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REVIEW

Recent Advances, Challenges, and Analytical Perspectives in Starch-Based Bioplastics

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ABSTRACT: The environmental concerns of petroleum-based plastics, including their non-biodegradability, contribution to pollution, and reliance on finite fossil resources, have motivated growing global interest in biodegradable alternatives, with starch-based bioplastics emerging as a promising solution due to their renewability, biodegradability, cost-effectiveness, and compatibility with existing processing technologies. This review synthesizes recent developments, challenges, and analytical techniques related to starch-based bioplastics. It examines the physicochemical properties of starch, modification methods such as plasticization, blending, and chemical treatments, and key production techniques including extrusion, injection molding, and 3D printing. Mechanical, thermal, and barrier properties are evaluated through standardized testing approaches, and the influence of various additives is discussed in detail. While starch-based bioplastics show potential in packaging, agriculture, and biomedical applications, they face limitations related to moisture sensitivity, thermal instability, and production scalability. Analytical tools like Scanning Electron Microscope, X-ray Diffraction, and Thermogravimetric Analysis provide critical insights into structural and functional optimization. The review also addresses sustainability metrics through life cycle analysis and outlines key barriers to commercialization. Overall, starch-based bioplastics represent a viable path toward a circular economy, contingent upon continued innovation and policy support.

KEYWORDS: Advances; biodegradability; challenges; mechanical properties; physicochemical properties; renewable resources; starch-based bioplastics; thermal stability

1 Introduction

The global dependency on petroleum-based plastics has led to a severe environmental crisis, primarily due to plastic pollution and the unsustainable depletion of fossil fuel resources. Over 300 million metric tons of plastic are produced annually, with a significant portion accumulating in landfills and marine ecosystems, where they persist for hundreds of years, disrupting ecological balance and endangering wildlife [1,2] The urgency to transition toward biodegradable and sustainable alternatives has intensified, prompting policymakers, researchers, and industries to explore eco-friendly polymer solutions. The European Green Deal, among other international policies, actively promotes biodegradable materials as a key step toward

achieving a circular economy and carbon neutrality by 2050. Within this context, starch-based bioplastics have emerged as one of the most promising sustainable alternatives due to their abundant availability, biodegradability, and cost-effectiveness [3]. Starch, a naturally occurring polysaccharide, is widely available from renewable agricultural sources such as corn, wheat, cassava, and potatoes. Its biodegradability, renewability, and compatibility with conventional plastic processing techniques make it a strong candidate for replacing synthetic polymers in various applications, including food packaging, biomedical devices, and agricultural films [4,5]. Unlike petroleum-based plastics, which require centuries to degrade, starch-based bioplastics decompose within months under suitable environmental conditions, significantly reducing the risk of long-term environmental pollution [6]. Moreover, the adoption of starch-based bioplastics aligns with global sustainability initiatives aimed at reducing greenhouse gas (GHG) emissions, mitigating resource depletion, and fostering the circular economy concept [7]. Despite their potential benefits, starch-based bioplastics face several technical and economic challenges that hinder their large-scale commercialization. One of the primary limitations is their inherent hydrophilicity, which makes them highly susceptible to moisture absorption, leading to poor mechanical properties and low durability in humid environments [8]. Additionally, their low thermal stability restricts their application in high-temperature conditions, making it difficult to process them using conventional thermoplastic manufacturing techniques like extrusion and injection moulding [3]. Addressing these limitations requires extensive research into material modifications, polymer blending, and reinforcement strategies. For instance, the incorporation of nano-fillers such as cellulose nanofibers, montmorillonite, and graphene oxide has been shown to enhance the mechanical strength, barrier properties, and thermal stability of starch-based bioplastics [4]. The economic feasibility of starch-based bioplastics remains another significant challenge. Compared to conventional plastics, the production costs of bioplastics are higher due to raw material sourcing, processing complexities, and the need for functional additives to improve performance [9]. Furthermore, the competition for starch as a food resource raises ethical and sustainability concerns, as increased demand for starch-based polymers could impact food security, particularly in developing regions [8,10]. To address these issues, researchers are exploring alternative sources such as agricultural waste, microalgae-derived starch, and genetically engineered crops with higher starch yields [7]. Innovations in production technologies, coupled with policy incentives and industry collaborations, are crucial to making starch-based bioplastics a commercially viable alternative. Advancements in analytical and characterization techniques have also played a critical role in improving the understanding of starch-based bioplastics. Techniques such as scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and thermogravimetric analysis (TGA) have been widely employed to investigate the structural, thermal, and mechanical properties of starch-based materials [11]. SEM offers valuable insights into the surface morphology of bioplastic films. By producing high-resolution micrographs, it allows researchers to visualize how starch granules, plasticizers, and fillers are distributed within the matrix. Such images often reveal distinct differences between native and modified systems. Native starch films typically display granular, uneven, or porous surfaces, reflecting incomplete gelatinization or weak intermolecular bonding. In contrast, films reinforced with inorganic fillers tend to exhibit smoother and more compact structures. This improvement in morphology is frequently attributed to enhanced filler–matrix interactions, which contribute to better mechanical performance [12]. FTIR complements this morphological analysis by offering a molecular-level understanding of interactions within the polymer network. Through the identification of characteristic functional groups and their vibrational changes, FTIR spectra provide clues about hydrogen bonding, compatibility between polymer components, and the effects of added fillers or plasticizers. Shifts or variations in the intensity of O–H, C–O, and C–H stretching bands, for example, indicate modified intermolecular interactions within the film. These spectral changes often correlate with improved hydrophobicity, reduced moisture absorption, or enhanced flexibility properties that are essential for the functional performance of bioplastics [13]. XRD serves

