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Review

Application of Biopolymers as Sustainable Cladding Materials: A Review

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Abstract: The application of biopolymer materials in cladding presents a promising avenue for enhancing building sustainability, while addressing the limitations of conventional synthetic polymers. Cladding serves a dual purpose of protection and aesthetics for buildings, but increasing global energy consumption and environmental concerns necessitate the adoption of sustainable practices. The construction sector's substantial energy usage and greenhouse gas emissions highlight the urgent need for sustainable building materials. Conventional cladding materials often lack sustainability and environmental compatibility. Biopolymers, derived from living organisms or by-products, offer a potential solution with their biodegradability, renewability, and low embodied energy. These materials can revolutionise cladding practices by providing eco-friendly alternatives aligned with sustainable construction demands. Integrating biopolymers with synthetic polymers can enhance material biodegradability, contributing to overall degradation. Prominent biopolymers like PLA, PHAs, starch-based polymers, cellulose, PHB, and PBS exhibit biodegradability and sustainability, positioning them in the front rank for cladding applications. Despite significant research in biopolymer applications in different fields, there is limited research to identify the application and limitations of biopolymers as building cladding materials. This review paper aims to bridge the research gaps by comprehensively analysing diverse biopolymer cladding materials based on their properties and exploring their cross-domain utility, thereby highlighting their transformative role in sustainable construction practices. The expanding biopolymer market in building cladding materials underscores their potential to drive innovation, with projected growth emphasising their importance.

Keywords: biopolymer; sustainability; cladding materials; manufacturing methods; thermal properties

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1. Introduction

Cladding is used as the outer layer in high-rise buildings to protect the building from weather conditions and enhance its visual appeal. Its primary function is to shield structures from environmental factors such as radiant sunlight and moisture, thereby preserving their structural integrity [1,2]. However, escalating global energy consumption and environmental challenges have brought the necessity for energy efficiency in buildings to the forefront of architectural considerations [3]. With the construction sector accounting for more than 40% of worldwide energy usage and a significant contribution to greenhouse gas emissions, adopting sustainable building practices has never been more urgent [4]. The conventional array of cladding materials, encompassing metals, concrete, glass, plastics, and composites, has effectively provided protection; however, these materials often fall short in terms of sustainability and ecological impact [5]. While conventional synthetic polymer-based cladding materials have been widely used, their production from fossil fuels raises concerns about environmental sustainability, including greenhouse gas emissions and waste generation [6].

Conventional cladding materials are not sustainable. Polymer-based cladding materials are derived from non-renewable fossil fuels, which contribute to greenhouse gas

emissions and global warming. They are also not eco-friendly, so they will persist in landfills and the environment for a long time, which is a threat to the environment. Additionally, they release toxic and harmful gases when on fire. Conventional cladding materials are also difficult to recycle, releasing harmful chemicals during disposal [7]. As the world seeks pathways toward a more sustainable future, the emergence of biopolymer-based materials offers a promising avenue for transforming the cladding landscape (Figure 1) [3–5].

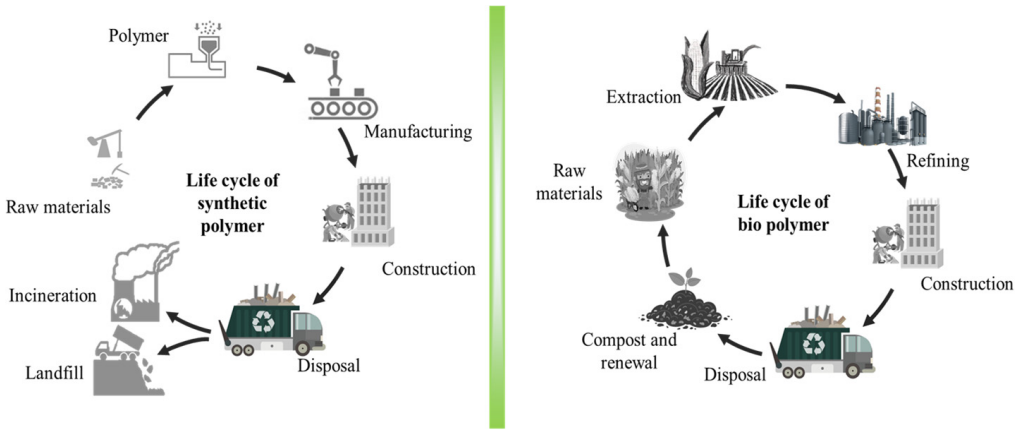

Figure 1. Life cycle of synthetic polymer and biopolymer.

Biopolymers, derived from living organisms or their by-products, have garnered significant attention as a potential solution to the limitations of conventional synthetic polymers. These materials, including starch [8], cellulose [9], chitin [10], proteins [11], and lignin [12], exhibit attractive ecological attributes such as biodegradability, renewability, carbon sequestration potential, and notably low embodied energy requirements [1]. As such, biopolymer-based materials hold the potential to revolutionise cladding practices by providing environmentally friendly alternatives that align with the growing demand for sustainable construction materials [13] (Figure 2). Moreover, the integration of biopolymers into synthetic polymers can offer pathways to enhancing the biodegradability of materials. By blending synthetic polymers with biopolymer constituents like starches or infusing bioactive agents, the resulting composite materials facilitate the breakdown of the polymers into smaller components, contributing to the overall degradation process. Recently, biopolymers, like polylactic acid (PLA) [14], polyhydroxyalkanoates (PHAs) [15], starch-based polymers [16], cellulose [17], polyhydroxybutyrate (PHB) [18], and polybutylene succinate (PBS) [19], attract more attention in the biopolymer research field due to their biodegradable, waste disposal-friendly, and ecologically sustainable properties. However, most of the study mainly focused on packaging materials but rarely on building cladding products [20]. The intrinsic eco-friendly nature of biopolymer-based materials positions them not only as suitable for packaging material applications but also as sustainable cladding materials for future building uses.

As the global biopolymer market expands continuously, there is a notable shift toward recognising their advantages over conventional polymers. This trend is evident in the market's projected growth, with estimates indicating a rise from USD 13.7 billion in 2021 to a forecasted USD 35.25 billion by 2030, boasting a significant compound annual growth rate (CAGR) of 11.07% [17,18]. This growth trajectory emphasises the increasing recognition of biopolymer materials as a critical driver of innovation in the construction industry and beyond. While research exploring the potential of biopolymer-based materials in cladding applications is ongoing, a research gap exists in the literature.

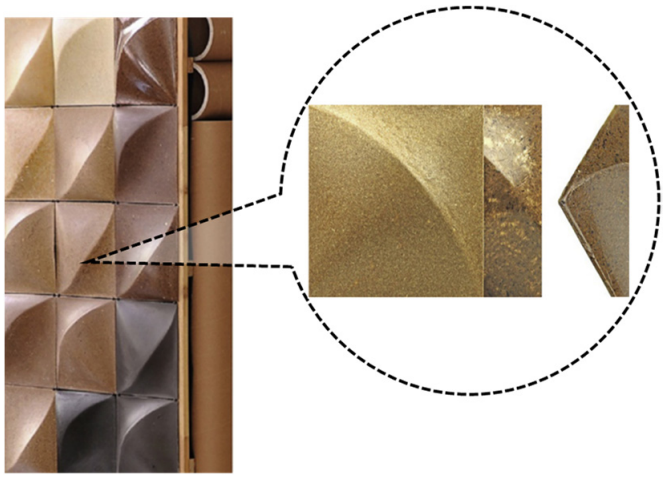

Figure 2. Bio-based cladding structure [21].

Current studies often focus on specific biopolymer types, overlooking comprehensive analyses of diverse biopolymer cladding materials and their broader applications in the construction industry. Recent studies are underway to investigate the applications of specific biopolymers in industries such as medical, automotive, packaging, etc. However, there is a noticeable research gap in biopolymer materials for cladding purposes. The investigation of biopolymer materials in cladding applications remains comparatively limited. Additionally, the field of biopolymers has a vast scope for exploration, which offers significant potential for advancements in various sectors.

This review paper aims to address the gap mentioned above by providing a comprehensive analysis and discussion of various biopolymer materials suitable for cladding applications according to their physical properties, chemical properties, thermal properties, ecological impact, economic impact, and flame retardancy properties. Furthermore, it explores the potential cross-domain utility of these materials, shedding light on their transformative role in sustainable construction practices and further challenges.

2. Research Methodology

This descriptive research study falls under the category of conclusive research. Several steps have been followed in this research study to explore the topic in a particular field, as illustrated in Figure 3. Initially, the gap in previous research was identified, and concurrently, the research aim was defined. In the next step, proper data were collected. During this step, the most relevant articles were identified and selected from various databases, including Google Scholar, ResearchGate, and Web of Science. The chosen sources were ensured to align with the research focus. Additionally, appropriate information directly related to the research focus was collected. Finally, a thorough literature review was conducted, focusing on the application of biopolymers in cladding, their properties, and the associated manufacturing processes. Additionally, the collected data in the context of literature selection was analysed. At the end, the future prospects for biopolymers in cladding panels have been discussed, and the challenges currently faced by researchers have also been presented in this study to provide future research directions for sustainable biopolymer cladding panels.

