Interactions (2024) 245:288
https://doi.org/10.1007/s10751-024-02116-4

RESEARCH

Greening packaging: a step towards biopolymers in multilayer films

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Accepted: 31 August 2024

Abstract
Synthetic polymers, both in monolayer and multilayer forms, have been widely utilized in the packaging industry for several decades. However, they have faced significant competition from other biodegradable materials such as paper and paperboard laminates in flexible packaging applications. The inherent structure of synthetic polymers affords them various properties such as flexibility, strong barrier capabilities, and favourable physical and optical characteristics. Moreover, they often prove to be economically advantageous given prevailing market prices.

With the escalating challenges of solid waste management and the diminishing reserves of natural fossil fuels, which serve as the raw materials for synthetic polymer production, there has been growing interest in biopolymers as an eco-friendly alternative for packaging materials. However, biopolymers must demonstrate comparable barrier properties to synthetic polymers, particularly concerning oxygen and moisture transmission rates. While biopolymers, like paper, offer biodegradability advantages, paper typically lacks the requisite strength and exhibits poor barrier properties.

Various formulations have been explored, incorporating different biopolymers through grafting and blending techniques, aimed at enhancing overall performance. This paper investigates the theoretical foundations supporting the future potential of biopolymers in packaging, explaining their types and the intricate relationship between their structures and properties as a greener alternative.

Keywords Biopolymers · Green polymers · Biodegradable polymers · Compostable polymers · Recyclable polymers

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Published online: 23 September 2024

1 Introduction

In the realm of packaging materials, the discussion often centers on synthetic polymers and their eco-friendly alternatives, particularly biopolymers. Synthetic polymers, used in both monolayer and multilayer forms, have dominated the packaging industry for decades. However, they now face increasing competition from paper and paperboard laminates, which are favored in flexible packaging applications. Synthetic polymers are valued for their flexibility, strong barrier capabilities, and desirable physical and optical characteristics. Additionally, their economic benefits make them a popular choice given current market conditions.

Biopolymers, however, are gaining traction as a greener alternative due to their potential to lessen reliance on fossil fuels and reduce the environmental impacts associated with traditional synthetic polymers. The diverse structures and properties of biopolymers make them promising candidates for various packaging applications. With the growing challenges of solid waste management and the depletion of fossil fuel reserves used in synthetic polymer production, biopolymers are increasingly viewed as an eco-friendly option. Nonetheless, to be viable alternatives, biopolymers must exhibit barrier properties comparable to those of synthetic polymers, particularly in terms of oxygen and moisture transmission rates. While biopolymers, like paper, offer biodegradability advantages, paper often falls short in strength and barrier performance [1].

Innovative formulations are being explored to enhance biopolymer performance through grafting and blending techniques. This paper delves into the theoretical foundations of biopolymers as a sustainable packaging solution, highlighting their types and the complex relationship between their structures and properties as greener alternatives [2].

The term “biodegradable” often conjures images of materials decomposing effortlessly and leaving no lasting trace. However, what does this term truly entail? According to the Standard Terminology Relating to Plastics ASTM D883-23, biodegradable plastics are those in which degradation results from the action of naturally occurring microorganisms such as bacteria, fungi, and algae [3]. The rate of biodegradation can vary depending on factors like humidity, temperature, and specific environmental conditions [4].

In today’s context, there is a strong desire for individuals and organizations to be perceived as environmentally conscious, often referred to as “green” [5]. However, there is also a concern about “greenwashing,” where exaggerated or misleading claims about environmental benefits are made. Ironically, the use of progressive-sounding environmental terminology can sometimes limit our choices and freedoms.

For waste disposal, two key terms are “recyclable” and “degradable,” with the latter further categorized into “biodegradable” and “compostable.” Refer Fig. 1.

Many within the plastics and packaging industries have noticed this lesson earnestly. Nowadays, sustainability claims regarding materials are often accompanied by certifications from recognized authorities to substantiate their credibility.

