Review

Advances in Microbial and Plant Based Biopolymers: Synthesis and Applications in Next-Generation Materials

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Advances in Microbial and Plant Based Biopolymers: Synthesis and Applications in Next-Generation Materials

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Abstract: Biopolymers have made significant strides in recent years, driven by the increasing demand for sustainable alternatives to petroleum-based plastics. They are derived from renewable sources and are biodegradable, making them appealing solutions for addressing plastic waste and reducing environmental impact. In this direction, plant-based (lignin, cellulose) and bacterial (PHA) based biopolymers are gaining significant attention. These biopolymers are highly researched for innovations and technology development due to their demand in sustainable, renewable materials for a wide range of applications. The present review discusses the state of art in plant based and bacterial biopolymers in terms of bioproduction, downstream processing, high-end applications in next generation materials and scope of future applications. The challenges associated with cost of production, processing and scalability are also discussed. This review enables researchers in the bio-based space to visualize a broader perspective of plant based and bacterial biopolymers towards replacing petroleum-based products in a more sustainable and environmentally friendly interventions and envisages a paradigm shift a linear to a circular and bio based economy.

Keywords: Biopolymers; microfabrication; Bioinspired; Biomimetics; self-assembly; re-organization; lignin; cellulose; Copolymers; PHB-PHV

1. Introduction

Excessive use of non-renewable sources of energy and raw materials, and the unlimited generation of waste in the vast majority of industrial processes, have wide impact on the environmental sustainability (Akinsemolu, 2018). Biomaterials have the potential to improve and protect the environment, through the development of biodegradable materials which can reduce the amount of waste generation at a global scale. Biomaterials are designed or engineered to interact with biological systems. The use of biomaterials is becoming increasingly important as it reduces the environmental footprint of industrial products, which are more sustainable and have a lower environmental impact.

The major fraction of biomaterials include biopolymers which are biologically de-rived chain of molecules or structures with specific structural and functional roles in liv-ing organisms. Biopolymers are materials made up of natural polymers like polysaccha-rides (polymeric carbohydrates), polynucleotides (like nucleic acids RNA & DNA), or polypeptides. They comprise extensive polymeric chains formed by the sequential linkage of monomeric subunits, such as amino acids, nucleotides, or monosaccharides, through covalent bonding interactions. These biopolymers are highly bio-degradable and biocompatible making them useful in variety of applications, such as emulsions, edible films, packaging materials in the food industry, and as drug transport materials, medical implants, synthetic organs, wound healing, tissue scaffolds, and dressing materials, smart textiles and fabrics, aerospace research, aviation and flight equipments. Biopolymers, in conjunction with nanoparticles, play a crucial role in cancer treatment, as biopolymer-based nanoparticles serve as highly effective nanocarriers for delivering therapeutic drugs directly to the site of infection. Biopolymers are used in a variety of biomedical applications such as drug delivery (Rebitski 2020), gene delivery (Gheorghit 2021) and tissue engineering. In recent days researchers are more curious to do research on biopolymers like cellulose, lignin, poly-hydroxy alkanoates (PHA), gelatin, chitosan, agarose, pec-tin and alginate. Polysaccharide based biomaterials can be developed from a range of agricultural resources and widely been used in cosmetics, food industries, pharmaceutical and biomedical fields. Polysaccharide-derived biomaterials, including chitin and chitosan, are extracted from fungal origins and crustacean exoskeletons (Troy et al., 2021). Alginates which are obtained from seaweed and it is the most prevalent polysaccharide cellulose (Chudasama et al., 2021). Several polysaccharides show excellent biocompatibility, bio-degradability, stability and they are abundant in nature. Adding functionalities such as conductivity, magnetic properties, bioactivity, water repellence, self-cleaning surface effect, and flame retardance can further improve their competitiveness (Lundahl et al., 2017; Wei et al., 2020). While taking advantage of their nano-scalar dimension, spinning nanocelluloses without solvents provides the possibility of incorporating additives in the filament dope solution while avoiding the use of solvents which are environmentally damaging and highly recalcitrant.

In this review, several plant and bacterial based biopolymers will be discussed along with their futuristic trends and applications in next generation materials. Advances in enhancing the structural and functional capabilities of these biopolymers will be discussed in depth to understand the true potential and state of art in biopolymers research and applications in biomaterials space.

Bacterial Biopolymers

2.1. PHB copolymers

Table 1. Types of PHA polymers.

Chemical name	Abbreviation	Side groups	Structure
Poly(3-hydroxybutyrate)	P3HB	Methyl	Homopolymer
Poly(4-hydroxybutyrate)	P4HB	Hydrogen	Homopolymer
Poly(3-hydroxyvalerate)	P3HV	Ethyl	Homopolymer
Poly(3-hydroxyheptanoate)	P3HHp	Butyl	Homopolymer
Poly(3-hydroxyoctanoate)	P3HO	Pentyl	Homopolymer
Poly(3-hydroxynonanoate)	P3HN	Hexyl	Homopolymer
Poly(3-hydroxydecanoate)	P3HD	Heptyl	Homopolymer
Poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate)	PHBV	Methyl/ ethyl	Copolymer
Poly(3-hydroxybutyrate-*co*-4-hydroxybutyrate)	P3HB4HB	Methyl/ hydrogen	Copolymer
Poly(3-hydroxybutyrate-*co*-3-hydroxyhexanoate)	PHBHHx	Methyl/ propyl	Copolymer
Poly(3-hydroxybutyrate-*co*-3-hydroxyoctanoate)	PHBO	Methyl/ heptyl	Copolymer

Poly(3-hydroxybutyrate-*co*-3-hydroxydecanoate)	PHBD	Methyl/ pentyl	Copolymer
Poly(3-hydroxybutyrate-*co*-3-hydroxypropionate)	PHBP	Methyl	Copolymer

2.2. Bacterial Nanocellulose

Bacterial Nanocellulose (BNC) represents the purest form of cellulose (Ma et al., 2021). BNC is obtained directly from sugars by a bottom-up approach which is extremely useful in pharmaceutical technology. Its crystallinity and degree of polymerization are somewhat inferior to the crystallinity of cellulose polymer produced by plants, since bacterial nanocellulose contains Iα allomorph to a higher extent than cellulose synthesized by plants. Due to these intriguing properties, nanocellulose displays unique potentialities in various fields such as wound dressing, textiles and clothing food, cosmetics, regenerative medicines, tissue engineering, energy, optoelectronics, bioprinting, environmental remediation, etc.