as a powerful technique for assessing the crystalline structure of starch-based materials. The degree of crystallinity plays a central role in determining mechanical strength, thermal stability, and barrier properties. Native starch commonly exhibits distinct A- or B-type crystalline patterns. However, processes such as gelatinization, crosslinking, or reinforcement with mineral fillers often alter these diffraction patterns. In many cases, the introduction of nanoclays or calcium carbonate increases the crystallinity of the composite by promoting more ordered molecular arrangements. Enhanced crystallinity is typically associated with improved stiffness, reduced permeability, and greater resistance to thermal degradation [14]. TGA further enhances this understanding by revealing the thermal stability and degradation profile of the bioplastic. Native starch tends to undergo a single dominant thermal degradation step, reflecting the decomposition of its polysaccharide chains. Modified or filler-reinforced starch films, however, often show delayed onset of degradation and higher residual mass at elevated temperatures. This behavior is largely due to the presence of inorganic fillers, which act as thermal shields by slowing heat transfer and restricting polymer chain mobility. TGA curves thus provide quantitative confirmation of improved thermal stability, validating the role of fillers or chemical treatments in enhancing performance [15]. Taken together, these characterization techniques offer a comprehensive view of how starch-based bioplastics respond to modification. SEM reveals structural uniformity, FTIR captures molecular interactions, XRD highlights changes in crystallinity, and TGA quantifies thermal stability. The integration of these methods not only strengthens the interpretation of experimental findings but also ensures that the material behavior is understood from morphological, chemical, and thermal perspectives. As a result, the application of these analytical tools has become indispensable in advancing the development, optimization, and reliability of starch-based bioplastic materials. These analytical tools provide valuable insights into starch-polymer interactions, degradation mechanisms, and the effects of chemical modifications [16], enabling the optimization of bioplastic formulations for enhanced performance [3]. Regulatory frameworks and consumer acceptance also play a vital role in shaping the future of starch-based bioplastics. Countries such as Germany, France, and the United States have implemented policies that ban single-use plastics and encourage the adoption of biodegradable alternatives. However, consumer awareness and market adoption remain significant barriers, as many biodegradable plastics require specific composting conditions to achieve complete degradation [8]. Ensuring proper waste management infrastructure and educating consumers about the benefits and disposal methods of bioplastics are essential steps in promoting their widespread adoption [17]. This review provides an in-depth analysis of the advancements, challenges, and analytical perspectives in starch-based bioplastics. It examines the latest research trends in material modification, processing techniques, and characterization methods while critically discussing the limitations that hinder the large-scale implementation of these biopolymers. By addressing these challenges, starch-based bioplastics can play a pivotal role in the global transition toward sustainable and environmentally friendly polymer solutions.