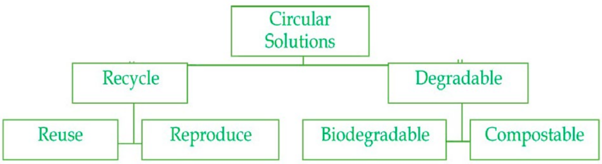

Fig. 1 Circular solutions

However, complications arise, particularly with multi-layered films or tubes featuring adhesives, coatings, or laminations. For instance, a detailed description might reveal a structure comprising two layers: one less than 50 µm thick and the other 90 µm thick, with adhesive sandwiched between them. Surprisingly, such a construction could claim a significantly smaller carbon footprint compared to an equivalent Coex film with equal layers. The question then arises: should this film be certified as a monolayer and recycled under a single material stream, or designated as double-walled and certified as non-recyclable, albeit with a greater carbon footprint than any mono-layered film? Moreover, if one layer of such a film is biodegradable with water or solid waste material, the whole film can not be labelled as biodegradable and considered a "circular solution" [6, 7]?

While biopolymers hold promise, they often face challenges in achieving performance equivalence with synthetic polymers, particularly in barrier properties and processing efficiency. Additionally, the variability in sourcing raw materials (e.g., agricultural products for soy protein and whey) can impact cost and scalability.

Moreover, the transition from traditional synthetic polymers to biopolymers involves navigating regulatory frameworks and consumer perceptions. Clear definitions and standards (e.g., biodegradability certifications) are crucial to prevent greenwashing and ensure accurate environmental claims in packaging materials [8].

Given the potential for confusion and misrepresentation, regulations governing plastics and packaging products must become more stringent and precisely articulated. Exaggerated claims about recycling achievements should be avoided, and adherence to factual accuracy should be paramount.

1.1 Understanding the terminology

Therefore, it is essential to delve into the accurate terminology, illustrated with examples in Fig. 2:

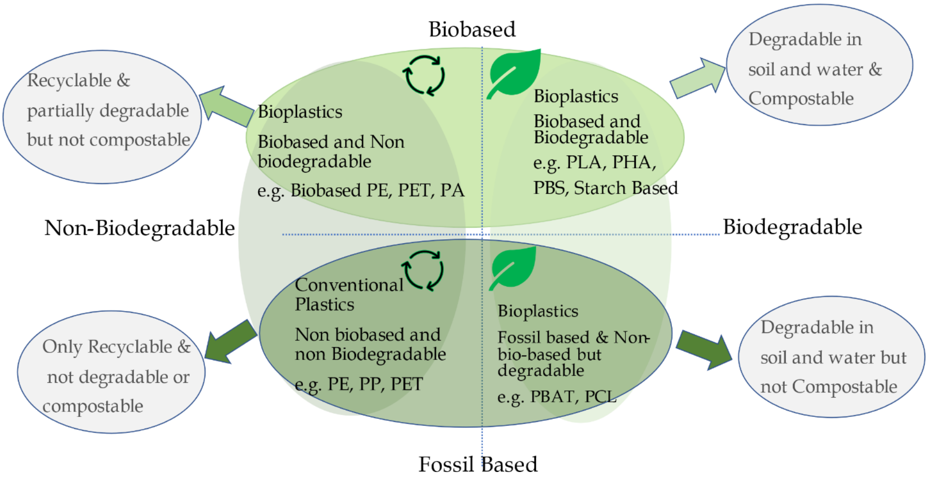

Fig. 2 Types of biopolymers

1.2 Biodegradability vs. composting

In today's plastics landscape, there is often confusion between biodegradability and composting. Although both terms pertain to the breakdown of materials, they differ in their processes and environmental impacts. Biodegradable plastics [9, 10] can decompose into natural components under various conditions, whereas compostable plastics specifically break down into compost [11], which enriches soil health.

Consumers frequently conflate terms like "biodegradable" with "bio-based," presuming that products derived from natural sources inherently possess biodegradability. However, various factors, such as the material's chemical structure and crystallinity, influence biodegradability. Consequently, while some bio-based plastics may not readily biodegrade, certain petroleum-based plastics can exhibit biodegradable properties, as illustrated in the Fig. 2.

1.3 Properties and structural considerations

Biopolymers offer unique advantages such as biodegradability and renewability, which are increasingly valued in sustainable packaging. However, their structural complexity and variability require tailored processing techniques to optimize their properties. For instance, blending biopolymers or modifying their molecular structure through chemical treatments can enhance mechanical strength, barrier properties, and water resistance.