Chemical modifications applied to nanocellulose can also induce additional characteristics such as adhesion, preservation, and antimicrobial properties. The growing demand for textile items is one example of this. Significant volumes of water and chemicals, such as fertilizers and insecticides for growing raw materials like cotton, are needed for everything from the manufacture of raw materials to spinning, weaving, and dying. Downstream, consumers' use also bare a significant environmental footprint from the consumption of water, energy, and chemicals from washing, drying, and ironing For a commercial competitive edge lignocellulose-based materials must possess qualities that are on par with or superior to those found in fossil fuels. An alternative to wood/plant cellulose is bacterial nanocellulose (BNC), a homo-polysaccharide extruded by Gram negative species of the genera *Komagataeibacter*, *Acetobacter*, *Rhizobium*, *Agrobacterium*, *Pseudomonas*, *Salmonella*, *Alcaligenes*, and *Sarcina*, exclusively bacterial species that are Gram-positive (Jonas and Farah, 1998; Dourado et al., 2016b). Different bacteria produce cellulose with distinct morphology, structure, properties, and yields (Wang et al., 2019). *Komagataeibacter xylinus* is one of the highest cellulose-producing species that must be used to get high BNC yields (Dourado et al., 2016b). The symbiotic colony of bacteria and yeast that produces kombucha, a fermented beverage with a cellulose film woven on the culture media air interface, is where the BNC biosynthesis was initially discovered. It was first reported by Brown (1886), who identified a film with a structure chemically equivalent to that of plant cellulose. BNC consists of <100 nm ribbon-shaped fibrils, with 7–8 nm wide nanofibrils randomly aggregated into bundles, without lignin or hemicellulose (Gorgieva and Trcek, 2019).

Chemical structure of BNC is similar to plant cellulose. Linear homopolymer of glucose monomers are linked by beta-(1,4) glycosidic linkage with the chemical formula ($C_6H_{10}O_5$) n. Nevertheless, it has different macro-molecular structure and properties (Ullah et al., 2019). During pulping and purification, the polymerization degrees decrease, falling between 2000 and 6000 for BNC and 13,000 and 14,000 for plant cellulose. Strong intra- and intermolecular hydrogen interactions hold the unbranched cellulose chains together to form the supramolecular structure and elementary fibres (Choi and Shin, 2020; Fang et al., 2020, Picheth et al., 2017). Because of these characteristics, BNC has been used in a wide range of applications across the biomedical field, including wound dressing, tissue regeneration/substitution, drug delivery systems, biosensors, and cancer diagnosis; in the paper and textile industries for fibre composites and coatings; and in the food and cosmetic industries as an emulsifier and viscosifier. The primary use is still as nata de coco, a culinary product that is mostly made and eaten in Asian nations. Because BNC's production costs are typically regarded as quite costly, the scale of production cannot increase to industrial levels. In fact, the price of nata de coco ranges from $50 to $80 USD per kilogram (dry weight equivalent). One major obstacle to the large-scale manufacturing of BNC has been identified as the high cost of the fermentation medium. This can be addressed by employing food industry leftovers as an inexpensive medium, which not only lowers production costs but also aids in resolving waste disposal-related environmental issues (Ul-Islam et al., 2020). Other authors, however, contend that the utilization of food industry leftovers may result in more highly charged wastewaters, which would be more costly to treat, and that the influence of nutrients on the ultimate cost is not particularly significant (Dourado et al., 2016a). The low BNC yield presents still another significant challenge (Zhong, 2020). Additionally, it must be acknowledged that a thorough evaluation of BNC's very large-scale manufacturing capacity has not yet been completed; as a result, its potential as a sustainable substitute for the textile industry cannot now be fully determined.

3. Plant based biopolymers

3.1. Cellulose

The main sources of cellulose are cotton and wood. Furthermore, it can also be acquired from some animal sources. While bacterial cellulose (BC) is made from bacteria and shares chemical similarities with plant cellulose, plant cellulose is still a major component of plant cell walls (Seddiqi et al., 2021). Both configurations of cellulose have great mechanical, physical and biochemical features as well as bio-logical activity, good mechanics and biocompatibility. A common organic substance, cellulose serves as the main structural element of a wide variety of green plants, including cotton, bamboo, some crops, and marine algae. Consisting of linear β-1, 4-linked D-glucose units, it is a straight chain polymer. Because cellulose has a large number of hydroxyl (-OH) active groups, it has a tendency to create strong hydrogen bonds. Six free hydroxyl groups in D-glucose interact to create hydrogen bonds both within and between chains. These cellulose molecules exhibit van der Waals forces between adjacent polymeric chains in plants. Additionally, cellulose has great axial stiffness, stability, and tensile strength (Schutyser et al., 2018). Among the most effective and widely used substrates for sensing devices are cellulose and its derivatives due to their abundance of surface hydroxyl groups, large specific surface area, high aspect ratio, high crystallinity, exceptional mechanical properties, and high thermal resistance (Galletti et al., 2012, Smit et al., 2022).

Several methods, such as high-speed grinding (Haile et al., 2021) and TEM-PO-mediated oxidation (Patil et al., 2020), are employed to obtain CNFs with a remarkable mechanical strength that are 5–100 nm in diameter and a few microns long (Sun et al., 2004). One of the main sources of cellulose is plants. These plant cells consist of multiple cellulose molecule chains which associate with each other, resulting in the formation of linear structures, known as cellulose microfibrils. These cellulose microfibrils have high tensile strength and consist of hemicellulose, para-crystalline cellulose and crystalline cellulose. The cellulose molecule is made of a hydrate glucose linked by beta 1–4 link-ages. Strong acid hydrolysis is carried out to synthesize nanocellulose and bacteria is used to obtain cellulose nanofibers.

Cellulose is the most abundant renewable compound found in the biosphere with an estimated production of 1,012 tonnes annually by photosynthesis (Sundarraj and Ranganathan, 2018). The D-glucose units that make up this unbranched polymer are joined by β (1,4) glycosidic linkages. In relation to its neighbours, each monomer unit in the chain is twisted 180 degrees. A disaccharide called cellobiose is the repeating unit of cellulose (Gardner and Blackwell, 1974). Long homo polymer cellulose chains are created by joining cellobiose molecules. During biosynthesis, van der Waals forces and hydrogen bonds between adjacent cellulose chains encourage the stacking of the chains into elementary fibrils. Numerous elementary fibrils are further packed together to make micro-fibrils, which in turn are bundled to form macro-fibrils or cellulosic fibres. Both ordered (crystalline) and disordered (amorphous) domains make up native cellulose fibres. Its crystallinity can range from 40 to 70% varying on the basis of the source and the extraction procedure. Depending on the cellulose's source and the separation method, the degree of polymerization of native cellulose ranges from 1,500 to 3,500. Natural Cellulose is synthesized in plant cells by an enzymatic transmembrane complex called cellulose synthase (CESA), according to a bottom-up approach (Khan et al., 2022). The enzymatic complex extrudes cellulose chains from the cell wall. Because the chains are extruded in tandem, interchain hydrogen bonds can form simultaneously. The Fibrous domains of native cellulose are crystalline and classified as allomorphs Iαand Iβ (Zhou et al., 2022).