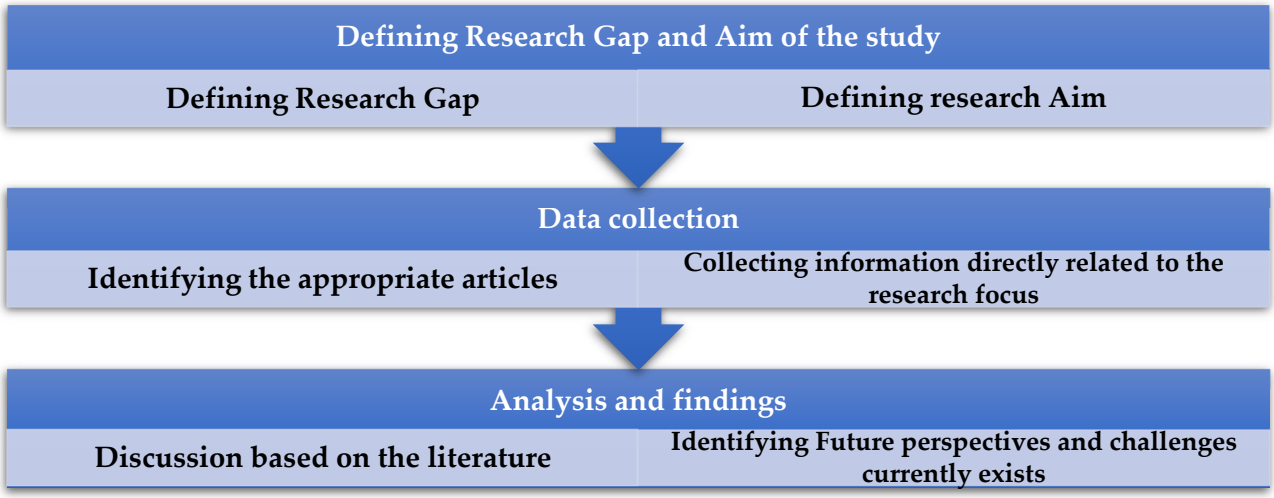

Figure 3. Flowchart illustrating the methodology of the research.

3. Different Types of Biopolymers Used in Cladding

Different types of biopolymer-based materials have been explored in board cladding applications since they are great alternatives to conventional synthetic polymers. These biopolymer-based materials are great substitutes which offer a wide range of benefits such as biodegradability, renewable sourcing, reduced carbon footprint, enhanced environmental performance, etc. The most commonly used biopolymer-based materials used in cladding have been discussed in the following sub-sections.

3.1. Polylactic Acid (PLA)

Polylactic acid (PLA) is a biodegradable polymer that comes from renewable resources like corn starch, sugarcane, or other plant-based materials [22]. Its outstanding performance as a cladding material has gained it a great name and attention. It has excellent mechanical properties, low toxicity, and innate biodegradability [14]. PLA is a thermoplastic polymer made from lactic acid (Figure 4). Lactic acid is mainly produced by microbial fermentation of plant starch and is produced in two stereoisomeric forms of lactic acid, which are L-lactic acid and D-lactic acid [23]. The formulation of polylactic acid needs a monomer. Lactic acid is the monomer obtained through the polycondensation process [24]. PLA formulation also involves a catalyst, a solvent, and additives. The standard metal catalyst for polylactic acid is tin octoate [25]. PLA can be made from lactic acid monomer through two different methods, which are ring-opening polymerisation (ROP) and direct polycondensation (DP). While polycondensation directly connects lactic acid molecules, ROP breaks down lactide cyclic dimers [26]. The ultimate properties of polylactic acid depend on the stereoisomeric form of its production and the catalyst used during synthesis [27]. ROP creates large, well-structured, and crystalline polylactic acid molecules; however, lactic acid monomers directly react in the DP process, and water is removed by vacuum or azeotropic distillation. This process produces moderate-weight polylactic acid with lower cost and less environmental impact [28]. PLA is biodegradable under industrial composting conditions and has a lower carbon footprint compared to petroleum-based plastics.

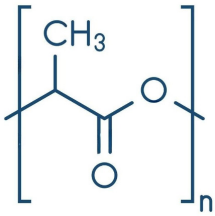

Figure 4. Chemical structure of PLA [29].

3.2. Polyhydroxyalkanoates (PHAs)

Another fascinating biopolymer group is polyhydroxyalkanoates (PHAs), which are widely used in the cladding industry. PHAs show a wide range of excellent properties, including biodegradability, thermoplasticity, and mechanical strength [15]. Furthermore, the physical and chemical properties of PHAs can be tailored to cater to specific cladding requirements, making them a versatile option. PHAs are easily biodegradable in soil, ocean, and industrial composting conditions. They offer less reliance on fossil fuels and have less of an impact on the environment [15].

PHAs are a type of biopolymer that are naturally produced by bacteria. PHAs can be synthesised by large numbers of Gram-positive and Gram-negative bacteria from 75 different genres. PHAs can be produced through a variety of metabolic routes, depending on the particular microbe and its surrounding environment [30]. PHAs are a straight-chain polyester which is formed through the chemical ring-opening polymerisation of β-lactones [31]. Additionally, both Gram-positive and Gram-negative bacteria spontaneously make them under unfavourable circumstances, such as nutritional or physical stress [32]. The most common hydroxyalkanoates used for PHAs' production are 3-hydroxybutyrate (3HB) and 3-hydroxyvalerate (3HV) [33,34]. PHAs are obtained from the microbial cells through different types of extraction techniques. In biological methods, the cell wall is disintegrated by enzymes or other microbes, allowing the separation of PHAs for retrieval. PHAs are purified using many techniques, such as precipitation, filtration, centrifugation, or chromatography. Their performance and properties depend on the purification [35,36].

3.3. Starch-Based Polymers (SBP)

Starch-based polymers such as thermoplastic starch (TPS) are mainly derived from natural renewable sources like corn, potatoes, wheat, etc. (Figure 5). These polymers usually blend with other biodegradable polymers to enhance their properties, such as mechanical strength, processability, high dimensional stability, and moisture resistance. Starch-based polymers are biodegradable, renewable, and have a reduced carbon footprint compared to petroleum-based plastics, making starch-based polymers an appealing choice for cladding [16,37].

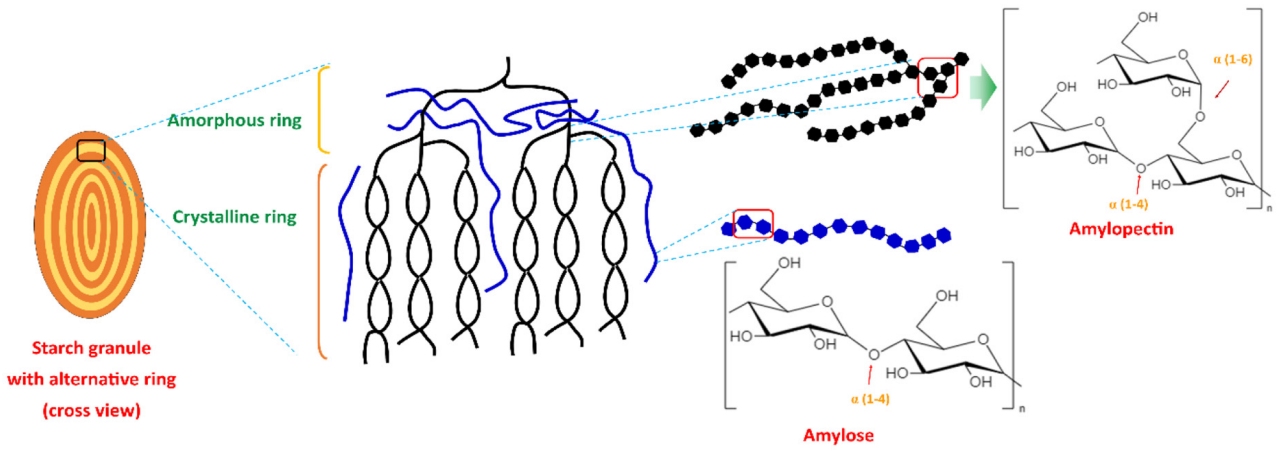

Figure 5. Chemical structure of amylose and amylopectin in the starch granule [38].