Biopolymers exhibit a wide range of structures and properties due to the diversity of their natural sources. This variability can pose challenges in processing and application, requiring specific techniques to tailor their properties to meet the demands of various packaging applications.

1.3.1 Tailored processing techniques

To enhance the properties of biopolymers for packaging, several processing techniques are employed:

1.3.1.1 Blending Blending involves combining two or more biopolymers to create a material with enhanced properties. For example, blending polylactic acid (PLA) with polyhydroxyalkanoates (PHAs) can improve the flexibility and toughness of the resulting material. This technique allows for the customization of properties to suit specific applications.

1.3.1.2 Chemical modifications Chemical treatments can be used to modify the molecular structure of biopolymers, enhancing their performance. For instance, cross-linking, grafting, and copolymerization are common methods used to improve mechanical strength, barrier properties, and water resistance. Cross-linking creates a network of bonds between polymer chains, increasing the material's strength and stability. Grafting involves attaching functional groups to the polymer backbone, which can improve compatibility with other materials and enhance specific properties.

1.3.1.3 Plasticizers Adding plasticizers to biopolymers can increase their flexibility and reduce brittleness. Plasticizers work by inserting themselves between polymer chains, reducing intermolecular forces and allowing the chains to move more freely. This is particularly useful for applications requiring flexible packaging materials.

1.3.1.4 Nanocomposites Incorporating nanoparticles into biopolymers can significantly enhance their barrier properties and mechanical strength. Nanocomposites can provide improved gas and moisture barrier performance, making them suitable for food packaging applications where shelf life is a concern.

1.3.2 Enhancing specific properties

1.3.2.1 Mechanical strength To compete with synthetic polymers, biopolymers must exhibit sufficient mechanical strength. Techniques like blending with stronger biopolymers, incorporating reinforcing fillers, and using chemical cross-linking can enhance the mechanical properties of biopolymers, making them suitable for more demanding packaging applications.

1.3.2.2 Barrier properties Effective barrier properties against gases and moisture are crucial for many packaging applications. Biopolymers often require modifications to achieve these properties. For example, coatings or multilayer structures can be used to enhance barrier performance. Additionally, the incorporation of nanomaterials or the use of certain chemical treatments can improve the material's resistance to gas and moisture transmission.

1.3.2.3 Water resistance Many biopolymers are hydrophilic, meaning they absorb water, which can be detrimental to their performance in packaging. Chemical modifications, such as acetylation or the addition of hydrophobic groups, can improve the water-resistance of biopolymers. Creating multilayer structures with a water-resistant outer layer is another effective approach.

Biopolymers hold significant promise for sustainable packaging solutions due to their biodegradability and renewability. However, their inherent structural complexity and variability necessitate tailored processing techniques to optimize their properties for specific applications. By employing methods such as blending, chemical modifications, the use of plasticizers, and the incorporation of nanocomposites, biopolymers can achieve enhanced mechanical strength, barrier properties, and water resistance. As research and development in this field continue to advance, biopolymers are likely to play an increasingly important role in the future of sustainable packaging [12].