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The plant gains strength and stiffness from the hydroxyl groups on one cellulose chain joining with the other to form stable, stiff molecules. Cellulose is insoluble in water due to hydrogen bonds between its chains (Thomas et al., 2020). When cellulose molecules are joined, fibrils are created. Fibrils then group together to form bundles, which the plant uses to create the cell wall along with lignin and hemicelluloses (Lundahl, 2018). The morphology of cellulose fibrils exhibits a structure like a net. Plant nanocellulose (NC) is generally categorized into cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs) (Amorim et al., 2020). The final chemical and physical properties of NC depend directly on the source and manufacture conditions (Kargarzadeh et al., 2017). High strength and stiffness, low density, biodegradability, high surface area, and low thermal expansion are some of the properties of NCs that have sparked a lot of study and development over the past 20 years. According to Cruz and Tecante (2019), NCs can be made from a variety of raw materials, including coconut husk fiber, mengkuang leaves (*Pandanus tectorius*), cotton, Agave tequilana, barley wastes, tomato peels, garlic straw residues, forest residues, corncob residue, *Gigantochloa scortechinni* bamboo culms, industrial waste cotton, sugar palm fibers (*Arenga pinnata*), corn straw, and sago seed shells. The raw material must be pre-treated by milling, pulping, and bleaching in order to eliminate lignin and hemicellulose. CNCs, also named cellulose whiskers, nanowhiskers, or nanorods, are manufactured by transverse cleavage of cellulose using strong acids such as sulfuric and hydrochloric under defined conditions of temperature, agitation, and time (Clemons, 2016; Charreau et al., 2020). CNCs are distributed at nanoscales, with a diameter of 4–55 and a length of 90–400 nm (Zinge and Kandasubramanian, 2020). Following washing, filtration/centrifugation, and dialysis to remove any leftover acid, CNC is produced following acid hydrolysis (Charreau et al., 2020). Due to higher crystalline structure of CNC, it has less flexibility than CNF (Zinge and Kandasubramanian, 2020). CNC is currently produced in commercial amounts ranging from 2 to 260 tons annually. Mechanical disintegration produces cellulose nanofibers, also known as cellulose nanofibrils or nanofibrillated cellulose (Amorim et al., 2020). CNFs are high aspect ratio cellulose structures with both crystalline and amorphous areas. Although CNF isolation is associated with mechanical destructuring methods (pressure, cavitation, shear, and impact forces), the high energy consumption needed has led to the integration of pre-treatments to facilitate further fibrillation.

Cellulose, as a class of well-known natural biopolymers on the Earth, presents dis-tinctive integrated merits of good biocompatibility and biodegradability, easy processability into diverse material formats, sustainable production in large scale, and as well as intrinsic shape anisotropy, surface charge/chemistry, superior physical and mechanical properties. Over the past few years, wearable and smart cellulose-containing sensors have undergone ongoing innovation due to these special benefits. With the rapid development of fabrication techniques in material processing and progress in research, cellulose has been engineered into multidimensional architectures including 1D (nano-fibers, fibers, and yarns), 2D (paper, films, and fabrics), and 3D (hydrogels, aerogels, foams, and sponges), which are further transformed into electrically conductive car-bonaceous materials with tailorable structures and properties. Cellulose-derived mate-rials have been developed as flexible biosupports or biosubstrates, sensing layers, electrodes and active components for wearable sensors by virtue of their favourable and unique material merits.

3.2. Lignin

Plant ligno-cellulosic biomass is one of the most abundant raw materials and sus-tainable resources in the world, with a production rate of 21011 tons/year. Lignocellu-losic biomass (LCB), a complex heterogeneous mixture comprising carbohydrate polymers, namely cellulose (40–45% w/w) and hemicellulose (25–35% w/w) and lignin (15–30 wt%), includes agricultural residues, energy crops (temperate grasses), and wood residues. Its abundance in nature could potentially solve the problem of the rap-idly depleting resources if it is used as renewable resource or valorized to higher value materials. LCB is by far the largest proportion of the natural material available on terrestrial earth for sustainable production of energy and chemicals. Between 2021 and 2026, the world's demand for biofuels is expected to increase by 41 billion liters, or 28%. They often produce ethanol, diesel, methane, and other fuels in second-generation biofuel plants. By 2022, the Energy Security and Independence Act of 2007 requested that around 80 billion L of second-generation biofuels be produced annually, which translates to about 62 million tons of lignin by-product (Vasile and Bajcan, 2023).

Lignin is synthetized mainly from p-coumaroyl alcohol, coniferyl alcohol, and sinapyl alcohol monomers via an enzyme-initiated dehydrogenation, radical coupling, and dimerization reactions, resulting in an amorphous and three-dimensional (3D) material with both ether and carbon-carbon bonds (Moreno and Sipponen, 2020). Lignin has been mostly used as a source of renewable energy by the pulp and paper industry, where lignin-containing black liquors derived from pulping processes are still largely burned to recover inorganics and energy for the mills. However, as the production of lignin exceeds the demand for its use as a fuel and as interest for renewable chemical has increased, increasing attention is being given to lignin valorisation into new chemicals and materials, since it is by far the most abundant natural source of renewable aromatic molecules on earth. Given the prominence of aromatic functionalities in important chemical sectors such as fragrances, flavors, polymers, coatings, and resins, these areas have all explored the use of lignin. Due to its low toxicity, ecological friendliness, and strong biocompatibility, lignin is being investigated extensively for high-value products rather than burning. Its aromatic qualities also allow it to be used in place of phenol to create phenolic resin adhesives (Bertella and Luterbacher, 2020).

By a variety of methods, including enzymatic hydrolysis, soda, kraft, organosolv, and steam explosion. In accordance with the 2007 U.S. Energy Security and Independence Act, 79 billion liters of second-generation biofuels must be produced by 2022. According to the assumption, one ton of dry biomass can yield 355 L of bioethanol, and 223 million tons of dry biomass are processed annually, producing 62 million tons of lignin (Chauhan, 2020). An organic polymer called lignin has the potential to be imported and used as a raw material in the chemical and biological sciences sectors. With a heating value comparable to carbon, lignin, the second most abundant renewable biopolymer on Earth, is the second-biggest renewable source of carbon and one of the largest natural renewable sources of aromatic structures. Its aromatic compounds have significant biological effects and a variety of unique chemical characteristics. According to some research on the energy requirements of bioethanol plants, lignin has a higher energy content than what is required to produce ethanol; this will always result in an energy surplus that can be utilized for other things, such as external applications or as a raw material for chemicals.

As fundamental monolignols, these three main aromatic motifs are the outcome of lignin decomposition. The deconstruction method and source, as well as various extraction processes, influence their composition and characteristics (Zhou et al., 2022). These three elements are frequently joined by a number of chemical bonds, such as spirodienone and dibenzodioxocin. Softwood, which has a high proportion of guaiacyl lignin (G), hardwood, which has a specific composition of G and syringyl units (S) and a very small amount of *p*-coumaryl alcohol or p-hydroxyphenyl units (H), and herbaceous, which has a higher proportion of G units and a lower proportion of H units, are the three types of wood that can be distinguished by the different numbers of the main lignin units.