Starch-based polymers are members of the biodegradable polymer family, and their source is from renewable natural resources like corn, potato, wheat, rice, and cassava [39]. Starch is a naturally occurring carbohydrate that is made of glucose units joined by α-1,4 and α-1,6 glycosidic bonds, and these two different forms of polymer chains are called amylose and amylopectin. Amylopectin contains α-1,4 glycosidic bonds, which are connected to the α-1,6 glycosidic bonds. On the other hand, amylose consists of a long straight

chain containing only 1,4-glycosidic linkages [40,41]. Various types of physical or chemical modifications are applied to improve its properties [42]. Thermoplastic starch (TPS) is produced by mixing the starch-based polymer with other biopolymers, such as poly (lactic acid), poly (butylene adipate-co-terephthalate), poly(ε-caprolactone), and poly (vinyl alcohol). Adding these biopolymers enhances the mechanical properties, thermal stability, water resistance, and biodegradability of starch-based polymers. Thermoplastic starch can be reshaped through extrusion, injection, moulding, etc. [43]. Chemical alteration of starch-based biopolymers is another method to improve their properties, and it is normally achieved by reaction with the hydroxyl group in the starch molecule [44]. The resulting derivatives have different physicochemical characteristics in comparison with the original starch, while retaining their inherent biodegradability. Therefore, adding or changing some groups or chains on the hydroxyl parts can make different biodegradable starch-based materials that serve different purposes [43]. Compared to cellulose and other polysaccharides, starch has a diverse origin, different molecular weights, and distinct functional characteristics. Starch shows better processability and compatibility with other biopolymers. These qualities are highly relevant to its position within the biodegradable polymer sectors, highlighting its usefulness in supporting environmentally concerned enterprises [45].

3.4. Cellulose-Based Polymers (CBP)

Cellulose is one of the most common and natural polymers. It can be processed into various shapes and forms, like powders, films, gels, etc. [17]. Cellulose can also be chemically modified to produce cellulose-derivative biopolymers, such as cellulose acetate and cellulose nitrate, with desirable properties for cladding and various applications [17,46]. Plastic or synthetic polymers can be melted and reshaped, but cellulose cannot be melted or reshaped this way because of the strong connection between its molecules and hydrogen bonds [47]. Thermoplastics can be created by adding additional components to cellulose derivatives in a solvent state. However, this method can be costly because of using chemical agents such as cellulose ester [48]. There are different methods of making cellulose-based biopolymers, such as the hot-pressing process [49,50], directed deformation assembly process [51], and bacterial cellulose synthesis process [52]. In the hot-pressing process, cellulose molecular chains are guided to align in various directions but in a fixed dimension. As a result of this alignment, the cellulose undergoes a change in its shape and structure, ultimately leading to deformation [49,50]. The bacterial cellulose (BC) process is conducted with various bacterial species, such as acetobacter, agrobacterium, rhizobium, sarcina, and others. This complex procedure takes place under many environmental and growth circumstances, which help to produce the result [52]. It has excellent properties, such as biodegradability, biocompatibility, thermal stability, and good mechanical and barrier properties. Wood pulp, cotton, bacterial cellulose, etc., are the most common sources of cellulose-based polymers [46,53].

3.5. Polyhydroxybutyrate (PHB)

PHB is a biodegradable polymer produced from renewable and sustainable sources like food waste. It has a great capacity to break down in specific biological conditions, and these factors make it a strong substitute for artificial polymers such as PVC, PP, and PE [18]. However, the production cost of PHB is relatively higher than that of petrochemical-based plastics. Recent research has identified methods for lower PHB manufacturing costs, including increased bacterial strains, simplified fermentation, and improved recovery methods [54,55]. PHB is biosynthesised and accumulated by a number of specialised bacterial strains such as Alcaligenes eutrophus, Bacillus megaterium, Pseudomonas oleovorans, strains using a variety of organic substances that are found naturally and unutilised (wasted) as carbon sources. PHB can be blended or combined with other polymers or fillers like wood, metal, glass, etc, to improve its properties and performance, especially to form hybrid cladding systems [56–58]. The formulation of PHB can be divided into two main steps: the production of PHB by microorganisms and the extraction of PHB [59].

For the production of PHB, specific bacteria need to be selected and grown in a nutrient environment for 24 h at 37 °C. According to one report, around 5% of thriving bacteria was added to the 50 mL of modified mineral salt and left to grow for 72 h at 37 °C with gentle agitation (120 rpm) [60]. After the bacteria multiplied, these were separated from the liquid, the dried bacterial clumps were collected, and they were soaked in sodium hypochlorite to release the PHB materials. A filter was used to remove unwanted components from PHB material [61].

3.6. Polybutylene Adipate Terephthalate (PBAT)

PBAT's speciality lies in its ability to break down naturally in the environment, and the reason behind that is its ester linkage. The ester bond breaks down through the water and enzymes in the environment [62]. PBAT has good qualities of both synthetic and bio-based polymers. Although it is produced from regular petrochemicals such as purified terephthalic acid (PTA), butanediol, and adipic acid, it is biodegradable [19]. PBAT shows great water resistance properties, and its manufacturing process is much easier [63]. It has the perfect characteristics to create flexible films just like regular plastic materials [62]. However, PBAT is not strong enough for certain uses and is also more costly than other biopolymers [64].

In the PBAT synthesis process, adipic acid and 1,4-butanediol are added to a stainless-steel reactor in a fixed mole ratio. Stirring is used to bring the reactants' temperature up, and distillation is used to get rid of the water that is produced during the reaction [65]. After 1–2 h, tetrabutylorthotitanate (TBOT) is added to the mixture at room temperature. Under vacuum, the reaction temperature is elevated for 4h, and dimethyl-terephthalate (DMT), 1,4-butanediol, and TBOT are added in a specific ratio. The temperature needs to be maintained, and the process takes around 20h under a high vacuum [65].

3.7. Polybutylene Succinate (PBS)

Polybutylene succinate (PBS) is a semi-crystalline polymer which is produced through a direct reaction of succinic acid and 1,4-butanediol. It is environmentally friendly because it breaks down more rapidly than traditional petrochemical plastics and leaves no toxic materials behind [66]. However, polybutylene succinate (PBS) is much more expensive compared to petrochemicals such as polystyrene (PS), polyamides (PAs), polyethylene terephthalate (PET), and polyethylene (PE), because it involves special processing and combining succinic acid and 1,4-butanediol in the process [67].

Polybutylene succinate (PBS) can be produced in various ways, including polycondensation of succinic acid and 1,4-butanediol, where monomers come from fossil-based or renewable sources. This method has potential in the case of enhanced thermal and mechanical properties [68]. In the fermentation process, microorganisms can be used to make succinic acid. To create bio-based PBS, numerous microorganisms have been examined and put to the test [69]. In the chemical synthesis process, chemically synthesised aliphatic polyesters with high molecular weights can improve the properties of PBS. For instance, poly (butylene succinate-co-ethylene succinate) is synthesised through direct polycondensation in the presence of N35 catalyst [70].

3.8. Polycaprolactone (PCL)

Polycaprolactone (PCL) is a member of the biodegradable synthetic polyesters group which has proven incredibly valuable in various applications [71]. In the 1930s, researchers produced polycaprolactone (PCL) polymer materials from the ε-caprolactone monomer for the first time with a cyclic polymerisation process facilitated by initiators (Figure 6). Polycaprolactone (PCL) is non-toxic in nature, which makes it safe for living organisms [72]. It has a great ability to break down naturally in the environment, and it also has excellent stability and compatibility with biological systems [73]. Additionally, PCL shows great crystallinity, which means it is in solid form at room temperature and is strong. It gets thick and sticky in its liquid state [74].

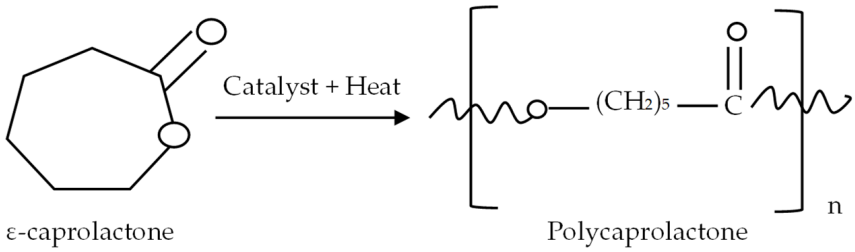

Figure 6. Ring-opening polymerisation process of polycaprolactone (PCL) [75].

PCL is mostly produced through a ring-opening polymerisation process by linking ε-caprolactone molecules together. This method was invented in the 1930s. Different types of catalysts are used in this process, such as stannous octoate, which is used to speed up the polymerisation process [75]. Different mechanisms, including anionic, cationic, coordination, and radical processes, influence the polymerisation process. These methods influence the resulting polymer, in terms such as molecular size, distribution, the composition of end groups, and the chemical structure [75]. Polycaprolactone (PCL) is a versatile and promising biopolymer, and mixing it with other polymers changes its properties [76]. It is a synthetic polymer that breaks down slowly in nature over time. It is also hydrophobic. Its interesting properties make it quite intriguing for the preparation of long-term implantable devices [77].