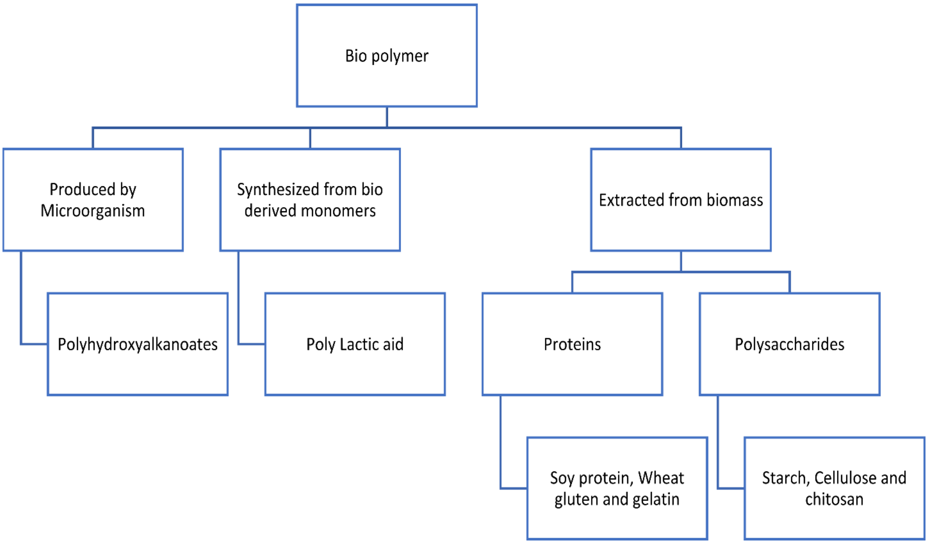

Fig. 3 Classification of biopolymers

2 Types of biopolymers

Despite many chemicals being used during pulp and paper milling, either desired properties are not acquired, or a lot of energy is consumed, and waste is generated. Polyacrylamides, EVA, PE, and styrene acrylates all are coated to increase the mechanical and barrier properties of paper substrates, but all these are non-biodegradable and possess toxicity concerning the life cycle of paper products. Biopolymer materials having specific desired properties are formulated to make the paper suitable as a packaging material.

Great attempts have been made to formulate biopolymers that have considerable strength (tensile strength, elongations, and tear resistance). These have been divided/categorized based on primary functional groups. Among them, starch and polylactic acid have shown remarkable results [13]. Refer Fig. 3. For types of biopolymers.

2.1 Protein-based biopolymers

Proteins from both plant and animal resources can make polymeric compounds that could be used to coat over paper. Protein films having sufficient mechanical strength have been extruded. They have shown excellent barrier and gas resistance properties against several gases. They have also been able to preserve the odour and colour of food items packed inside. This has enabled them to be used to wrap several food items. Their hydrophilic nature allows them to absorb water therefore leading to higher water vapor permeation and less water resistivity [14, 15].

2.1.1 Caseins

Caseins are protein structures found in milk. These are less soluble in water and can act as emulsifiers. They are used to formulate edible food coatings and sprayed over food products to improve/alter the surface properties. Sodium caseinate (NaCAS) shows intermolecular hydrogen bonds. These are hydrophobic and random, leading to high inter-branching and good film-forming capability. Further, they also possess a good barrier against oxygen transmission due to their polar nature. This makes them suitable for coating on paper and having multiple applications of the coated paper. Casein, derived from milk, forms a viscoelastic gel structure due to its amphiphilic nature. It can be used to produce films and coatings with excellent barrier properties against gases and aromas. Casein films are biodegradable but may require modifications to enhance their water resistance and mechanical strength for packaging use [16].

2.1.2 Whey protein

These are proteins extracted from cheese products and are obtained usually as by-products along with different varieties of cheese. Whey protein films have lower oxygen permeation rates and are resistant to movement of aroma and grease. The transmission rates are comparable to widely used synthetic oxygen barrier coatings such as Ethylene Vinyl Alcohols. These films are heavily crosslinked due to intermolecular disulphide bonds. Different research has shown the advantages of coating whey protein over paper to get desired modifications in the properties of paper substrate. However, getting an even coating and compatibility between paper and whey protein coatings remains a challenge. Whey protein, a byproduct of cheese production, is another biopolymer explored for packaging. Its structure includes globular proteins such as β-lactoglobulin and α-lactalbumin, which can form films with good mechanical strength and barrier properties. However, its water sensitivity remains a challenge for certain applications [17].

2.1.3 Soy protein

Derived from plant resources, soy films are weak and have poor water vapour barrier properties due to the hydrophilic nature of their intermolecular bonds. They are crosslinked using agents such as formaldehyde or montmorillonite clay. The gas and oil barrier properties of soy protein isolate coatings are good enough to enable them to be used for such applications where oily substances are to be handled. Soy protein is derived from soybeans and can be processed into films and coatings suitable for packaging. Structurally, it consists of amino acids linked by peptide bonds, forming a flexible polymer network. This network provides good film-forming ability and barrier properties against oxygen and moisture, comparable to synthetic polymers in some applications [18].

Biopolymers like soy protein, whey protein, casein, and chitosan present viable alternatives to synthetic polymers in packaging applications. Their structures and properties can be tailored through advanced processing techniques to meet specific performance requirements. However, achieving widespread adoption hinges on addressing technical challenges, enhancing regulatory clarity, and aligning with evolving sustainability goals in the packaging industry.