Due to its intra- and intermolecular hydrogen bonds, lignin possesses thermoplastic qualities at low temperatures, which makes it valuable for biobased polymers and film materials made from lignin. Its significant crosslinking also makes it a thermoset at high temperatures (T > 200 C). Significant deterioration may occur at high temperatures (Gautam et al., 2024). Thus, due to its high carbon content, low cost, and bio-renewability, lignin has enormous promise for the creation of a wide range of products (Bhakyaraj et al., 2022, Vasile and Bajcan, 2023). Pulp and paper mills, new cellulosic biorefineries, and forestry and agricultural waste are the primary sources of technical lignin. Industrial lignin is mainly obtained as a by-product from the pulp or paper industry and emerging cellulosic bio-refineries, while a cellulosic ethanol plant can generate 100,000–200,000 tons lignin/year (Martínez et al., 2013). Presently, only ~2% of lignin as a by-product is recovered, while 98% is burned for energy or dumped in landfills, this alternative creating a major disposal issue(Kaplan et al., 2022) . Commercial lignin is a by-product of the pulp and paper manufacturing operations. The small fraction of lignin (~2%) is used for manufacturing of vanillin, dispersants, animal feed, cement fillers, carbon fibres, agglomerates, adhesives, renewable materials, etc. Because of its chemical characteristics, lignin and its derivatives can be used to make high-value materials. Furthermore, lignin is a perfect precursor for carbon materials due to its high carbon concentration.

Carbon products produced from lignin are widely employed in a variety of applications, including catalyst carriers, adsorbents, and energy storage. There have been numerous attempts in recent years to transform lignin into highly engineered materials. Actually, lignin is an aromatic biopolymer that has several desirable qualities, including a high carbon content (>60 atoms), high thermal stability, biodegradability, antioxidant activity, UV irradiation absorption, and antibacterial activity. Low molecular weight phenolic molecules can be produced from lignin by cleavage of inter-unit linkages, among which aryl ether linkages (β-O-4′) typically account more than 50% of bonds formed during the polymerization process. Other relevant linkages include resinol (β-β), phenyl coumaran (β-5′), biphenyl (5-5′), diphenyl ether (4- O-5′) and diphenyl methane (β-1), which are significantly more complicated to degrade. The chemical structure of lignin is strongly related to their botanical origin and the isolation process, and recent progress in different analytical techniques have made analysis of the chemical bonds a less daunting task. Thermochemical treatments break down lignin from cellulosic fibres, causing it to depolymerize and become soluble while also forming non-native "condensed" linkages at the reactive locations. The most relevant technical lignin for material applications are lignosulfonates (LS), kraft lignin (KL), organosolv lignin (OSL) and soda lignin (SL). It is important to mention that the selection of the lignin type is strongly related to the application category. For instance, less pure preparations might be readily accessible to lignin-derived plastics or composites whereas highly purified or fractionated lignin should be considered for high-performance materials such as biomedical applications.

Chemical modification of lignin has been postulated as the main alternative to improve its properties for material production. These processes increase the reactivity of lignin by targeting its functional groups such as hydroxyl, methoxyl, carbonyl, and carboxyl groups through chemical modification processes such as hydoxyalkylation, esterification, and amination, among others. Most of these chemical modifications have attempted to convert lignin macromolecules into macromonomers and subsequently graft classical monomers or polymers, and in this way, synthetize lignin-based functional polymers.

The structure of lignin is an aromatic substance with numerous phenolic rings, which makes it challenging to obtain some forms of lignin nanoparticles (LNPs). Many forms of nanosized lignins, including irregular nanoparticles, hollow nanotubes, hollow nanospheres, and nanofibers, are now created after these challenges were resolved. The preparation of lignin-based nanoparticles (LNPs) transforms unordered and complicated lignin materials into ordered nanoparticles with uniform size and morphology and excellent properties such as controlled structures and sizes, better miscibility with polymers, and improved antioxidant activity. LNPs are obtained by different methods, such as self-assembly; solvent exchange; acid precipitation; polymerization; ultrasonication, crosslinking; electro-spinning; and CO_2 use as a non-solvent. In the self-assembly process, an ordered or organized morphology results because of some specific intermolecular non-covalent interactions such as hydrophobic, electrostatic, hydrogen-bonding, and Van der Waals interactions in the absence of any external factor. LNPs are obtained by solvent ex-change following dissolution (in tetrahydrofuran, dioxane, dimethyl sulfoxide, ace-tone, ethanol changed by water); precipitation; ultrasonication; oil-in-water emulsions, which are used for microcapsules (0.3–1.4 m); preparation by ultra-stirring when lignin micro- and nanocapsules are obtained; or by electrospinning of softwood organosolv in the presence of 2 wt % $FeCl_3$. Nanospheres made of hollow lignin with a diameter of about 200 nm were created. Tetrahydrofuran (THF) was used to dissolve the lignin first, and then, under extremely particular circumstances, water was added. An anticancer medication that was loaded into these LNPs was successfully released under carefully monitored circumstances. Compared to many other potential carriers, lignin has superior biocompatibility and lacks cytotoxicity. Before the nanospheres formed, cyclodextrin was grafted onto the lignin to fix the anticancer medication inside the spheres. It is possible to prepare LNP using hydrolysis lignin, kraft/alkali lignin, lignosulfonate, enzymatic hydrolysis lignin, and organosolv lignin. The -Cyclodextrin-modified LHNPs exhibited a good sustained-release (SR) capability for the antitumor hydroxycamptothecin (HCPT) drug.

4. Physicochemical properties

4.1. PHB

Natural origin Polyhydroxy butyrate (PHB) has three forms: high-molar mass PHB, low-molar mass PHB, and short-chain OHB (oligo-hydroxybutyrate). The PHB repeat unit's molecular weight (Mw) is 86.09 gmol^{-1}, with Mw values exhibiting significant variability based on feedstock, growth circumstances, and extraction methods (Briassoulis et al., 2021). PHB is characterized by optical activity, piezoelectric properties, and effective barriers against hydrophobic compounds and water vapour, contingent upon its degree of crystallinity (Xc) (Etxabide et al., 2022). The exceptional oxygen barrier qualities have garnered significant interest for food packaging applications. PHAs and related composites, such as PHB and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), have excellent gas barrier qualities, making them appropriate for films and coated paper applications. They also possess elevated water vapor permeability, which is ideal for EMAP packaging of fresh food (Keskin et al., 2017). The crystallinity of PHB influences its physical and mechanical properties, resulting in poor ductility and restricted processing capabilities. The use of pure PHB is constrained by its intrinsic brittleness, rendering it excessively fragile for most practical uses. The copolymerization of PHB with structural segments of specific natural PHAs can reduce its crystallinity and enhance its mechanical characteristics. Nonetheless, the PHBV polymer retains the brittleness characteristic of PHB (Yeo et al., 2018). PHB exhibits thermal instability, leading to a reduction in molar mass and viscosity during processing. The melting point (Tm) of PHB ranges from 173 °C to 180 °C, whereas the glass transition temperature (Tg) is roughly 5 °C. The principal thermal degradation mechanism involves chain cleavage at high temperatures, significantly decreasing Mw (Abdelwahab et al., 2012).