4. Manufacturing Methods for Biopolymers

Biopolymer-based cladding is mainly used to cover and protect buildings from rough weather conditions and heat radiation. Biopolymer in the composite matrix preserves the shape of the composite and protects the core reinforcement. Depending on the demands of size and shape, there are various ways to make biopolymer composites. These production processes can be divided into two methods: traditional and additive (Figure 7). Traditional techniques shape and mould the biopolymer cladding using pressure, heat, or chemicals. Extrusion, injection, moulding, coating and thermoforming are a few examples of traditional methods [78]. In additive methods, digital models and layer-by-layer fabrication are used to create the biopolymer cladding. Three-dimensional (3D) painting techniques such as fused filament fabrication (FFF), selective laser sintering (SLS), and stereolithography (SLA) are some examples of additive methods [79,80].

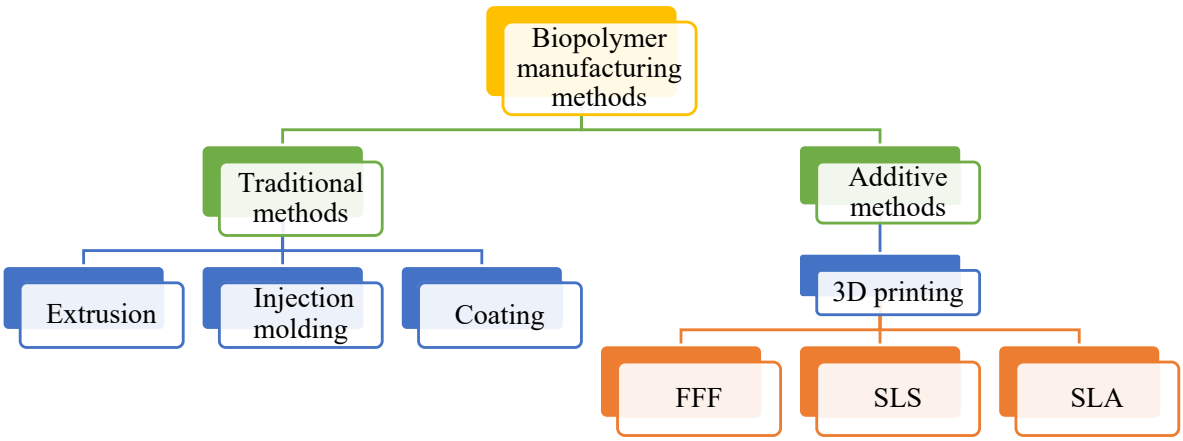

Figure 7. Different manufacturing methods of biopolymers.

4.1. Traditional Manufacturing Techniques

Polymer composite manufacturing techniques are used to create polymer products with new properties. Traditional methods, including extrusion, injection moulding, calendaring, and hot-pressing (see Table 1), are repeatable, with precise control, excellent quality,

and complicated shapes [78]. Nevertheless, as the product becomes more complex, the difficulty of moulding them also grows [78].

Table 1. Advantages and limitations of different types of Traditional manufacturing process of biopolymers.

Manufacturing Process	Advantages	Limitations	Biopolymers	Ref.
Extrusion	• Variety of shapes and sizes • High production rates • Additives for modified properties	• Thermal degradation, oxidation • Poor dispersion of additives • Waste generation, emissions	Polylactic acid (PLA), Polyhydroxyalkanoates (PHA), and starch-based polymers	[81–83]
Injection Molding	• High-quality parts with low variability • High production rates • Complex geometries • Biodegradable material options	• High initial investment, maintenance costs • Thermal degradation, oxidation • Residual stresses, warping. • Harmful emissions, odours	Polyhydroxyalkanoates (PHA), polylactic acid (PLA), and polyethylene furanoate (PEF) 910	[84,85]
Coating	• Improved properties • Reduced material consumption. • Incorporation of active agents • Low production costs, low waste • Complex geometries and structures • Biodegradable material options	• Thermal degradation, oxidation • Poor adhesion, compatibility • Harmful emissions, odours • Thermal degradation, oxidation • Poor mechanical properties, biocompatibility • Harmful emissions, odours	Cellulose, chitosan, Alginate, and collagen	[86,87]

4.1.1. Extrusion

The extrusion process is a process where extruders are commonly used as devices, and biopolymers or polymers are used as raw materials. In this process, these biopolymers obtain new shapes, which is the most efficient process for enhancing the properties of biopolymers [88,89]. There are many different types of extrusion process, but blown film, cast film, and extrusion coating are the common types of extrusion process [90], and single-screw or twin-screw types are the major types of extruders [88]. The processing temperature depends on the type of extrusion, and the processing temperature also depends on the biopolymers. In this process, various additives are used in the biopolymers to improve strength and gain the desired properties [90]. This process involves feeding the biopolymer into a heated barrel, where the biopolymer is melted at a fixed temperature with a rotating screw. Then, it is forced through a die, which gives the biopolymer its final shape. The final product is usually cooled with water or air [91]. To make the desired biopolymer-based cladding, it is important to choose the right simulation tool to analyse the operation. LUDOVIC®, Morex, SIGMA, and Akron-Co-Twin Screw® are common types of extrusion modelling simulation tools [88].

4.1.2. Injection Moulding

Injection moulding is a method of making biopolymer-based products using a process that involves feeding, melting, injecting, and cooling the material in a mould [84]. The injection moulding technique is widely used for the mass production of biopolymers because it offers cost-efficient manufacturing and the ability to make a vast range of shapes. Due to its economic advantages and versatility in shaping products, it has gained industrial attention [92]. Compounding is one of the important steps in injection moulding, where different materials are mixed to improve the strength of the product. Next, the material is granulated after compounding and put into the injection moulding machine. Melted material is injected into moulds during the process to produce objects [84].

4.1.3. Coating

In the process of coating, a thin layer of biopolymer is applied to the surface of a substrate. Biopolymer coatings on the surface of other materials can be created through various methods. They are classified into physical and chemical techniques [93]. In physical

methods, biopolymers can be applied to the surface directly through spin coating, dip coating, electrospinning, or vapour transport processes. On the other hand, chemical methods occur in reaction between the biopolymer and the surface using complex chemical treatments [93]. There are many other methods of coating and films. For example, there is the layer-by-layer (LBL) method, where various charged polymers are successfully coated. It is a flexible method and can create versatile coatings [94]. Another method is Langmuir–Blodgett (LB) films. In this process, the substrate is coated with molecules from the polymer solution [95]. The polymer brushes method is used where a soft material is attached to the surface [96]. In the dip coating process, the sample is dipped into the biopolymer solution, and the sample absorbs the biopolymer. There are many more coating methods, and the choice of coating method depends on the purpose of coating [93].

4.2. Additive Manufacturing Technique and 3D Printing

Additive manufacturing (AM) is an innovative methodology for material fabrication. It is recognised as rapid prototyping (RP) and revolves around the practice of 3D printing (3DP). In this method, there are a range of methods that employ a layer-by-layer methodology in constructing intricate and uniquely contoured parts or components [14,23]. This technique gives design flexibility such as small size, complex tailored design, and hybrid structures, and reduces energy footprints [14,23,24]. AM is an excellent tool in various industrial areas due to its adaptability, versatility, and extensive customisability [24]. Its most advantageous side is that it does not need any elaborate moulding tools, making it a departure from traditional manufacturing methods and less time-consuming. Computer-aided design (CAD) is used to create digital designs and detailed 3D models [25].

With the help of CAD, creating intricate shapes affordably has become a new focus in 3D printing research [26]. The field of 3D printing is also known as additive layer manufacturing (ALM), and it has grown exponentially in the last few years [15]. Regular polymers have some limitations in strength and printing. For 3D printing, researchers are developing better polymer blends and combinations to remove these limitations [26]. These new materials offer many advantages, including precision, affordability, and waste reduction. They can also create incredibly detailed shapes using less chemicals 26.

There are several 3D printing techniques (Table 2) that are commonly used, such as fused filament fabrication (FFF), binder jetting 3D printing (BJP), selective laser sintering (SLS), and stereolithography (SLA). Particle, fibre, and even nanomaterial-reinforced polymer composites are used to improve the properties of the individual polymer in these techniques [80]. Three-dimensional (3D) printing methods can create many synthetic and biodegradable polymer objects designed for particular applications, including fixation devices, scaffolds, complicated bone-like structures, implants, packaging materials, and even automotive sector components [16].

Table 2. Advantages and limitations of different types of Additive manufacturing process of biopolymers.

