composites are all used for packaging claims (Wang, Euring, et al., 2022). Nanocrystals and nanofibers are the most common forms of bio-based nanomaterials developed so far; both comprise numerous polymer chains, with nanocrystals typically having a diameter in nanometers and a length ranging from nanometers to micrometers. Larger in diameter, natural fibers also include one or more chemical elements. The mechanical strength, barrier qualities, antibacterial activities, and antioxidant roles of biomaterials, as well as their practical uses in food packaging, are explored. However, most people are worried about nanoparticles and other potentially dangerous food additives migrating into the food supply. Although several methods have been used for food packaging, there is widespread worry about the safety of these products, particularly AP and nanotechnology-based packaging methods.

11.6.1.1 Active/intelligent food packaging

Intelligent food packaging systems are compact, simple, and affordable systems that generally ensure food quality by providing good storage conditions. Food is protected and preserved by active and intelligent packaging materials, which protect against microbial and other physicochemical attacks until its utilization. In contrast to conventional materials, this type of packaging consists polymeric materials that contain a variety of additives such as antimicrobials, antioxidants, gas absorbers, and pH indicators to protect it from easy degradation. In this context, few studies have analyzed the efficacy of intelligent, AP in the food sector. Bio-based natural polymers, such as starch, cellulose, hemicellulose, chitosan/chitin, lignin, pectin, alginate, and paper, as well as bio-derived fibers, such as CNFs and CNCs, were investigated to recognize their feasibility in food packaging by using contemporary techniques. Few studies highlighted the practice of chitosan-based hydrogels for this purpose. Active containers for active packages, with antioxidant or antimicrobial components, improve the shelf life of packed items and reduce the formation of food-borne contaminations. Because of the minimal environmental effect, biopolymers are chosen as active materials for single-use packages. Some biopolymers may be generated from agro-industry wastes and their extensive utilization offers a circular economy (Dainelli et al., 2008; Dobrucka & Przekop, 2019).

Chitosan, a biodegradable polymer produced from chitin with antibacterial properties acquired from fishing industry waste, is a clear example. EOs derived from such sources were extensively researched as additives for the creation of AP because of their antioxidant and antibacterial potential status. As a result, using active chemicals obtained from agricultural by-products not only aids their retrieval but also adds value to extracted chemicals. PBS is another polymer used in markets for packaging where biodegradability is more important than oxygen permeability. Waste bags, film wrapping for perishable goods, biodegradable pouches, plates, and silverware are all examples of products that are used in this way. Because of its biodegradability, PBS could be used effectively as mulch film, nets, and trappings in the agricultural and forestry sectors. PBS has promising applications in the healthcare sector as well. PBS is appealing due to its potential usage in numerous weight-bearing medicinal applications, including bone and cartilage restoration. However, the limited adaptability of PBS requires its blending with PLA.

11.6.2 Fertilizer delivery systems as agricultural inputs

Polysaccharide-based materials have received a lot of interest in enhanced efficiency fertilizer research during the last 20 years. These polymers are useful for agricultural applications because of their water solubility, biodegradability, swellability, nontoxicity, and simplicity of modification. The developments in polysaccharide-based enhanced efficiency fertilizers require the choice of superior polymer and relevant comaterials, techniques, and chemical/structure features required for acceptable manufacturing. Chitosan, starch, and alginate are the most often utilized polysaccharides for this purpose, where non-Fickian model best captures its release process, which is based on polymer chain relaxation caused by matrix swelling following nutrient transport. The production and use of controlled-release fertilizers (CRFs) developed from bio-based PU have shown great promise. Physical, chemical, and biological methods can be employed to synthesize polyols from nonpetroleum sources, such as plant and animal oils, starch, lignin, and cellulose. To lessen the environmental impact of plastic mulch film disposal following crop harvest, biodegradable films were established and tested. Because recovered films are often highly polluted with waste, their recyclability is challenging and expensive. The major problem noted is that it is impossible to pick up all the thin mulch and it requires more time and people to do so. Hence, enhanced efficiency fertilizers based on polymers could be constructed with dense structures to minimize direct interaction of the fertilizer with the water source, boosting enricher retaining. Additionally, the grounding processes will govern the material's scale-up (Ortega et al., 2022).