Poly(3-hydroxybutyrate) (P3HB) is a highly crystalline polymer characterized by a linear chain structure, comprising both amorphous and crystalline phases. It is a prominent alternative to synthetic polypropylene (PP) and polyethylene (PE). P3(HB) is generated via bacterial fermentation and offers advantages over synthetic polymers for packaging applications, including enhanced barrier permeability, stiffness, and biodegradability. It exhibits greater resistance to deterioration in biologically active conditions such as soil, waters, aerobic and anaerobic composting (Alves et al., 2017). P3(HB) is defined by a methyl functional group (CH_3) and an ester linkage group (−COOR), which provides thermoplasticity, hydrophobicity, high crystallinity, and brittleness. The thermal characteristics of PHB and its derivatives encompass two primary temperatures: the glass transition temperature (Tg) for the amorphous phase and the melting temperature (Tm) for the crystalline phase. The degradation temperature (Td) is the temperature at which the material deteriorates (Djouonkep et al., 2022). Differential Scanning Calorimetry (DSC) and X-Ray Diffraction (XRD) are analytical techniques employed to ascertain the Tm, Tg, and Td of PHB. However, FTIR analysis is a prevalent analytical method for elucidating the molecular structure of materials and assessing their purification degree. P3(HB) has been evaluated against PP, polyethylene terephthalate (PET), PE, and polylactic acid (PLA) for mechanical characteristics (Cavalcante et al., 2017).

Crystallinity is an essential attribute of polymer materials, influencing their mechanical characteristics. P3(HB) has a crystallinity value beyond 50%, often ranging from 60% to 70%. Increased crystallinity yields a stiffer, stronger, and more brittle material. It also affects tacticity, hardness, modulus, density, transparency, and the characteristics of cold drawing or ductile flows (Fernandez-Ronco et al., 2017). P3(HB) materials encounter difficulties due to their limited processability window, particularly the disparity between the melting temperature (Tm) and the degradation temperature (Td), rendering them vulnerable to thermal deterioration at temperatures close to the melting point. Numerous methodologies have been assessed to enhance processability, including the alteration of monomer ratios utilized in polymerization. Adding extra units of 3 HV enhances impact strength while concurrently diminishing tensile strength and modulus. P4(HB) is a novel substance produced via condensation processes of 4-hydroxybutyric acid (4HB) or through ring-opening polymerization (ROP) of γ-lactone. The materials are non-toxic, biocompatible, optically active, stable under UV radiation, and may be treated by extrusion, injection molding, blowing, and thermoforming. They are appropriate for application in the biomedical sector inside medical devices owing to their non-toxic and biocompatible characteristics (McAdam et al., 2022).

4.1. Lignin

Lignin, a natural substance exhibiting a colorless or pale-yellow hue, can undergo color alteration when subjected to acid or alkali treatment. The molecular weights of separated lignin vary from 1000 to 20,000 g/mol; however, estimating the degree of polymerization is challenging due to fragmentation occurring during extraction. Heating lignin to temperatures of around 150-160°C enhances its molecular weight. The Tg (total grain size) is a crucial statistic that quantifies the extent of the rubbery zone in a material and serves as an indirect indicator of crosslinking and crystallinity (Andrianova et al., 2018). Lignin possesses degradable characteristics, with hydrogenation and oxidation being the two predominant methods employed for its degradation. It possesses several other attributes, including elevated thermal stability, antioxidant capabilities, biodegradability, antibacterial properties, adhesive characteristics, dust dispersal, and blending qualities. Lignin exhibits capabilities as an additive, dust dispersion, and blending agent (Lizundia et al., 2021).

4.1. Cellulose

Cellulose, which is the primary component of plant cell walls, is the natural substance that is found in the greatest abundance. Depending on the species of plant, native plant cellulose is a fi-D-(1-4) glucan that contains between one thousand and eight thousand polymerized glucose units. A common chain length range for cellulose fibers separated from wood pulp is between 500 and 2000 glucose units (Hallac, 2011). The ability of cellulose to be replaced with bigger groups, such as nitrate or acetate, has been a significant factor in the creation of commercial plastics. This substitution has allowed for a reduction in the intermolecular interactions and an increase in the solubility of the plastic. There is also the possibility of processing cellulose by means of solubilization, which involves derivatization and the subsequent removal of modifying groups. This process ultimately results in the manufacture of rayon fibers and cellophane. Compostable polymers that are appropriate for use in a variety of molding processes within the plastic industry have recently been described. These thermoplastics are manufactured from 10070 cellulose-based resins (Vasile & Cazacu, 2013).

5. Methods of Synthesis/Extraction/fabrication

5.1. PHB extraction

Solvent extraction, chemical digestion using surfactants, and enzymatic digestion are used to extract PHB from microorganisms to make bioplastics. Some PHB processes are pure yet ecologically harmful in large-scale use (Gautam et al., 2024). Chemical digestion surfactants like SDS break down cell membranes, allowing PHB to enter the lysis solution. However, these methods have limitations, such as high costs and complicated recoveries (Raza et al., 2018). Bioextraction delivers revolutionary PHB extraction methods from producer cells that eliminate the need for environmentally damaging agents, reduce the usage of unacceptable chemicals, and save money. Strategic development of green technology solutions for the extraction of ultrapure PHB with environmentally friendly properties requires a thorough understanding of bioextraction processes. Bacteriophage-related, predatory, and mealworm digestive bioextraction systems are receiving interest for their self-disruption and predatory digesting extraction capabilities. Phage lysis, a new PHB extraction process, occurs during cell wall disintegration by lytic-phage infection and is eco-friendly and cost-effective. Holin,

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endolysin, late transcription factors, and a tandem are essential to the lytic apparatus. The breaking of the cell wall by lytic-phage infection causes cell lysis, allowing bacterial biomass extraction (Wang et al., 2019). Martínez et al. (2011) created KT2440, a stable *P. putida* strain, to modulate the expression of EJ-1 phage-derived extrinsic holin-endolysin system genes. The pCNBHL, made from *xylS/pm* and *ejh/ejl* cassettes, is frequently used for gene and gene cluster expression, recombinant protein synthesis, and reporter gene expression in gram-negative and gram-positive bacteria. *P. putida* BXHL with a *tolB/pal* mutation produced inducible self-disruptive genes to increase PHB production. This strain regulates genetically designed cell death and releases PHB while having less environmental and economic drawbacks than the wild type.