Ethical Considerations and Sustainable Use of Wild Cocoyam Starch for Bioplastic Applications

The growing interest in starch-based bioplastics has prompted ethical concerns regarding the diversion of edible starch sources from the food chain to industrial applications. Common starch feedstocks such as maize, cassava, and potato are staple food crops in many regions, and their use in non-food materials may intensify food security challenges, particularly in developing countries. This ethical issue, often described as the "*food* vs. *materials*" dilemma, necessitates the exploration of alternative, non-food starch sources for sustainable bioplastic development [18]. In this context, wild cocoyam represents a promising and ethically favorable starch source. Unlike cultivated cocoyam varieties widely consumed as food, wild cocoyam is largely underutilized or considered unsuitable for direct human consumption due to the presence of antinutritional factors such as calcium oxalate crystals. As a result, wild cocoyam often remains unexploited or treated as agricultural waste, making it an attractive non-food biomass for material applications.

The utilization of starch extracted from wild cocoyam therefore minimizes competition with food resources while simultaneously adding value to an otherwise neglected plant material [19]. Previous studies have shown that cocoyam starch possesses favorable physicochemical properties, including high starch yield, good film-forming ability, and tunable thermal and mechanical behavior after modification, which are desirable for bioplastic production [19]. When sourced from wild cocoyam, these functional advantages can be harnessed without ethical concerns associated with food crop diversion. Moreover, valorizing wild cocoyam starch supports circular economy principles by promoting the productive use of underutilized plant resources and reducing reliance on edible starch feedstocks.

Consequently, the use of wild cocoyam starch in bioplastic formulations aligns with both ethical sustainability and environmental responsibility. Future research should focus on optimizing starch extraction, modification, and composite reinforcement strategies for wild cocoyam-based bioplastics, thereby advancing their technical performance while maintaining ethical integrity and socio-economic acceptability.

Above all, there isn't such an overarching review to consolidate advancements across different bio-based materials, evaluate lifecycle sustainability, or break barriers to scalability, which is a gap this paper aims to fill [20]. Although the potential for bio-based nonwovens to disrupt plastic litter and resource exhaustion is great, literature lacks an analysis of lifecycle sustainability, scalability challenges, and cross-industry applications.

2 Methodology

The methodology adopted for this review involved a systematic and comprehensive approach to analysing advances, challenges, and analytical perspectives in starch-based bioplastics through the synthesis of secondary data from relevant scholarly works. A thorough literature search was conducted across reputable databases, including Google Scholar, ResearchGate (RG), and ScienceDirect, focusing on articles published between 1994 and 2025. The search was guided by a keyword mind map (Fig. 1) developed to streamline relevant topics. Key search terms included starch-based bioplastics, biodegradability, mechanical properties, thermal stability, starch modification techniques, and sustainable bioplastic applications. The initial search identified 340 articles, which were subjected to a rigorous screening process based on titles, abstracts, and full-text reviews. The inclusion criteria prioritized peer-reviewed English-language publications, including journal articles, conference papers, and book chapters. The majority (90%) of selected studies were from 2015–2025, ensuring the analysis remained current, while a minor portion of older, foundational publications was included where necessary to provide historical context and theoretical background. After applying these filters, 200 high-quality articles were selected for detailed analysis.

Temporal Trends Analyses (2015–2025)

Although the reviewed studies span 2015–2025, quantitative trend analysis is constrained by heterogeneity in formulations, fillers, film thicknesses and testing standards. Nonetheless, a qualitative temporal assessment indicates progressive improvement in wild cocoyam–based bioplastic films [21]. Early studies (2015–2018) mainly reported neat or plasticized starch films with low mechanical strength, poor moisture resistance, and limited thermal stability [21]. From 2019 onward, increased use of reinforcement and optimization strategies corresponds with enhanced mechanical, barrier, and thermal properties, particularly in recent application-oriented studies (2022–2025).