2.2 Polysaccharide-based biopolymers

These are the most widely available and most widely used biopolymers. Like proteins, polysaccharides also have good film-forming capabilities but are more prone to water vapour diffusion owing to the hydrophilic nature of their bonds [19, 20].

2.2.1 Chitosan

With strong film-forming capability and appreciable barrier against several migrants, chitosan has been suitable for many applications and therefore is used as an additive in the paper-making process. Its high crystallinity and polar nature make it a great barrier against oxygen, gases, and oils. Hence it is being used in the packaging of many materials in conjunction with a paper substrate. Chitosan is derived from chitin, a natural polymer found in the shells of crustaceans like shrimp and crabs. Its structure consists of repeating units of glucosamine and N-acetylglucosamine. Chitosan films exhibit antimicrobial properties, making them suitable for food packaging applications. They also show good barrier properties against oxygen, but their water vapor barrier needs improvement for broader use [21].

2.2.2 Starch

Starch is considered a renewable and cheap resource for making biodegradable plastics and coating materials. Starch-based films are strong, odourless, colourless, and tasteless. They are relatively inexpensive and readily available. Modified starches or starch derivatives have been used to improve mechanical properties. However, native starch cannot be utilized as a thin film because of its strong intermolecular hydrogen bonding and dense packing structure, leading to brittleness. To overcome this, plasticizers are used. Plasticized starch can then be extruded into thin films or coatings. However, these films exhibit high water vapour transmission rates, which limits their application in humid environments [22].

2.3 Lipid-based biopolymers

Lipid-based biopolymers are derived from natural oils and fats, often employed for their hydrophobic properties, which can enhance water resistance in paper coatings. They are often combined with other biopolymers to improve barrier properties against moisture and gases [23].

2.3.1 Waxes and fats

Natural waxes and fats, such as beeswax and carnauba wax, have been used to coat paper, providing excellent water vapour resistance. These coatings can be applied using techniques like spraying or dipping. However, their application is limited by their brittleness and the potential for migration of wax components into the packaged product [24].

2.3.2 Polyhydroxyalkanoates (PHAs)

PHAs are a family of biodegradable polyesters produced by microbial fermentation of sugars or lipids. They exhibit properties similar to those of synthetic thermoplastics but are biodegradable. PHAs have been researched for coating applications due to their good barrier properties and biodegradability. However, their high production costs remain a challenge for widespread application [25, 26].

2.3.3 Poly lactic acid (PLA)

These belong to a category of biopolymers synthesized from naturally biologically available monomer units. PLA [27, 28] is compostable and is also recognized as a safe component by food quality checking authorities. PLA films have high transparency and good processability. Their high crystallization though makes them rigid. Also, the synthesis of PLA from a monomer unit is difficult. Conventionally produced by ring-opening polymerization, new techniques involving direct polycondensation have been researched off late to make them economically more viable.

Lactic acid degradation does not allow easy polymerization into long chain poly lactic acid molecules. Further D/L configuration affects their properties as well. Hence maintaining the process parameters during PLA synthesis is very important. Direct polycondensation and ring-opening polymerization are the methods used to synthesize PLA from lactic acid.

Direct polycondensation of lactic acid involves dehydrating lactic acid and condensing it with low molecular weight polylactic acid. This is further improvised by using chelating agents and other sizing additives to increase molecular weight and hence the tensile strength of PLA film.

Ring-opening polymerization is a more widely used method to synthesize PLLA/PDLA as it gives more control as compared to direct polycondensation. This method involves the formation of lactide molecules and using catalysts and initiators to open the lactide ring and support long-chain formations of lactic acid. Lactic acid monomers form a chain upon dehydration at around 150 °C to give oligomers of lactic acid. Further increasing the temperature and reducing pressure leads to the formation of lactide ring crystals. These lactide rings when opened using Zinc and tin-based catalyst, give long chain poly Lactic acid macromolecules. Isotactic D/L lactic acid chains tend to have crystalline PLA films with a well-defined structure. Meso configuration of random D and L units of Lactic acid in PLA have an amorphous nature which gives a range of melting points and elasticity to PLA films.

3 Advantages and challenges of biopolymers

Biopolymers offer several advantages over synthetic polymers, such as biodegradability, reduced reliance on fossil fuels, and the potential for compostability. However, they also face significant challenges, including inferior mechanical and barrier properties compared to synthetic polymers, higher production costs, and limited availability. Find the summary of Advantages, challenges and Properties comparison with synthetic polymers of biopolymers in Table 1.