Manufacturing Process	Advantages	Limitations	Biopolymers	Ref.
FFF	• Low-cost and accessible • High strength & stiffness • Biodegradable material options • Complex geometries	• Limited resolution and accuracy • Anisotropic properties • Warping, cracking, delamination	Polylactic acid (PLA), polyhydroxyalkanoates (PHA), polyethylene furanoate (PEF), and starch-based polymers.	[97–100]
SLS	• Complex shapes with high accuracy • Biodegradable material options • Porous structures for tissue engineering	• Thermal degradation, oxidation • Residual stresses, distortions • Harmful fumes, dust generation	Polyamide 11 (PA 11), polycaprolactone (PCL), and poly-3-hydroxybutyrate (PHB)	[101–104]

Table 2. *Cont.*

Manufacturing Process	Advantages	Limitations	Biopolymers	Ref.
SLA	• High-resolution complex shapes • Biodegradable material options • Porous structures for tissue engineering	• Thermal degradation, oxidation • Residual stresses, distortions • Harmful fumes, dust generation	Polyethylene glycol diacrylate (PEGDA), gelatin methacrylate (GelMA), and cellulose acetate	[105–107]

4.2.1. Fused Filament Fabrication (FFF)

Fused filament fabrication (FFF) is a 3D printing process where a computer numerically controlled (CNC) machine forms material in layers to create objects with extruder nozzles. The parameters of the process depend on the materials, fabrication conditions, and the preferences of the designer [108]. Materials are selected for FFF based on their mechanical and thermo-physical characteristics, such as strength, stiffness, and low thermal expansion [109]. In the FFF process, it is essential that the polymer must be in a molten state. Molten polymer deposits itself onto the cooling prior layer after passing through the extruder because of cyclic temperature variations. This causes the layer to re-heat. Optimising temperature profiles is required to improve the bonding between adjacent filaments [110]. FFF processes and machines are significantly lower in price than other additive manufacturing (AM) machines. RepRap Project is the best example [109]. However, the FFF process produces products with weak mechanical properties by nature, which is its drawback [110]. This FFF process is also used to make various polymers or composites, including PLA, ABS, PETG, nylon, carbon fibre etc. This technique is mainly followed for prototyping and the low-volume production of customised products [80,111].

4.2.2. Selective Laser Sintering (SLS)

This process uses a selectively high-power laser beam for melting and fusing powder particles of a polymer or a composite material on a powder bed. The powder can be manufactured from various materials, including polystyrene, PA, PE, and PEEK [80,81,111]. Selective laser sintering (SLS) is a method of making biopolymer-based composites by using AM technology [101]. In the SLS process, a variant of the powder bed fusion AM process is used. It is a special way of 3D printing called powder bed fusion. Once, it was one of the first methods used to make complex 3D objects in the world of 3D printing [112]. As the SLS process can work with a wide range of materials like wax, different types of plastics, ceramics, squishy materials, and mixes of metal and plastic in powder form, SLS has become a standard for 3D printing work with powder [113,114].

In the SLS process, a part is built layer by layer using a laser to fuse powdered materials. It is an additive manufacturing process [115]. At the start of this process, a CAD model is turned into layers, and then the laser fuses each layer on a powder bed. The bed goes down, and then new powder is added on the top for the next layer, and this cycle continues. Preheating the powder bed is compulsory to prevent distortion before sintering [116,117]. A carbon dioxide laser is used in this system, and a smart controller controls it. The construction volume can be up to 550 mm $\times$ 550 mm $\times$ 750 mm, and the deposition precision is approximately 125–250 m. The maximum scanning speed is 10,000 mm/s [118].

4.2.3. Stereolithography (SLA)

In this method, a liquid resin is selectively cured into a solid polymer on a build platform using a UV laser beam. Epoxy, acrylic, polyurethane, and other photopolymers can all be used to make resin. High-resolution, smooth, and detailed parts with complex geometries can be created with this technology [81,111].

AM technology is used to make an eco-friendly biopolymer-based composite with the stereolithography method. It is a highly versatile method that can accurately create compli-

cated 3D structures at an affordable cost [98]. In order to create three-dimensional objects according to a CAD model, stereolithography utilises a high-power laser to selectively heat and fuse tiny particles of a thermoplastic material and an inorganic filler, such as calcium phosphate [106]. Stereolithography starts with a file called standard tessellation language (STL), which represents the 3D design [119]. This file is sliced into 2D sections, and the physical object is built layer by layer based on these 2D sections. Triangles are used in the STL file format to generate the 3D model, with each triangle having three coordinates and a normal direction [120,121]. The curing reaction of resins is the key to stereolithography, and the chemical reactions are triggered by UV light [122,123]. In this process, there are two stages, which are gelation and vitrification. In gelation, the material becomes thicker, like rubber, and it transforms from liquid to solid in vitrification. By carefully controlling the curing process, these actions help to layer-by-layer construct the final 3D object [124,125].

5. Different Properties and Applications of Biopolymer Materials

There are ultimately four properties of biopolymer materials: mechanical properties, thermal properties, chemical properties, and barrier properties. The overall performance of a biopolymer material depends on these properties. Mechanical properties are one of the most important properties for cladding materials for better durability, stability, and resistance to external loads and impacts. Thermal properties are crucial for cladding materials because they have an impact on a building's dimensional stability, fire safety, and energy efficiency. The chemical properties of biopolymer-based materials in cladding are important due to their impact on the material's performance, sustainability, and compatibility. The environmental effect, functionality, and durability of biopolymer-based materials used in cladding are also influenced by their chemical qualities. The barrier capabilities of biopolymer-based materials used for cladding are essential for protection. Their unique barrier qualities are essential for their performance in different environments.

5.1. Mechanical Properties

In this section, the mechanical properties of different types of biopolymers (PLA, SBP, PHAs, CBP, PHB, PBAT, PCL) are described in a broad sense. The average tensile strength of each biopolymer material is plotted in Figure 8a. The tensile strength of PLA varies from 50 to 70 MPa [126], while this value ranges from 38–69 MPa for SBP. PLA is a strong biopolymer with great mechanical properties, but its brittle character makes it prone to cracking under stress. This is because of its low elongation and impact resistance. When the PLA biopolymer is blended with other biodegradable polymers such as PBAT, PBS, or PCL in a definite proportion or reinforced with natural fibres or nanofillers, its mechanical properties can be improved. SBP has lower tensile strength compared to traditional synthetic polymers. By blending it with other compatible polymers or reinforcing it with fillers like natural fibres, its mechanical properties can be improved significantly [126–128].

The tensile strength of PHAs, CBP, PBAT, and PBS are 40, 305, 8.31, and 32.0, respectively. It is observed from the data analysis that CBP has a maximum tensile strength of 305 MPa [27,129–131], and PBAT has a lower tensile strength of 8.31 MPa [130]. CBP has the highest tensile strength among other biopolymers. This is due to its strong hydrogen bonding interaction between the cellulose chains, which form a stable, dense, and compact network structure. CBP is not affected even by alkalis and dilute acids [132]. CBP is a combination of cellulose acetate or cellulose esters with moderate mechanical properties. They are often used as additives to enhance the performance of other biopolymer materials. Cellulose acetate or cellulose esters in CBP can improve the general toughness, adaptability, and other desirable properties of diverse biopolymers, making them more adaptable and environmentally benign in many applications [129,133,134]. On the other hand, PBS has a hydrophobic nature and high resistance to thermo-oxidative degradation. However, this might mean PBS has a low tensile strength [70]. PBAT also has the lowest tensile strength because of its crystallinity. PHAs are a large group of biopolymers that have a good balance

of tensile strength and flexibility compared to other polymers like PBAT, PBS and PHB. However, their eco-friendliness and adaptability make them highly appealing for a variety of applications. PHB is an impressive biopolymer with good mechanical properties similar to conventional plastics. PHB shows a tensile strength of 40 MPa, while PCL has a lower tensile strength ranging from 12 to 30 MPa. Figure 8a illustrates the variation in tensile strength among various types of biopolymers, highlighting the average tensile strength for each biopolymer material.

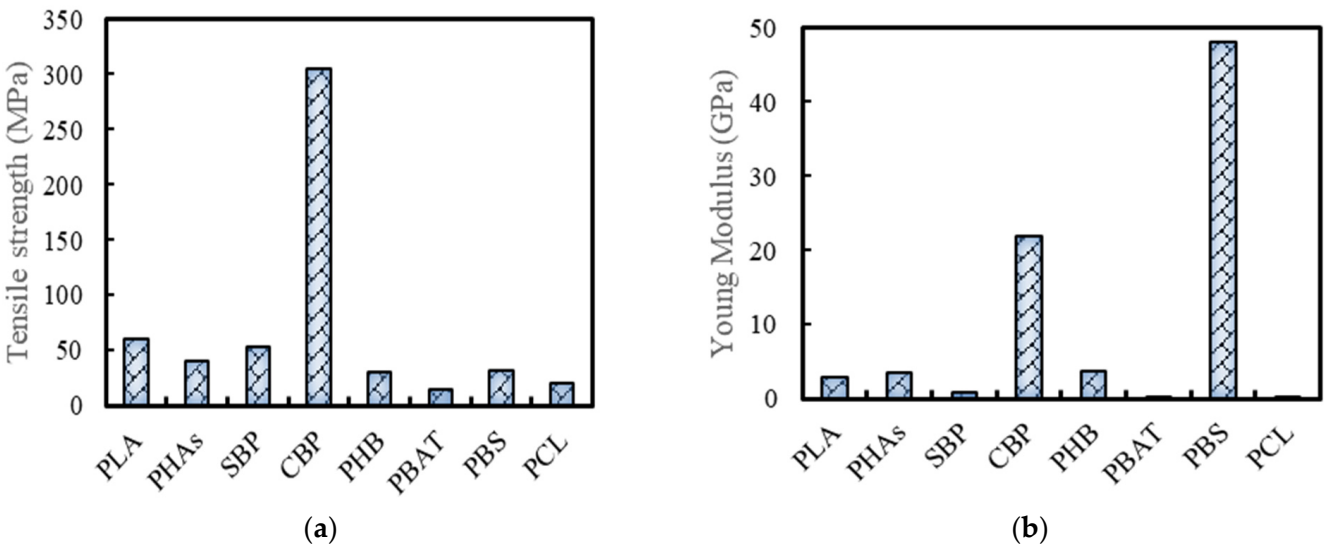

Figure 8. Mechanical properties of different biopolymers. (**a**) Tensile strength (Pa). (**b**) Young's modulus (GPa).