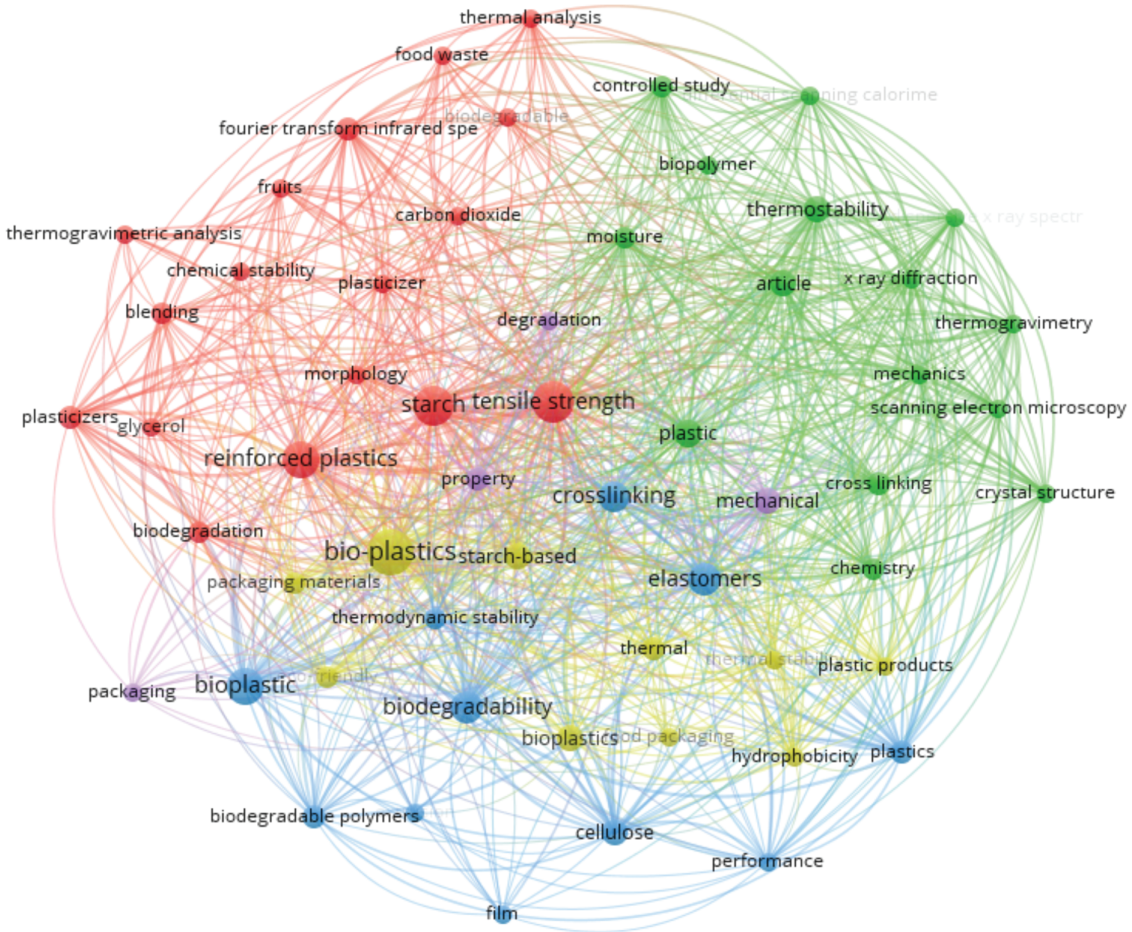

Figure 1: Keyword mind map for bioplastics.

The final set of articles underwent a structured data extraction process focusing on material properties (e.g., mechanical strength, biodegradability, thermal behaviour), processing techniques (plasticization, blending, reinforcement), performance challenges (moisture sensitivity, thermal instability), and recent advancements (nanocomposite formation, chemical modifications, alternative starch sources). To manage heterogeneity in experimental conditions and testing standards across studies, several strategies were implemented:

- **Normalization of data:** Quantitative results were converted to common units and, where possible, standardized for sample size, thickness, and test conditions to facilitate meaningful comparisons [22].
- **Grouping by methodology:** Studies were categorized according to comparable experimental protocols and testing standards (e.g., ASTM vs. ISO), temperature, humidity, or strain rate, allowing intra-group comparisons with higher reliability [23].
- **Trend-based analysis:** When direct quantitative comparison was not feasible due to methodological differences, qualitative trends and relative performance outcomes were emphasized to identify generalizable insights rather than absolute values [24].
- **Explicit acknowledgment of discrepancies:** Variations and potential sources of conflict between studies were critically discussed, providing transparency regarding uncertainties in the reported data [25]. A thematic analysis approach was used to organize findings under three core themes: advances, challenges,

and analytical perspectives. Quantitative results were compared across studies to identify performance trends, while qualitative insights were synthesized to discuss broader implications. The quality of the included studies was assessed based on citation impact, journal ranking and the robustness of research methodologies employed. This ensured that only credible, high-impact literature informed the review. Although no ethical clearance was required due to the secondary nature of the data, strict adherence to academic integrity was maintained through proper citation of all referenced works. Overall, this methodology guarantees a balanced, evidence-based, and insightful synthesis of current research in starch-based bioplastics, providing valuable guidance for future academic and industrial advancements.

2.1 Chemical and Physical Properties of Starch

2.1.1 Chemical/Structural Properties

Understanding the physicochemical characteristics of starch makes it possible to choose starch with the qualities needed for a given application. It is also helpful in choosing the source of starch and the best modification technique to achieve the functional qualities needed for a given end use. According to [26], Starch is a naturally occurring polysaccharide composed primarily of two glucose polymers, amylose and amylopectin, which differ markedly in their molecular architecture. Amylose consists mainly of linear α-(1→4) glycosidic linkages, while amylopectin possesses a highly branched structure due to the presence of α-(1→6) glycosidic bonds at branch points in addition to α-(1→4) linkages. The relative proportion and structural organization of these two components vary among botanical sources and play a fundamental role in defining the internal arrangement of starch granules. Previous studies have shown that amylopectin is largely responsible for the formation of ordered double-helical structures, whereas amylose tends to occupy amorphous regions within the granule, influencing chain packing and molecular mobility [27]. Starch is made up of molecules of amylopectin and amylose, which are made up of D-glucose monomers as seen in Fig. 2.

The swelling and solubility characteristics of the biopolymer can be influenced by the distinct amylose and amylopectin structures found in starch. Studies on the link between swelling characteristics, amylose content, and amylopectin fine structure have shown that a high proportion of amylopectin long chain improves swelling characteristics, while amylose inhibits them. Reduced swelling and solubility are characteristics of starch with reduced levels of amylopectin long chains.

The disintegration of granule sizes and instability of swollen granules brought about by high temperatures and shear forces are the causes of variations in shear thinning in starches [28]. Higher proportions of amylose and amylopectin molecular sizes and amylopectin long chain lengths result in a greater interaction between amylose and amylopectin chain lengths which is why swollen granules exhibit greater resistance to shearing especially for high resistant starches with high amylose content. Starches are characterized by some chemical changes such as;

- Hydrophiliicity: The presence of hydroxyl (O-H) groups in starches gives way to their hydrophilic behavioral pattern which allows to absorb water and swell.
- Gelatinization: When subjected to heating in the presence of water, starches undergo gelatinization leading to the breakdown of crystalline regions in the polymer structure and the formation of gel-like substances.
- Hydrolysis: In the presence of enzymes or acid catalysts, starches are broken down to simple sugars such as glucose, maltose.
- Derivatizations: Chemical modification through acetylation, phosphorylation oxidation or cross-linking of starches is utilized to introduce new functional groups that alter or enhance the starch properties and application.