Table 1 Advantages, challenges and properties comparision with synthetic polymers of biopolymers

	Biopolymer	Advantages	Challenges	Properties Comparison with Synthetic Polymers
1	Protein-Based Biopolymers			
	Protein-Based Biopolymers	Biocompatible, biodegradable, renewable	Variable mechanical properties, sensitivity to moisture, potential for allergenicity	Typically, more biocompatible and biodegradable than synthetic polymers
	Caseins	Good film-forming properties, excellent oxygen barrier	Susceptibility to moisture, limited mechanical strength	Better oxygen barrier properties, less mechanical strength than many synthetic polymers
	Whey protein	Good barrier properties, high nutritional value	Sensitivity to heat and moisture, potential allergenicity	Superior barrier properties, but more sensitive to environmental conditions
	Soy Protein	Renewable, good film-forming properties, relatively low cost	Poor mechanical properties, sensitivity to moisture and pH variations	More environmentally friendly, but generally weaker mechanically
2	Polysaccharide-Based Biopolymers			
	Chitosan	Biodegradable, biocompatible, antimicrobial properties	Limited mechanical strength, solubility issues in water	Superior biodegradability and antimicrobial properties, but often less strong mechanically
	Starch	Renewable, biodegradable, low cost	High sensitivity to moisture, poor mechanical properties	Better biodegradability and cost-effectiveness, but significantly less durable
3	Lipid-Based Biopolymers			
	Waxes and Fats	Good barrier properties, renewable	Low mechanical strength, limited applications due to brittleness	Better barrier properties in some applications, but weaker and more brittle
4	Polyhydroxyalkanoates (PHAs)			
	Polyhydroxyalkanoates (PHAs)	Biodegradable, good mechanical properties, produced from renewable resources	High production cost, complex manufacturing process	Comparable mechanical properties, and superior biodegradability, but more expensive to produce
	Poly Lactic Acid (PLA)	Biodegradable, compostable, derived from renewable resources	Brittleness, sensitivity to heat, slower degradation in certain environments	Better biodegradability and renewability, but less thermal stability and more brittle

3.1 Advantages

3.1.1 Advantages of bioplastics

- carbon footprint.
- energy savings in production.
- not involve the consumption of non-renewable raw materials.
- reduces non-biodegradable waste that contaminates the environment.
- not contain additives that are harmful to health, such as phthalates or bisphenol A.
- not change the flavour or scent of the food contained.

Table 2 Advantages, challenges and properties comparison with synthetic polymers of biopolymers [14–28]

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3.1.2 Environmental benefits

Biopolymers can reduce the environmental impact associated with plastic waste and fossil fuel depletion. They are derived from renewable resources and are often biodegradable or compostable.

3.1.3 Reduced carbon footprint

The production and disposal of biopolymers generally result in lower greenhouse gas emissions compared to synthetic polymers.

3.1.4 Consumer appeal

As consumers become more environmentally conscious, the demand for sustainable packaging solutions increases. Biopolymers can help companies meet these consumer preferences and enhance their brand image.

3.1.5 Fabrication techniques

The same fabrication techniques can be used for synthetic polymers which are applied to biopolymers.

3.2 Challenges

3.2.1 Mechanical properties

Biopolymers often exhibit inferior mechanical properties, such as lower tensile strength and impact resistance, compared to synthetic polymers. This can limit their application in certain packaging scenarios.

3.2.2 Barrier properties

Many biopolymers have poor barrier properties against moisture, oxygen, and other gases, which can affect the shelf life and quality of packaged products.

3.2.3 Cost and scalability

The production of biopolymers is often more expensive than that of synthetic polymers due to higher raw material costs and less established manufacturing processes. This can hinder their adoption in cost-sensitive markets.

3.2.4 Processing and compatibility

Integrating biopolymers into existing production lines and ensuring compatibility with other packaging materials can be challenging. Additionally, biopolymers may require different processing conditions compared to synthetic polymers.

4 Film properties

4.1 Sealing properties

The packaging material used must be sealed securely. A good seal prevents material and volatiles from leaking out. It reduces the possibility of microbial contamination while also reducing variations in headspace gases and moisture content. As a result, in order to prevent quality changes and assure the safety of food items, the integrity of the seal area must be considered in flexible food packaging [29].