In Figure 8b, a comparison of Young's modulus is plotted for different types of biopolymers. Similar to tensile strength, the average Young's modulus is taken to avoid complications. It is noticed that PBS shows maximum stiffness, and the value of Young's modulus is 48 GPa [74]. The value of Young's modulus depends on the structure of the material. PBS has a semi-crystalline structure. In PBS, there is a strong intermolecular hydrogen bond. Both its semi-crystalline structure and strong intermolecular hydrogen bond contribute to PBS having a high Young's modulus, which makes it resistant to deformation [70]. On the other hand, the stiffness of PCL and PBAT is negligible and the Young's modulus values are 0.21–0.44 GPa and 0.02592 GPa, respectively. The Young's modulus of CBP is 22 GPa, which is higher than other biopolymers.

The impact strength and elongation at the breaking point of all types of biopolymers are demonstrated in Figure 9a,b. It is observed that the impact strength of PBAT, PBS, and PCL are 35.75 kJ/m^2, 12 kJ/m^2, and 22 kJ/m^2, respectively. PBAT shows a maximum impact strength compared to all other types of biopolymers. PBAT has a lower glass transition temperature [135] and a higher elongation break, which helps it to deform more easily under stress. PBAT also has lower crystallinity. Because of these characteristics, PBAT has higher impact strength than other biopolymers [136]. The impact strength of other types of biopolymers varies from 1.30 to 5.50 kJ/m^2. The details of the mechanical properties of all biopolymers are presented in Table 3.

Table 3. Mechanical properties of biopolymer materials reported in the literature.

Biopolymers	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (GPa)	Impact Strength (kJ/m^2)	References
PLA	50–70	7.3	3	1.3	[126,137]
PHAs	15–40	1–15	3.5	0.1–10	[27,138]
SBP	38–69	—	—	0.1–10	[128,137]

Table 3. *Cont.*

Biopolymers	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (GPa)	Impact Strength (kJ/m^2)	References
CBP	~305	5–10	~22	1–10	[129,133,134,139]
PHB	40	5–8	3.5–4	3.36	[27]
PBAT	8.31	—	0.02592	26.2–45.3	[130]
PBS	32.0	21.5	48	12	[131]
PCL	12–30	—	0.21–0.44	6–38	[27,74,128]

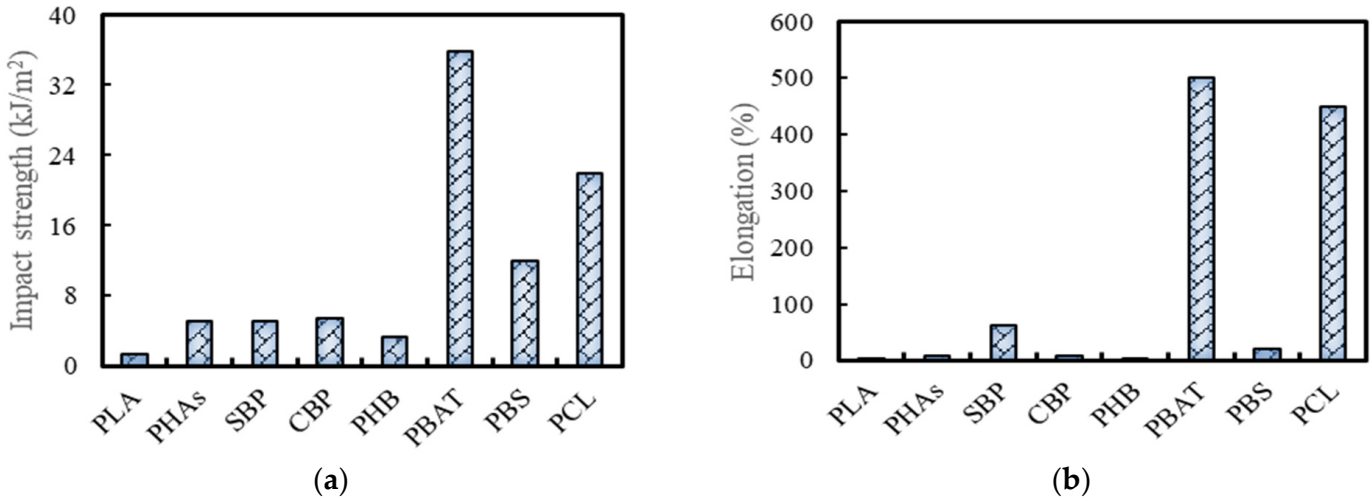

Figure 9. Mechanical properties of different biopolymers. (**a**) Impact strength (MPa). (**b**) Elongation (%).

5.2. Chemical Properties

All biopolymers listed in Table 4 are eco-friendly and biodegradable, which indicates the suitability of those polymers. All information for the biopolymers is assembled from well-cited research papers. However, the rate of degradability varies depending on the type of polymer. All types of polymers are biodegradable in the form of composting. The biodegradability rate is not similar for all types of polymers when the polymers are disposed of in a natural environment. In cases of disposal in a natural environment, PLA, PBAT, and PBS polymers show degradable rates. For instance, PLA can take up to a year at temperatures of 20 °C for degradation. Degradation can occur within 12 weeks when the temperature is greater than 25 °C [140,141]. PBAT degrades slowly in the environment compared to the others, eventually disappearing without causing harm to the environment. PBS degrades slowly in the environment without leaving any harmful substance behind in the environment. Its distinctive chemical composition gives adaptability and powerful mechanical qualities. SBP can degrade in soil at relatively low temperatures. PHAs and CBP offer incredible biodegradability rates in soil or the environment. PHB is a remarkable biodegradable polymer that can be broken down by microorganisms naturally. PCL is an environment-friendly polymer which degrades easily in the environment with the help of microorganisms. All polymers have recyclability and are easily compatible with the other polymers when mixed at a certain percentage. Some polymers like PBS and PBAT can be mechanically recycled and gain a new life [142,143].

Table 4. List of biopolymers with chemical properties.

Biopolymer	Biodegradability (Composting)	Biodegradability	Recyclability	Compatibility with Other Polymers	Reference
PLA	Yes	Slow	Yes	Yes	[141]
PHAs	Yes	Yes	Yes	Yes	[144]
SBP	Yes	Yes	Yes	Yes	[145]
CBP	Yes	Yes	Yes	Yes	[146]
PHB	Yes	Yes	Yes	Yes	[142]
PBAT	Yes	Slow	Yes	Yes	[146]
PBS	Yes	Slow	Yes	Yes	[143]
PCL	Yes	Yes	Yes	Yes	[147]

5.3. Thermal Properties

PLA has a relatively lower glass transition temperature (Tg) of approximately 60 °C [148] and a melting temperature (Tm) of 180 °C, which heightens its stability and versatility [148]. Above 200 °C, PLA tends to degrade quickly, which may limit its use in high-temperature applications. It is eco-friendly and has excellent properties at low temperatures [148,149]. The unique thermal properties of PLA include a crystallinity range of 23–26% [129]. PHAs are partial crystalline polymers [150]. The thermal properties of PHAs depend on the composition of the materials. While some PHAs have very low melting points with good thermal stability, others may have higher melting points [150,151]. The glass transition temperature (°C) of polyhydroxyalkanoates (PHAs) is −50 to 4 °C, crystallinity ranges from 10 to 70%, with melting temperatures of 40 to 180 °C [151].

The thermal stability of starch-based polymers is lower than conventional synthetic plastics. These polymers may degrade at relatively low temperatures, which restricts their use in applications requiring greater heat resistance. Glass transition temperatures for starch-based polymers range from −75 to 10 degrees Celsius [152], whereas melting temperatures are 297 degrees Celsius [153], and crystallinity levels are between 14 to 45 percent [154]. Cellulose-based polymers are known for their amazing thermal stability. Neat cellulose acetate powder exhibits a high glass transition temperature close to its melting point [155]. They can endure moderate temperatures without undergoing significant degradation. This characteristic makes them suitable where heat resistance is essential. Cellulose-based polymers exhibit glass transition temperatures of 220 °C [156], melting temperatures of 248 °C [157], and crystallinity percentages in the range of 80–90% [158].