11.6.3 Biomedical applications

Recently, bio-composites are increasingly being used in a variety of biomedical applications, including tissue engineering and wound healing. The advancements in technology have helped to expand the structural and functional features of biodegradable polymers. Biocompatibility, biodegradability, renewability, and reduced antigenicity are some of the benefits that natural polymers provide over the traditional materials used for medical devices.

The creation of biomaterials from biopolymers has led to the development of new materials for tissue engineering and wound healing. The adaptability of biopolymers makes it possible to construct a wide variety of biomedical devices, including scaffolds and wound dressings, that have excellent performance, biomimetic qualities, and some other customized characteristics that provide numerous uses. These new materials are in line with engineering tactics that are based on nanotechnology (Biswas et al., 2021; Moohan et al., 2020). Generally, wound dressings and tissue engineering use the materials that are polymer-based nanofibers. For instance, the biodegradability and low-to-no toxicity of PHA have several potential uses in the medical and pharmaceutical sectors, which include the development of bone plates, sutures, grafts, and other implants. Technological advancements are constant in the pitch of tissue engineering that consider the creation of artificial tissues with physiological functionality. The goal of tissue engineering is to facilitate the rejuvenation of injured tissues through the utilization of a scaffold that serves as a sustenance for the creation of new cells. The importance of research into cell-seeded scaffolds is recognized well today; consequently, innovative resources have resulted in processed biocompatible systems (Balagangadharan et al., 2017).

Scaffolds are biocompatible bio-composites that allow human cells to arrange and raise around the polymer, facilitating rapid integration of tissues. Not only as supporting structures for cells, scaffolds are now being laden with growth-promoting biological substances. Scaffolds, for the regeneration of organs, have been created using organic-inorganic hybrid polymers and nanostructured biomaterials, including nanoparticles and nanocomposites. In tissue engineering, photopolymerized hydrogel scaffolds made of bio-based polymers are utilized in the place of photo-curable 3D printing as a potential substitute for injured tissue. Good emulsification stability, hydrophilicity, lipophilicity, high crystallinity, and exceptional mechanical characteristics are only few of the remarkable qualities of CNC-based composites that are used in cancer therapy to release curcumin gradually. Conversely, bio-based carriers that may be made in different dimensions are used in drug delivery for blood−brain barrier bridging and brain tumor-targeted treatment (Reddy et al., 2021; Van Vlierberghe et al., 2011; Wang, Shi, et al., 2022).

Wound dressing prevents microorganism accumulation and dehydration, and thereby improves healing by releasing bioactive molecules while maintaining epidermal reliability and homeostasis. Additionally, it could promote absolute skin healing with ideal and esthetic effects. Wound healing biomaterials have two basic categories: intrinsic wound therapy materials and therapeutic agent delivery vehicles. Biopolymer-based curative materials can fascinate tissue transudes, minimize wound dryness, permit oxygen to infiltrate the wound, and supply bioactive chemicals. For wound dressing, several novel bio-composite films and hydrogels with regulated active ingredients or drug release are described. The most often used biopolymers for wound dressing are cellulose, alginate, collagen, hyaluronan, fucoidan, chitosan, and carrageen. Because of their antibacterial, water retention, antiinflammatory, proliferative, and other focused activities on certain cells, they play an important part in the healing process. Wound dressings built on such biopolymers offer the properties such as high flexibility, water retention, less expensiveness, and mechanical resistance. Wound dressings made of collagen are available for a wide variety of wound types (Liu & Jia, 2018).