There are various techniques for sealing flexible packaging film. These procedures can involve the application of a cold-seal adhesive coating to the inner surface of the packing sheet or the melting and combining of sealant layers utilising heat sealing [30].

Heat sealing is the most prevalent method for shaping and closing plastic packaging materials in the food business, and it has been used for decades [31].

4.2 Barrier properties

Small molecules from the inside and/or outside of a package can travel through polymer films, affecting the quality of packed goods. Aroma is one of the most important quality requirements for a wide range of food and consumer goods. Flavour loss, scalping, and/or contamination can occur as a result of aroma transmission via packing materials, resulting in poor product quality [32].

Specific gases, aromas/odour, moisture vapour, water, oil, and grease should not penetrate a barrier coating or film applied to paper-based food packaging, as this might impair the sensory and sanitary integrity of the packed food product. Due to the oxidation or rancidity of unsaturated fats, gases, particularly oxygen, can cause discolouration, off-flavours, and texture changes in food. Hydrophobic Petro-based polymers such as PP, PVC, and PE are most commonly employed in food packaging as films or paper coatings for water vapour resistance. Grease resistance and water hydrophobicity are the major barrier qualities needed for short-term retail applications such as pizza, burgers, cookies, ice cream, and so on [33].

4.3 Water vapor permeability

The transmission rate of water vapour through thin film layers of biopolymers quantifies the barrier of biopolymers against moisture. It is measured by placing the test sample at standard test conditions and purging humid air through it. The transmission rate calculates the amount of vapour passing through the film in unit time. Multiple standard conditions are defined by the standard regulating authorities. The selection of correct conditions depends on film properties. The transmission rate is affected by the thickness and density of the film and test chamber envrionment. Material hygroscopicity affects the rate at which moisture transmits. Hence a better barrier can be achieved by having less porous, smooth surfaces [34].

4.4 Oxygen permeability

The oxygen barrier is another important characteristic desired in paper coatings. Inherently paper products have poor barriers and hence the coatings must provide a barrier against oxygen movement to keep food packed inside intact. Dense structures with small pore sizes are favourable to keep transmission rates low. OTR values are dependent on temperature and relative humidity maintained while conducting the tests. Like WVTR, multiple standards are defined for measuring oxygen transmittance as well [35].

4.5 Mechanical properties

The mechanical properties of thin films are evaluated to study the material properties such as Young's Modulus of elasticity and tensile strength. They convey more information about the intermolecular bonds and intermolecular forces being experienced at the atomic level in the formulation to be used as paper coatings. Yield strength, ultimate strength, elongation at break and stress-strain relation of the material define its mechanical properties. Young's modulus, which is the ratio of stress to strain, is the ratio quantifying the elasticity of a material. Plastic materials show permanent deformations and do not restore to their original shapes. Brittle polymer films have high young's modulus values, as they do not elongate much and rupture under stress without being much deformed. Apart from tensile strength, which measures the force a material can withstand in the axial direction, burst strength gives the amount of force required to break film by applying force perpendicular to the film/sheet.

$\sigma = \frac{F}{A}$, where σ is the stress experienced by the film
$\epsilon = \frac{\delta}{L}$, where ε is strain and δ is elongation in film
$E = \frac{\sigma}{\epsilon}$

Among different paper grades, kraft paper has high burst strength. Adding wet and dry strength additives further increases their strength. Using biopolymer coatings allows to increase their strength as the coatings form a thin film of their own and adhere to the paper surface. This results in increased strength of the coated paper and also makes it more flexible [36, 37].

4.6 Crystallinity

The behaviour of polymeric films is influenced by atomic arrangement at their lattices. Amorphous structures have randomly arranged atoms and therefore less strength. This short-chain random structure allows them more flexibility as compared to crystalline structures. Crystalline films on the other hand have high strength and strong intermolecular forces, making the film tough to break. Elastic films having crystalline structures are therefore laminated with amorphous films that could be sealed easily. Biopolymer films have weak intermolecular forces and hence their crystallinity becomes an important characteristic to control. Different plasticisers are used to alter the surface properties and change the crystallinity of the film. This also controls the adherence of coating to the paper substrates. Usually, crystalline films have less surface tension compared to amorphous materials owing to their smooth texture which allows less interlocking between molecules [38].