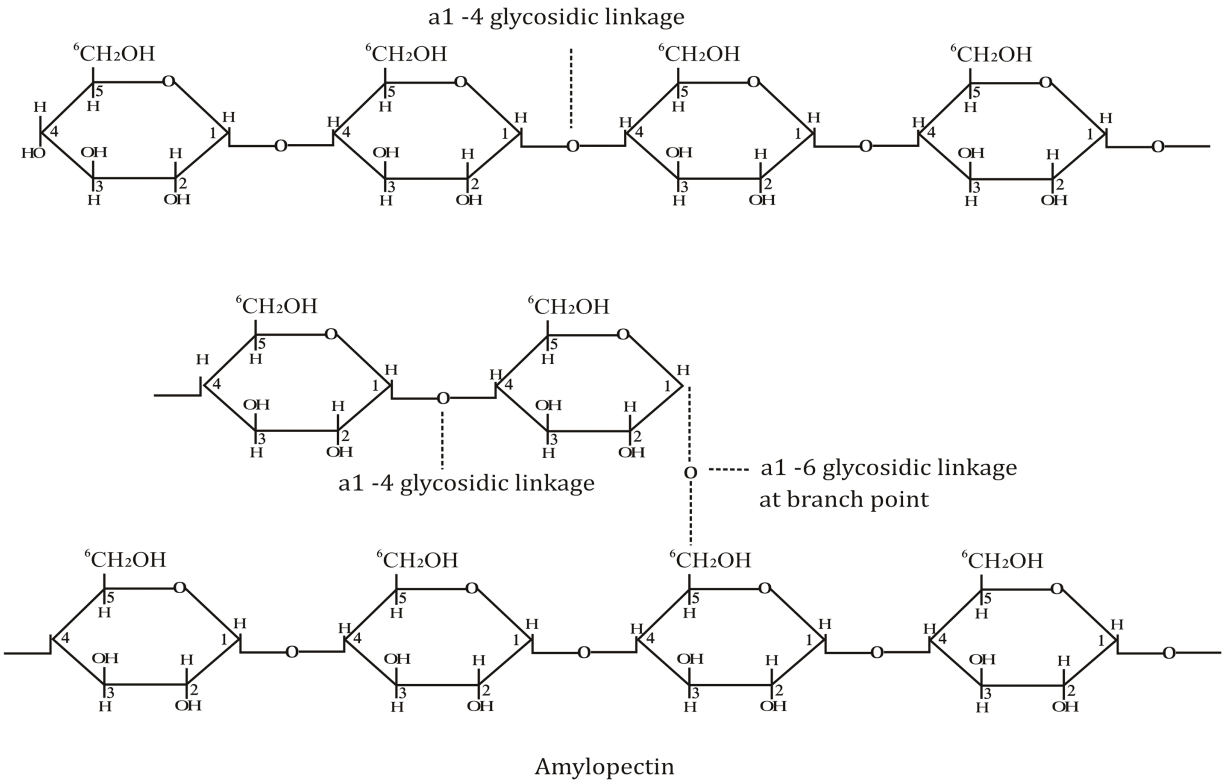

Figure 2: Structure of amylose and amylopectin.

2.1.2 Physical Properties

The complex carbohydrate known as starch is made up of molecules of amylose (a linear, crystalline, biopolymer) and amylopectin (branches and amorphous biopolymer). The molecular characteristics described in Fig. 2 directly translate into the physical properties of starch summarized in Fig. 3, including crystallinity, granule structure, moisture content, and molecular weight. A higher amylopectin content generally promotes increased crystallinity due to its branched architecture and ability to form stable double helices, while elevated amylose levels can disrupt crystalline regions, leading to reduced crystallinity and altered gelatinization behavior [29]. Furthermore, differences in amylose–amylopectin ratio affect water absorption and swelling behavior, as amylose tends to limit granule swelling whereas amylopectin facilitates greater hydration. These structure–property relationships critically influence starch performance in material applications, particularly in starch-based bioplastics where moisture sensitivity, thermal stability, and mechanical behavior are key considerations [30]. The physical attributes of starch have a substantial influence on the qualities and functionality of biopolymers.

- **Granular structure:** Granules formed by starch molecules have an impact on the bioplastics' reactivity and accessibility. Water vapor permeability, gelatinization temperature, pasting behavior, viscosity, stability, shelf life, tensile strength, and melting behavior are all influenced by the granular structure and crystallinity of starch
- **Crystallinity:** Granules of starch have crystalline regions that affect how they melt and interact with other molecules. Molecular weight and crystallinity affect how biodegradable a starch is; larger molecular weight and more crystalline starches are less biodegradable due to high resistance of amylose to enzyme degradation

- **Molecular weight:** The solubility, viscosity, and film-forming characteristics of starch molecules are influenced by their molecular weight. The amylose-to-amylopectin ratio and the molecular weight of starch affect the film-forming qualities of the substance, including its strength, flexibility, and transparency.
- **Amylose-to-amylopectin ratio:** Bioplastics' characteristics are influenced by the ratio of amylose to amylopectin, which also affects how starch gelatinizes, retrogrades, and forms films. Tensile strength, flexural strength, and impact resistance are among the mechanical characteristics of starch-based bioplastics that are influenced by the amylose-to-amylopectin ratio and the molecular weight of the starch.
- **Moisture content:** The moisture content of starch has an impact on its reactivity, flowability, and compressibility. The moisture content and amylose-to-amylopectin ratio of starch have an impact on the water vapor permeability of bioplastics derived from starch, which in turn affects how well-suited they are for packaging application