PHB has unique thermal properties. Its comparatively high melting point and low degradation temperature (~220 °C) limit its potential in thermal processing to prepare PHB films [159]. The properties of PHB include glass transition temperatures of 10 °C [160], melting temperatures of 175–180 °C [23], and crystallinity percentages of 60.5% [159]. The glass transition temperature of PBAT is much lower compared to PLA, which makes it more flexible. PBAT can be bent and stretched more efficiently, which makes it a great choice for applications that require materials with good flexibility and resilience [135,161]. The glass transition temperature of PBAT is −34 °C [162], the melting temperature is 109 °C [135], and the crystallinity percentage is 15% [161].

PBS has a low Tg and high Tm, which contribute to its high thermal stability. Because of this, it is commercially available. PBS can be blended with other biopolymers to enhance its properties [163]. PBS has a glass transition temperature of −3 °C [163], melting temperatures of 116.7 °C [164], and a range of crystallinity percentages 35–45% [165]. PCL has a low melting point, so it can be easily processed at lower temperatures. This characteristic makes it ideal for processing compared to certain other biopolymers. It can be easily moulded and shaped at lower temperatures [166]. PCL can be blended with other materials, and shape fixity and shape recovery ratios increase with increasing PCL molecular weight on that material [167]. The glass transition temperature for polycaprolactone (PCL) is −60 °C [166], melting temperature is 60 °C [166], and crystallinity percentage is 76.3% [168]. The thermal properties of some biopolymer-based cladding materials are reported in Table 5.

Table 5. Thermal properties of some biopolymer-based cladding materials.

Biopolymer	Glass Transition Temperature (°C)	Melting Temperature (°C)	Crystallinity (%)	Coefficient of Thermal Expansion (10^{-6}/K)	References
PLA	55 to 65	60 to 180	30 to 60	55 to 75	[136–149]
PHAs	−20 to 50	40 to 180	10 to 70	60 to 100	[150,151]
SBP	40 to 80	130 to 180	10 to 60	30 to 70	[152,153]
CBP	220 to 250	260 to 350	40 to 80	~10	[154–158]
PHB	4 to 7	175 to 180	50 to 90	15 to 20	[159,160]
PBAT	−30 to −20	120 to 130	20 to 60	10 to 20	[135,161]
PBS	−32	113 to 115	30 to 70	15 to 20	[163–165]
PCL	−60 to −65	58 to 60	35 to 75	15 to 20	[162,166–168]

5.4. Barrier Properties

PLA has very good resistance against oxygen and carbon dioxide; its oxygen permeability is between 0.015 and 0.025 cm3/m^2/day, proving it as a good barrier element [27]. However, its performance is relatively permeable in the case of moisture and UV rays. Its water vapour permeability is from 0.005 to 0.007 g/m^2/day, and carbon dioxide permeability is between 35 and 70mL mm/m^2/day/atm. Therefore, PLA might not be the ideal option [27,162,169], where carbon dioxide or UV protection is crucial. PHAs have a diverse variety, and their barrier properties depend on their composition. This type of polymer can be modified as needed, and gas, moisture, and UV resistance are high. Their design flexibility and versatility make them ideal for cladding, packaging, etc. [27,170,171]. SBPs have relatively lower barrier properties than others. As their origin is from starch, they have a more porous and open structure, which makes them permeable to moisture and gases [16,81,172].

CBPs usually blend with other biopolymers to provide excellent barrier properties, which give protection against moisture, UV radiation, and gases. Because of their adaptability, they are useful for environmentally friendly packaging and cladding [173–175]. As PHB is a biodegradable biopolymer, PHB naturally has the ability to act as a material barrier against gases and moisture, and its oxygen permeability is between 0.002 and 0.01 cm^3/m^2/day. Its water vapour permeability is from 0.001 to 0.005 g/m^2/day, and its carbon dioxide permeability is 3.0 mL mm/m^2/day1/atm1 [27]. PHB needs modifications to enhance its barrier properties. Customised engineering can improve its barrier performance to satisfy certain application needs [176,177]. PBAT provides effective protection against moisture and UV radiation. But it is oxygen and carbon dioxide permeable. Its suitability depends on specific application needs [178,179]. PBS exhibits good barrier properties in moisture and UV radiation situations, which makes it a suitable choice in various industries. However, it might not be the ideal choice for situations needing high gas barrier performance [180,181]. PCL has good barrier properties. PCL's oxygen permeability is 0.02–0.2 cm^3/m^2/day, which proves a good barrier element. Its gas resistance is comparatively less than others. Its water vapour permeability is 0.3 g/m^2/day [27,182,183].

5.5. Applications and Limitations

The applications and limitations of some biopolymer-based cladding materials are summarised in Table 6. There are multiple applications of biopolymers in the construction industry. Biopolymers can be used as additives, coating, pipes, insulation, etc., in the construction industry [184–186]. The application of biopolymer cladding in the packaging industry, including food, pharmaceuticals, cosmetics, and agricultural products, is massive [187]. Biopolymer cladding is a unique type of packaging material containing a thin layer of biopolymer film applied over a surface to a substrate, including paper, cardboard, etc. This cladding method embraces not only the mechanical strength, barrier, and optical properties of the substrate but also provides additional functionalities such as antimicrobial, antioxidant, and biodegradable features [188]. Biopolymer cladding in packaging offers a low toxicity risk; it is also easily biodegradable, a harmless product that has the ability

to become a part of the soil [189]. Biopolymers also have great potential in the medicine industry. Biopolymers have received great attention in the medical industry because of their extensive availability, low toxicity/non-toxicity, biodegradability, biocompatibility, chemical versatility, and inherent functionality [190].

Table 6. Applications and limitations of different biopolymer materials.

Biopolymers	Construction Industry	Medical Industry	Automotive Industry	Packaging Industry	Limitations	References
PLA (Polylactic Acid)	Eco-friendly exterior cladding panels, interior wall panels, roofing materials	Biodegradable medical facility components, drug delivery devices	Sustainable automotive interior trim dashboards, door panels	Compostable food packaging, disposable cutlery, cups and containers	low gas-barrier properties	[183,191–193]
PBS (Polybutylene Succinate)	Weather-resistant cladding materials, siding, insulation panel	Biodegradable medical devices, drug delivery systems, tissue, engineering scaffolds	Biodegradable medical devices, drug delivery systems, tissue engineering scaffolds	Eco-friendly automotive parts, interior trim panels	brittle and low thermal stability	[19,194]
PHA (Polyhydroxyalkanoates)	Green cladding solutions with biodegradability, thermal insulation properties	Biodegradable sutures, tissue engineering scaffolds, drug delivery systems	Environmentally friendly automotive components, door trims	Biodegradable and compostable packaging materials, food containers	High production cost	[171,195–198]
PHB (Polyhydroxybutyrate)	Environmentally friendly cladding materials, resistant to weather and UV degradation	Biodegradable medical packaging, drug delivery devices	Sustainable automotive components and parts	Biodegradable and compostable packaging materials, single-use food packaging	rigid, brittle, low elongation, high crystallinity properties	[58,196–198]

Biopolymers are extremely useful for tissue fixation, wound suturing, and even as adhesives. They are also excellent for dressing and sealing wounds, isolating particular areas, administering medications under control, and encouraging cell growth [82]. For example, the hydrogel patch was developed by mixing polymers containing NHS and acrylate with PEG diacrylate and biopolymers designed to rapidly repair vascular defects and surgical haemostasis [199]. Some hydrogels can be prepared from diverse synthetic or natural polymers, including chitosan, gelatin, hyaluronic acid, alginate, cellulose, polylactic acid (PLA), polyvinyl alcohol (PVA), and polyacrylic acid (PAAc) [200]. Biopolymers are an excellent choice for the automotive industry because of their high stiffness-to-weight ratio, improved fuel capacity, outstanding thermal insulation and low flammability [201]. Using cellulose from wood or agricultural waste, Röchling Automotive has produced a remarkable biopolymer which can be used for engine covers, underbody panels, and cladding. It has some great properties like being very lightweight but incredibly strong, and having great thermal insulation and low flammability [202,203]. The shelf-life of biopolymers depends on the environmental conditions. It also depends on the biopolymers' form, shape, etc. For example, the PLA scaffold has a shelf-life of 150 days in conditions away from sun radiation, at temperatures up to 25 °C, and a relative humidity up to 70% [204]. Shelf-life can be improved through blending with other materials.

Biopolymers have some limitations, such as poor mechanical properties, chemical resistance, and processability compared to conventional plastic materials. This issue can be solved through reinforcing them with fillers that can help to improve these properties [205].