4.7 Molecular weight

The molecular weight of the film/coating is another important characteristic property which is affected by the degree of polymerization. Higher average molecular weight tends to have higher tensile strength. Bigger macromolecules have a high tendency to branch out. This makes their intermolecular bonding stronger and increases their strength [39].

5 Future directions

To overcome the limitations of biopolymers and enhance their adoption in the packaging industry, several strategies can be pursued:

5.1 Research and development

Continued research into the modification and improvement of biopolymer properties is essential. This includes developing new biopolymer formulations, blending biopolymers with other materials, and investigating novel processing techniques. Advances in nanotechnology and biopolymer composites hold promise for enhancing mechanical and barrier properties [40].

5.2 Cost reduction

Efforts to reduce the production costs of biopolymers are crucial for their wider adoption. This can be achieved through optimizing raw material sources, improving fermentation and extraction processes, and scaling up production facilities. Government incentives and subsidies for sustainable materials can also play a role in making biopolymers more economically viable [41, 42].

5.3 Regulatory support

Clear and supportive regulatory frameworks can encourage the use of biopolymers in packaging. This includes establishing standards for biodegradability and compostability, promoting the use of renewable materials, and providing guidelines for labelling and certification [43].

5.4 Industry collaboration

Collaboration between industry stakeholders, including material suppliers, packaging manufacturers, and end-users, is vital for the successful integration of biopolymers into the packaging market. Sharing knowledge, resources, and best practices can accelerate the development and adoption of sustainable packaging solutions [44].

5.5 Consumer education

Educating consumers about the benefits and proper disposal of biopolymer-based packaging can enhance their acceptance and use. Clear labelling and communication about the environmental advantages of biopolymers can drive consumer demand for sustainable packaging [45].

6 Conclusion

Biopolymers represent a promising alternative to synthetic polymers in the packaging industry, offering significant environmental benefits and aligning with the growing demand for sustainable solutions. Derived from renewable resources, biopolymers can help reduce the reliance on fossil fuels and decrease the environmental impact associated with traditional plastic production and disposal.

However, several challenges need to be addressed to fully realize the potential of biopolymers. These include issues related to their mechanical and barrier properties, which are often inferior to those of conventional plastics. For instance, biopolymers may exhibit lower strength, flexibility, and resistance to moisture and gases, making them less suitable for certain packaging applications.

Cost is another significant barrier. Currently, the production of biopolymers is often more expensive than that of synthetic polymers due to factors such as raw material costs, processing complexities, and lower economies of scale. This cost disparity can make it difficult for biopolymers to compete in the market.

Scalability is also a critical challenge. The production processes for biopolymers need to be optimized to support large-scale manufacturing without compromising quality or environmental benefits. This requires advances in technology and infrastructure to enable efficient and sustainable production at a commercial scale.

To overcome these challenges, continued research and development are essential. Innovations in material science can lead to improved properties of biopolymers, making them more competitive with traditional plastics. Additionally, efforts to reduce production costs through technological advancements and increased production volumes can help make biopolymers more economically viable.

Regulatory support and industry collaboration are also crucial. Governments can play a key role by implementing policies that promote the use of biopolymers, such as subsidies, tax incentives, and stricter regulations on conventional plastics. Collaboration within the industry can drive standardization, share best practices, and foster innovation.

Lastly, consumer education is vital for the widespread adoption of biopolymers. Raising awareness about the environmental benefits and performance of biopolymer-based packaging can drive consumer demand and support market growth.

In summary, while biopolymers offer a promising path towards more sustainable packaging solutions, addressing their mechanical and barrier properties, cost, and scalability issues is essential. Through ongoing research, cost reduction efforts, regulatory support, industry collaboration, and consumer education, biopolymers can become a viable and widely adopted solution for greener packaging.

Acknowledgements Dr. Nimish Shah and Dr. Mamta Saiyad are thankful to GUJCOST (GUJCOST/STI/2023-24/374 dated 4th May 2023), Gandhinagar, Gujarat State - INDIA for the financial support.

Author contributions Dr. Nimish Shah and Dr. Mamta Saiyad wrote the main manuscript text and both of them done the research and prepared all the figures. All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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