(Hand et al. 2016) showed that bioextraction of PHB from *Pseudomonas oleovorans* using lytic bacteriophage Ke14 as a cell disruptor is successful. However, hydrophobic interactions between carbonosomes and cellular debris in water do not completely release PHB. Removal of PHB depolymerase from the host cell is essential to store PHB securely. Even during exponential development in *P. oleovorans*, less than 20% further accumulation may occur. Using an inexpensive cell wall self-disruption mechanism and cheap raw materials like crude glycerol, bacteriophage-mediated lysis can cut production costs. *Pseudomonas putida* produces protein-based hydrocarbons (PHB) and internal or extracellular PHB depolymerase breakdown, providing carbon and energy for metabolic activities. *Bdellovibrio bacteriovorus* (*B. bacteriovorus*) is isolated and cultured to get amino acids and macromolecules for protein synthesis (Kaplan et al., 2022).

To improve progeny and nutrition, *B. bacteriovorus* can prey on *P. putida*. PHB consumers have *B. bacteriovorus*, which possesses the *phaZBd* gene that encodes an extracellular PHA depolymerase to degrade and release PHA. The upshot is rapid development, predatory effectiveness, and mobility (Martínez et al., 2013). A novel predator strain extracted PHB better than earlier strains, resulting in high-quality biopolymer recovery during predator-mediated lysis. PHA biopolymers accumulated in *phaZ* knockout mutants due to a large metabolic reduction in PHB depolymerization. Metabolic engineering can produce more biopolymers in obligate predation systems. The *phaZ* mutants have a low polydispersity index (PDI), suggesting they might be used in industrial production and extraction operations (Cai et al., 2009). PHB recovery was increased in rats with lyophilized *C. necator* H16, but the growth rate decreased over one month, indicating kidney stone implications. The ideal digestive host for PHB-producing cells can help remove faeces biologically. Mealworm larvae may be biologically extracted with 89% purity using SDS. Due to its environmental drawbacks, this approach is ideal for low-chemical PHA production (Kunasundari et al., 2013).

The ecologically sustainable enzyme digestion method for PHB recovery uses moderate operating conditions. However, proteolytic enzymes, including proteases and glycosidases, have been investigated for higher purity, affordability, and specific action without environmental impacts. Lytic bacteriophages, predatory bacteria, and mealworms induce cell lysis, a green biotechnology technique that lowers production costs and environmental effects (Zhang et al., 2024).

Although economic and environmental factors are important, traditional methods are used in many applications. PHB is gathered as a carbon source contained in proteins needed for synthesis and depolymerization. Biotechnological technologies reduce production costs and resolve environmental challenges using solvents and chemical additives. Biotechnological enzymatic proteins destroy cell walls for PHB extraction (Bhakyaraj et al., 2022).

5.2. Cellulose Extraction

Cellulose can be directly extracted from wood. Industries have been using wood as it is the most renowned source of cellulose. However, cellulose needs to be purified from other components of wood i.e., lignin and hemicellulose. To purify cellulose, extraction of these other components is necessary. Extracting lignin and hemicellulose from plant tissue involves several steps. First, the dried plant tissue is digested at 80°C in a 4% sodium hydroxide solution for 4 hours to eliminate most of the lignin and a significant portion of hemicellulose. The product is then bleached using sodium chlorite and glacial acetic acid to remove any remaining lignin and hemicellulose. The bleached cellulose fibers undergo multiple washes to achieve a neutral pH (Radotić & Mićić, 2016). The process of isolating cellulose by ultrasonic treatment involves a sequential application of water at 55°C for 2 hours, followed by ultrasonic irradiation for 40 minutes. The material is then treated with 0.5 M NaOH, followed by 0.5 %, 1.0 %, 1.5 %, 2.0 %, and 3.0 % H2O2 in 0.5 M NaOH, and 2 M NaOH at 55°C for 2 hours. The insoluble residue is obtained using filtration, rinsed with distilled water until the filtrate reaches neutral pH, and dried at 60°C. Isolated cellulose fibers can be transformed into nanofibers using mechanical, chemical, physical, and biological processing techniques. The procedure selection depends on the nanofibers' desired final dimensions (Sun et al., 2004).

Enzymatic technology is used to isolate cellulose by selective hydrolysis of various components within the plant fiber (hemicelluloses, lignin) while preserving the cellulosic fraction. This process includes bioremediation, cryocrushing, and dilute acid pretreatment. Air-dried botanical material is processed using a Wiley mill, pre-soaked in a 1% dilute sulfuric acid solution at 5% dry solids for 4 hours, filtered, and rinsed with excess deionized water. The pretreated material is transferred to a 4560 mini-Parr 300 ml pressure reactor, heated to 160°C over 30 minutes, and maintained at 160°C for designated residence times. The pretreated slurry is further filtered, rinsed with an excess of deionized water, and dried overnight at ambient temperature (Chen et al., 2012). The yields for biomass obtained post-pretreatment vary from 75% to 85% by mass of the original material. However, the removal of hemicellulose and hydrothermal conditions can lead to cellulose annealing, potentially enhancing crystallinity and reducing the efficacy of this pretreatment approach (Bhutto et al., 2017).

5.3. Lignin extraction

Chemical treatment methods that break down lignin-carbohydrates complexes enable the industrially recovered lignin from cellulose fibers. Partial depolymerization of the complex lignin macromolecules occurs throughout this process to produce smaller fractions that improve solubility. Many reactive sites help to re-polymerize (condensation) inside the matrix, strengthening C–C linkages and altering the origi-nally used lignin structure (Patil et al., 2020). The diversity in feedstock and extraction techniques produces isolated lignin with different structures and a spectrum of physical properties. Currently, biorefineries and the paper pulping sector help enable com-mercial technological lignin production. The pulp and paper sector produces around 50 million metric tons of lignin, most of which is used as fuel for generating electricity to run the paper mills. Just 2% of the whole quantity finds use in the chemicals indus-try. Many excellent assessments incorporate methods of lignin extraction (Haile et al., 2021). The radical polymerization of lignin may be complicated by covalently linked reactive components to hemicelluloses, generating a lignin-carbohydrate complex (LCC) (Balakshin et al., 2014). Thus, lignin must be partially depolymerized to increase extractability and LCC linkages must be broken to separate it from carbohydrates. To increase biomass solubilization, depolymerization breaks down lignin into smaller pieces. As lignin and its fractions are very reactive, repolymerization (condensation) activities form new C-C bonds during extraction, resulting in distinct lignin intermediates with variable characteristics (Schutyser et al., 2018).