11.6.4 Other applications

Catalysis and industrial wastewater treatment are a few examples of the potential uses for copper nanoparticles. Because these nanoparticles are so effective in killing germs, they have been recommended for their use in treating textiles as well. For medical cleanliness clothes, this feature is highly significant, especially in the context of the COVID-19 pandemic, and could increase the safety of both health workers and patients. In fact, a polymeric chinstrap fabric with Cu and Ag nanoparticles retained its antimicrobial characteristics even after 15 washings. The application of bio-based nanocomposites for the treatment of water through pollutant elimination has also been documented in a few recent publications (Bhatt et al., 2023). To ensure the long-term availability of clean water, this kind of study is of paramount importance. A cobalt ferrite-alginate nanocomposite has been investigated to filter out toxic dyes from water. To remove contaminants from water, bio-composite membranes made of wood and gelatin were made and successfully utilized. In addition, a nanocomposite membrane based on biocide PLA was created by Dasari et al. for use in purifying potable water (Dasari et al., 2012). On the other hand, tannin-based foams may be used as adsorbents for wastewater treatment and as precursors for pyrolysis to produce carbon foams. They can also be used to depollute the extraction of metal ions ($Cu2^{+}$ and $Pb2^{+}$) from wastewater (Sánchez-Martín et al., 2013).

11.7 Future prospective of bio-based polymers

Generally, the bio-based materials have been used in many industries for over a few decades. Bio-based items were not prominent at earlier times because oil was so cheap and producing goods based on it presented so many commercial opportunities. However, several factors such as environmental concerns, technological breakthroughs, and the limited and unpredictable supply of fossil fuels have accelerated the expansion of bio-based polymers today. The advancements in biotechnology have made it possible to create such promising materials from renewable resources. As the debate over fuel vs. food grew more heated, technology began to focus on cellulose-based feedstocks, potentially including trash from solid waste streams and the wood and paper industries. An increasing number of these improvements are already intended to be compatible with many waste streams.

Several unique and ground-breaking uses for biopolymer-based composites and nanocomposites made from biomass have been recognized well. The utilization of agri-food sector wastes for biopolymer production is an overwhelming strategy to assure waste recycling along with sustainable development (Álvarez-Castillo et al., 2021). Bio-based polymers obtained from biomass wastes, such as cellulosic fillers, chitosan, PHAs, starch, proteins, PLA, and essential oils associated with healthy extracts of plants, have good antibacterial properties, which could be suitable for use in high wellbeing applications. Because of the unique characteristics, CNW have a range of specific uses. In the near future, they are expected to be superior in the food packaging, automotive, engineering, and biomedical sectors (Bahar et al., 2012).

Another potential use of biopolymers that cover a wide range is bio-plasticizers. Future bioplastic advances may result in better production efficiency, as well as the discovery of new uses and possibilities for bioplastics. The market for bioplastics will expand in the years to come because of the environmental benefits they provide. Manufacturing bioplastics by using microbial biotechnology is a possibility because of the potential of this technology for widespread use and commercialization in fields such as agriculture, medicine, pharmaceuticals, and veterinary medicine. Therefore, it is important to create a new set of standards and guidelines for bioplastic production, usage, and disposal on a worldwide scale. The product labeling, raw materials use, energy consumption, emissions during production, and probable uses could be done with existing regulations. To extend the longevity of materials and manufacturing processes throughout time, the produced bioplastics must be based on an integrated environmentally friendly strategy (Muneer et al., 2021; Nanda et al., 2022).

11.8 Conclusion

Bio-based polymers are becoming a more competitive alternative to conventional polymers today. Modern technologies and growing public awareness have led to the widespread usage of bio- polymers in several claims ranging from low tech to high tech. This chapter provides a view of current progress in the area of biopolymers and a doorway to a few prospects for the development of a cost-effective and sustainable infrastructure in this field. The introduction of new biopolymers for long-term survival still depends on a number of factors. The utilization of agro-industrial and food wastes is an overwhelming sustainable strategy that has been found to ensure more biomass sources for biopolymer production. Recently, biopolymers have been used for a variety of applications, including packing, fertilizer delivery, waste treatment, and biomedical sectors. However, several factors need to be considered when it comes to the actual use of these bio-based goods. As the need for food conservation and transport rises due to globalization, further research is needed to improve the performance of such materials. Proper biomaterials must be chosen, and their properties ought to be customized further by physical or chemical means rendering to the packing circumstances of the foods for which they are intended for packaging. Bio-plasticizers are a better option to ensure plasticizing properties apart from their degradative nature.

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