Additionally, biopolymers have other limitations, such as high production costs, low elongation, and high crystallinity properties.

6. Prospectives and Future Challenges

Biopolymer-based materials can be degraded naturally through microorganisms, which release zero toxic by-products in the environment. Additionally, the production cost of biopolymer-based cladding is much less than conventional plastics. So, it is a great energy-efficient and eco-friendly alternative to conventional plastics [206]. While the use of biopolymers in building materials holds great promise, challenges such as cost, scalability, and durability must be addressed for widespread adoption. As research and development continue in this field, biopolymers are poised to play a pivotal role in the construction industry's transition toward more sustainable and eco-friendly practices. Biopolymers have gained attention as potential cladding materials due to their eco-friendly nature, but they come with several challenges, particularly in terms of cost, scalability, durability, and fire properties:

6.1. Prospectives of Biopolymers

(a) Sustainability and lower carbon footprint

Biopolymers are derived from renewable resources such as plants, algae, and microorganisms and have a lower carbon footprint compared to traditional building materials like concrete and steel. Using biopolymers in construction can help mitigate the industry's contribution to greenhouse gas emissions. Some biopolymer-based building materials have excellent insulating properties, contributing to energy-efficient structures. These materials can help reduce heating and cooling costs in buildings. In recent years, several biopolymers have been used to make biopolymer composites for their biodegradable and sustainable nature [207]. Biopolymers are more sustainable and environmentally friendly than conventional synthetic polymers because of their renewable sources, lower carbon footprint, and potential for biodegradability.

(b) Enhanced mechanical and thermal properties

Biopolymer-based materials have high mechanical properties, including tensile strength, modulus, and impact resistance, which are strong enough to replace conventional materials like steel, concrete, or wood in constructing transient civil structures [208]. Biopolymer cladding can be used for external wall cladding, interior finishes, roofing, and insulation. Wood and other natural fibres are mixed with other materials to create sustainable hybrid materials [184]. For example, PBS has high heat resistance and favourable mechanical properties for construction. To improve its flame-retardant and other properties, it is blended with PLA [185]. Another example is plywood, which is manufactured through a bonding process of wood veneers and well-engineered wood products. Its application areas include floors, furniture, roofs, and structural components. Moreover, it has impressive strength, great flexibility, and a high ability to resist shrinking [209]. Certain biopolymers, like biodegradable plastics and bio-composites, can be designed with tailored thermal properties, which can be advantageous for building insulation and temperature regulation. Biopolymer-based materials can also be engineered to have good acoustic insulation properties, improving building comfort and noise levels.

(c) Improve environmental impact

Biopolymers have a great binding capacity and can help improve the compressive strength and durability of concrete materials. So, they can significantly reduce the environmental impact of cement production and consumption [210]. Biopolymers can also provide waterproofing, moisture-proofing, anticorrosion, fire retardance, sound insulation, heat insulation, and sealing, which are significant advantages for the construction industry [208]. Many biopolymers are biodegradable, making them ideal for applications where eventual disposal is required. This can reduce the amount of non-recyclable waste generated during demolition or renovation. Biopolymers can be produced from agricultural waste, forestry

residues, and other biomass byproducts. This incentivises the use of waste materials and reduces the burden on landfills.

(d) Regulatory support and innovation

As awareness of environmental issues grows, there is increasing regulatory support for sustainable building practices. Biopolymers align with these trends and may benefit from incentives and certifications focused on green construction. Ongoing research into biopolymer chemistry and engineering is likely to yield even more versatile and sustainable building materials in the future, expanding their use in construction. Biopolymers can often be sourced locally, reducing the environmental impact associated with transportation and supporting regional economies [208,211].

6.2. Future Challenges of Biopolymers

Biopolymer-based materials are made from renewable resources and have several advantages over traditional polymer materials, including sustainability, biodegradability, and low toxicity. The future of biopolymers is promising, as they offer great potential for many applications. The demand for sustainable materials in the construction industry and other applications is increasing daily. As a result, the biopolymer is becoming more and more popular [212]. However, there are challenges with biopolymer-based materials. Cost and efficiency are the major challenges for biopolymer-based materials [213]. Much research is being conducted on biopolymers because of their availability and biodegradability.

(a) Biodegradability vs. Durability Balance

Balancing the desire for biodegradability with the need for durability can be challenging. Biodegradable materials may break down too quickly in some applications, leading to premature failure. Biopolymers have inadequate moisture resistance and UV sensitivity. To solve these problems, biopolymers can be blended with other materials that offer tailored properties, and nanocomposites can also enhance the performance of biopolymer-based materials [212,214]. Production cost is another challenge for biopolymer-based materials, which can be solved through larger production runs [215].

(b) Fire Properties

Fire is a severe threat to humans and buildings. Biopolymers can play a role as a protection from fire to constructions and humans. Biopolymers need to improve their flammability by adding flame retardants, including metal oxides, nano compounds, cellulose fillers, IFRs, and phosphorus-containing chemicals [185]. The flammability and flame retardancy of biopolymer-based materials are important, especially in the thermal insulation of building materials. Natural fibres are highly flammable, and evaluating their fire resistance for safety is important. Different types of flame retardants, such as fillers or coatings, can be added to reduce combustibility and enhance fire resistance. For example, metal oxide (Sb_2O_3) and a phosphate-based additive were added as flame retardants to PBAT and PHBV [212]. Magnesium hydroxide filler is also a great example of a fire retardant which can improve the fire retardancy of biopolymer-based materials [215]. To improve the fire resistance of biopolymer-based materials, additives are added while producing biopolymer composites. These additives, such as zirconia and alumina, do not stick to the material but improve fire resistance and thermal stability by hindering ignition or flame spread, and some of them create less smoke while burning [216]. Reactive flame retardants can be added to the biopolymers, which stick to the biopolymer materials and ensure long-lasting fire protection [216]. The intentional design of novel architecture and structures is another way to enhance the flame retardancy of biopolymer-based materials. There are many techniques, such as electron-beam cross-linking of flame retardants, plasma flame-retardant treatments, sol–gel flame-retardant treatment, and layer-by-layer nano-deposition. Some of these techniques alter the molecular or supramolecular arrangement of biopolymers and make them naturally more resistant to catching fire or burning [217,218].

(c) Market Acceptance

Building industry and consumer acceptance of biopolymer cladding materials may take time, as these materials are relatively new and may require education and awareness-building efforts. PLA is biodegradable and moderately cost-effective. PHAs have varying properties depending on their composition. They are biodegradable but relatively more expensive. PHB is biodegradable and relatively more expensive. PBAT and PBS are both biodegradable and moderately cost-effective. SBP has lower mechanical properties and is less cost-effective. CBP has medium tensile strength and is less cost-effective. SBP has lower mechanical properties and is less cost-effective. Cellulose-based polymers have medium tensile strength and are less cost-effective. The best biopolymer for biopolymer-based cladding would depend on the specific project requirements, environmental considerations, and budget constraints. Different biopolymers may be suitable for different applications based on their properties and performance characteristics [219,220].

7. Conclusions

In conclusion, the increasing demand for sustainable construction materials has led to a shift towards exploring biopolymer-based materials for cladding applications. The limitations of conventional synthetic polymers have necessitated the search for alternatives that offer improved environmental compatibility and reduced ecological impact. The unique attributes of biopolymers, including biodegradability, renewability, and low embodied energy, position them as promising candidates for transforming the cladding landscape. Integrating biopolymers into synthetic polymers further enhances their biodegradability, contributing to sustainable waste management practices. Notable biopolymers such as PLA, PHAs, starch-based polymers, cellulose, PHB, and PBS have gained attention for their potential in cladding applications. The expanding biopolymer market underscores their growing importance in driving innovation and addressing environmental concerns in the construction industry. However, the current research landscape reveals a research gap in exploring the comprehensive use of biopolymer materials in building cladding. While various biopolymers exhibit promising properties, further research is needed to assess their suitability for specific cladding applications, considering factors such as physical, chemical, thermal, ecological, and economic impacts. A holistic understanding of these materials' properties and potential challenges will pave the way for their successful integration into sustainable construction practices. As the construction industry strives for greener and more sustainable solutions, biopolymer-based cladding materials hold the promise of meeting these demands and contributing to a more environmentally conscious built environment.

1. Suitable Shift: The increasing demand for sustainable construction materials is leading towards biopolymer-based cladding applications, which help to overcome the limitations of traditional synthetic polymers.
2. Environmental Compatibility: Biopolymers, with ultimate attributes of biodegradability, renewability, and low embodied energy, reduce ecological impact and offer better environmental compatibility.
3. Integration for Sustainability: Integrating biopolymers with synthetic polymers such as PLA, PHA, and starch-based biopolymers improves biodegradability for sustainable waste management.
4. Research Gap and Future Directions: Despite biopolymers being promising, a research gap exists in the comprehensive use of biopolymers in cladding. Further research studies are essential to assess their suitability for specific applications and promote successful integration into sustainable construction practices.

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