Biorefineries employ biomass as a renewable resource to make chemicals and fuel. Therefore, optimal utilization of all lignocellulose components—cellulose, hemicellulose, and lignin is crucial. Before selective conversion, lignocellulose components must be separated or isolated due to their varied physical and chemical characteristics. Lignin, hemicellulose, and cellulose are removed from biomass during pretreatment or fractionation (Galletti & Antonetti, 2012). Biorefining begins with biomass pretreatment to minimize recalcitrance for valorizing. Solvolysis fractionation, reductive or oxidative catalytic fractionation, acid hydrolysis, and alkaline hydrolysis are biomass pretreatment methods. Delignification efficiency, purity, and structure might vary even on the same biomass feedstock depending on the fractionation method and intensity (Smit et al., 2022).

6. Next Generation materials

Among other things, its regenerated forms have been applied as a coating for water or air filtration, electrical insulation, packaging, and building and transportation components. The production of paper and various cellulose products and derivatives is the primary industry associated with cellulose's technological significance (Aziz et al., 2022). In response to emerging material constraints, industry and academic research has begun to concentrate on turning cellulose into biofuels or other high-value goods. Cellulose, as a class of well-known natural biopolymers on the Earth, presents distinctive integrated merits of good biocompatibility and biodegradability, easy process ability into diverse material formats, sustainable production in large scale, and as well as intrinsic shape anisotropy, surface charge/chemistry, superior physical and mechanical properties.

Over the past few years, wearable and smart cellulose-containing sensors have undergone ongoing innovation due to these special benefits. With the rapid development of fabrication techniques in material processing and progress in research, cellulose has been engineered into multidimensional architectures. Cellulose-derived materials have been developed as flexible bio supports or bio substrates, sensing layers, electrodes and active components for wearable sensors by virtue of their favourable and unique material merited into electrically conductive carbonaceous materials with tailorable structures and properties. A number of nanocelluloses (NC) derived from plants and microorganisms have been investigated as potential textile fibre sources in recent years. The main reason for interest in NCs is to benefit from their increased crystallinity, which fosters excellent mechanical resistance (Nunes, 2014). NC is a family of materials with very varied properties, primarily because of their various sources and methods of synthesis, rather than a single material type. A promising alternative to petroleum-based polymers, which are hard to break down, for paper and textile coatings is nanocellulose (Chowdhury et al., 2021), which is the nanometric fibrillar form of natural cellulose. Nanocellulose in the form of rods or fibres, has attracted the interest of different industries, the scientific community and policy makers. This recent interest is justified by its appealing features such as high tensile modulus, high specific surface area, and sustainability (Wang et al., 2017). Furthermore, nano-cellulose is commonly considered non-toxic (Long et al., 2022), biocompatible (Kaur et al., 2021), and biodegradable. Nanocellulose has special potential for covering paper (Chen et al., 2023). It can form a strong hydrogen bond with paper fibres due to the presence of several surface hydroxyl groups, improving the paper's mechanical, barrier, and hydrophobic qualities. Similar Relevant Effects Are also expected the textile coating Nanofiber extraction from native cellulose can be achieved by mechanical, chemical, or combined mechanochemical chemical top-down approaches.

Lignin-based hydrogels are stimuli-responsive lignin polymers that have potential for tissue engineering and drug delivery applications. Their porous structure shares similarities with the biological extracellular matrix, and the stimuli-dependent swellability in water plays and important role for drug delivery applications. By grafting temperature-sensitive monomers into a lignin core, thermo-responsive lignin-based hydrogels have been synthetized for phase transitions at close to body temperatures. The presence of phenolic OH groups in the lignin backbone, which can crosslink with COOH groups of the co-joining monomer, is a crucial need for lignin in the synthesis of hydrogels. Kraft lignin has the highest concentration of phenolic OH groups, followed by soda lignin and organosolv. Soda lignin-based hydrogel has better mechanical qualities because it has stronger crosslinks, which make it more elastic. Organosolv-based hydrogel may be the best choice, while superior mechanical properties will necessitate the use of soda lignin-based hydrogels. Moreover, lignin is in its in-fancy as strength modifier, adhesive agents, or other functional fillers in hydrogels for lignin fractionation, wearable electronics, UV shielding, and biomaterials fabricated a lignin-contained cellulose hydrogel for lignin fractionation.

7. Applications in Next Generation materials

Cellulose is a versatile substance that has also become a next-generation material of interest. Over the past 15 years, nanoparticles have attracted much interest. Researchers have paid great interest in cellulose nanoparticles. Its uses were remarkable when combined with other molecules;

these included sustainable ecosystems, bioremediation, and medicine. The upcoming studies deal with the efficient application of cellulose. Because of their great mechanical strength, hydrophilicity, and outstanding bio-compatibility, cellulose nanofibers (CNF) show great promise for use in tissue engineering. Several methods may be used to create these scaffolds: electrospinning, freeze-drying, 3D printing, solvent casting. Among the several tissue engineering uses for them are cutaneous, vascular, neurological, muscular, hepatic, and ophthalmological tissue repair (Lamm et al., 2021). Nanocellulose creates structures that define an optimal environment for cellular adhesion, proliferation, and metabolism when coupled with PVA, GelMa, collagen, gelatin, and chitosan. Tensile strength, elastic modulus, indentation modulus, biocompatibility of scaffolds used for vascular tissue engineering are improved by CNC and CNF on fibre form. Nanocellulose scaffolds help neural cells develop in neural tissue engineering, therefore conserving the axon channel and promoting neural stimulation and activity (Tamo, 2024). Because of its high surface-to-volume ratio, which can encourage cell growth, migration, and adhesion, nanocellulose has been investigated for use as wound dressings The increased density of -OH groups on the nanocellulose surface creates a wet layer over wounds, therefore preventing microbial biofilms, washing injured tissues, reducing pain, and controlling odours. Bioactive wound dressings that prevent bacterial colonization have been produced using nanocellulose in concert with antibiotic treatments (Yuan et al., 2022).

Easy transformation of cellulose nanofibers into suspensions serving as carriers for pharmaceutical drugs is possible. Cellulose nanofibers (CNFs) have been used as a film for the fast release of poorly soluble drugs and as a matrix for continuous drug delivery. Further studies on the viability of drug delivery have looked at using BNC-acrylic acid (AA) hydrogels for this aim. For drug delivery, cellulose nanofibers (CNF) have been reported; some studies show slow discharge rates over time and others fast discharge rates inside the CNF network. Whereas beclomethasone dipropionate and itraconazole were delivered more slowly over a period of 90 days, indomethacin was released within 15 to 30 days (Khan et al., 2022). Comprising nanocellulose, cellulose derivatives, and cellulose-based composites, cellulose-based nanogenerators hold promise in improving the output performance of cellulose and tackling environ-mental pollution problems related with the non-biodegradability of conventional polymers. From an environmental standpoint, water's heavy metal recycling and detection are absolutely vital (Zhou et al., 2022)

Cellulose coated with gold Qatarized capillaries (Au-QC), enabled high-resolution protein separation by electrophoresis. The Au-QC coating has been successfully sepa-rated in glycoproteins and detected lysozyme in milk and tear samples, providing a new method for detecting lysozyme from various sources (Aziz et al., 2022). Turyanska et al. regenerated cellulose in AuNPs' aqueous dispersions, and AuNP networks were formed on cellulose sheets. The resistivity of composite films determines the mode of electrical conduction; low temperatures and high magnetic fields show negative magnetoresistance. AuNPs have been efficiently applied in hybrid films to enable technological gadgets and biological sensors. Brightness threefold greater than that of bacterial cellulose sheets, SiO2-cellulose paper with Au anodes produces a green substrate for flexible top-emission organic light-emitting diodes (TE-OLEDs) (Min et al., 2013).

In addition to having antibacterial capabilities and being non-cytotoxic in nature, hydrogels that are produced from lignin exhibit increased mechanical strength and stiffness. There has been research conducted on the potential of lignin-PLA composites as wound dressings. The results of this research have shown that these composites have enhanced wettability and lower fracture resistance. In vivo, it has been demonstrated that hydrogels that are biocompatible and composed of chitosan and alkali lignin are not harmful to mesenchymal stem cells and zebrafish at concentrations that approach 100 µg/mL (Wang et al., 2024). Hydrogels have been synthesized based on lignin with concentrations ranging from 24 to 40%, and these hydrogels have demonstrated water absorption capabilities of up to 500 percent. Because of its hydrophobic qualities, lignin could assist the incorporation of a hydrophobic drug model (curcumin), and it also gave a large amount of resistance to cell adhesion by bacteria (Lin et al., 2022). Lignin was mixed with microcrystalline cellulose and examined as an excipient in immediately compressed tetracycline tablets. This demonstrated the potential of lignin

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as an excipient in the pharmaceutical industry (Domínguez-Robles et al., 2019). Applications for the biodegradable polymer lignin, which is derived from wood, have been discovered in the field of radiative cooling technologies. When exposed to direct sun irradiation, a polymer film that had been improved with lignin demonstrated a cooling capacity of 77 W/m^2, resulting in the surface temperature reaching a level of 3.7°C lower than the ambient temperature, which was the surrounding temperature. A reduction of three degrees Celsius in the operating temperature was achieved by the incorporation of this structure into a solar cell. Additionally, the solar cell demonstrated a significant increase in absolute efficiency of 45% when compared to the reference cell when operating under the AM1.5G solar spectrum (Chowdhury, 2021).

An extraction of lignin from the residual biomass of sugarcane bagasse was carried out. Subsequently, chemical changes were made in order to produce a cationic surfactant. The inclusion of nano-clay into a polystyrene co-butyl acrylate latex matrix was proven to be facilitated by this surfactant, which indicated its potential to facilitate the process. The addition of lignin into this nanocomposite resulted in a significant improvement in its resistance to increasing amounts of ultraviolet light. As a result, these polymers are ideal for use in interplanetary environments, such as possible settlements on Mars (Wang et al., 2017). A melt extrusion technique known as fused deposition modeling (FDM), more generally known as 3D printing, is a technique that is utilized to produce three-dimensional structures. This technique involves the utilization of a nozzle that methodically deposits layers of thermoplastic polymer, adhering to a particular design. Acrylonitrile butadiene styrene, also known as ABS, is the thermoplastic that is most commonly used in three-dimensional printing. ABS is con-structed from petroleum-based materials. An amorphous polymer was produced due to the replacement of forty percent of the ABS with organosolv lignin. Despite this, the incorporation of 10% acrylonitrile butadiene rubber mitigated the adverse effects of lignin, resulting in a polymer that exhibited a fivefold increase in tensile strength and was appropriate for 3D printing (Long et al., 2022).

8. Challenges and limitations

Widespread adoption of biomass-derived lignin and cellulose biopolymers is hindered by common factors like intricate structure of lignocellulosic biomass, which makes it challenging to separate pure lignin and cellulose; the requirement for effective and sustainable pretreatment techniques to degrade the lignocellulose matrix; high production costs as a result of energy-intensive extraction procedures; and the variability of quality based on the biomass feedstock. Biomass requires pretreatment procedures, such as chemical or enzymatic operations, to break down lignin and hemicellulose in order to yield cellulose. These procedures can be energy-intensive and produce potentially hazardous byproducts. Because the cellulose concentration and composition of various biomass sources fluctuate, it might be challenging to optimize extraction procedures for constant quality. Pretreatment of biomass, lignin and cellulose extraction, and purification are multi-step processes that can be costly. While cellulose is highly crystalline, insoluble in water, non-reactive by its structural and molecular nature, lignin is highly reactive, toxic to environment and complex in structure and closely binded with cellulose and hemi cellulose. These challenges can be widely addressed using organic chemistry interventions like natural deep eutectic solvents (NADES) but have limited to research phase.

Solutions for lignocellulosic biopolymers can be developed by creating more sustainable and effective pretreatment techniques: studies on biological, ionic, and mild chemical treatments that enhance cellulose extraction while reducing environmental impact. modifying enzyme mixtures to efficiently break down cellulose derived from various biomass sources. Biorefinery based integrated processes to increase product yield and reduce energy use and produce more value from by product streams.

Currently, PHA manufacture is more costly than that of conventional plastics like polyethylene or polypropylene. This is mostly because the energy-intensive fermentation processes needed to synthesize them and the high cost of the raw ingredients (such as sugars, oils, or organic waste) are the main causes. PHA must be produced at a lower cost in order to compete with polymers derived from petroleum. Although PHAs are biodegradable, the characteristics of the final polymer greatly vary depending on the kind of PHA that is generated (e.g., PHA copolymers vs. homopolymers). Applications are limited by the brittleness and poor mechanical qualities of some PHA forms, such as polyhydroxybutyrate (PHB). One of the main challenges is creating PHA variations with improved performance attributes (such as strength, flexibility, and thermal stability). These challenges in biopolymers space has a wider scope for development of bio-based innovations at the interface of science, chemistry and engineering for enabling commercial deployment.

9. Conclusion and Future Perspectives

io-based polymers have a promising future, but there are still several obstacles to be addressed. To compete with well-established plastics derived from fossil fuels that control global markets, bio-based polymers need to get over obstacles related to cost and performance. Although bio-based polymers are more environmentally friendly than their petroleum-based equivalents, it is still important to carefully consider their entire environmental impact, taking into account resource usage, energy consumption, and changes in land use for feedstock production, to prevent unforeseen consequences. Developing infrastructure for proper disposal and recycling, as well as increasing consumer awareness and acceptance, is essential for bio-based polymers to truly replace traditional plastics. As they become increasingly scalable, adaptable, and economically viable, bio-based polymers have a bright future. With advancements in production technology, the use of sustainable feedstocks, and growing consumer demand for eco-friendly alternatives, they could play a vital role in reducing plastic pollution and driving the transition toward a more sustainable and circular economy. However, sustained innovation and cross-sector collaboration will be crucial to unlocking their full potential.

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