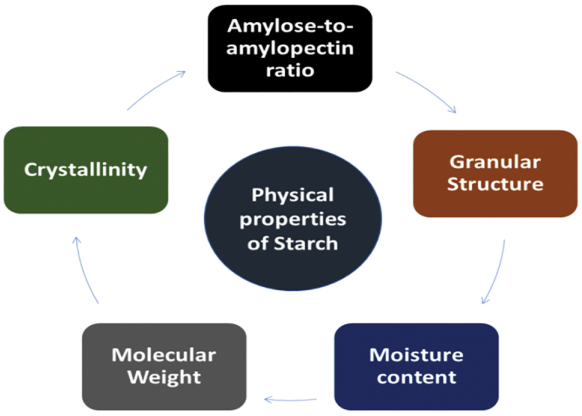

Figure 3: Physical attributes of starch.

2.2 Starch Modification Procedures

Several techniques have been devised to create modified starches with a range of properties and uses. In order to boost the starch polymer's value for the food and non-food industries, all of these methods change its physicochemical characteristics and structural features, making it extremely versatile. The following:

2.2.1 Plasticization

Thermoplastic starch (TPS) polymers made entirely of starch are extremely sensitive to water and can change their molecular weight significantly while being processed. Thus, in order to break down the crystalline granules and lower the glass transition temperature (Tg) and melting temperature (Tm), plasticizers are added to starch [31]. The hydrophilicity of this plasticizer may lead to a decrease in Tg when the concentration of glycerol rises. The inclusion of glycerol facilitates the adsorption of water molecules on the more active regions of starch films by exposing the hydrophilic hydroxyl groups. Due to its low molecular weight, water can act as a plasticizer, which enhances mobility. The addition of glycerol to starch films increases the molecular mobility of partly crystalline and amorphous polymers by increasing their free volume, which reduces the glass transition of the films.

2.2.2 Blending with Polymers

Since these materials are made entirely of renewable resources, including thermoplastic starch and biodegradable polymers, researchers have recently paid more attention to environmentally friendly biodegradable starch-based blends and composites [32]. Lactic acid and hydroxybutyrate are two of these renewable polymers that have garnered a lot of interest due to their aliphatic nature and some advantageous traits and qualities that are paramount to those of synthetic polymers. All three of these materials thermoplastic starch, poly(hydroxybutyrate), and poly(lactic acid) have certain drawbacks, such as brittleness and lower elongation values than synthetic polymers. Their distinctive chemical structure, which lacks the required flexibility, is the source of these disadvantages. Interestingly, poly(vinyl) alcohol is a biodegradable polymer even though it is a synthetic one. This water-soluble, highly polar polymer performs effectively for creating blends with other natural polymers. According to the percentage of O-H and ester groups, poly(vinyl) alcohols are really divided into various grades with varying polarity [33]. Thus, it is possible to make poly(vinyl) alcohols that are comparatively less polar in certain organic solvents. However, poly (lactic acid) made from renewable resources is more biodegradable than poly(vinyl) alcohol. Accordingly, combining poly(vinyl) alcohol with starch can be a useful strategy to increase the rate of biodegradation and lower overall expenses [34]. It is interesting to note that the enhanced biodegradability of pure starch is diminished when poly(vinyl) alcohol is blended with it. The fact that microbes first devour the starch portion of poly(vinyl) alcohol before breaking down the amorphous phase of the alcohol supports the idea that starch is more biodegradable than poly(vinyl) alcohol [35].

2.2.3 Chemical Modifications

The molecular structure and functional properties of starches are altered by a variety of chemical processes, including oxidation, acid hydrolysis, esterification, etherification, and cross-linking [16]. These chemical modification techniques are useful for improving specific elements of starch functioning, such as retrogradation, swelling, and gelatinization [36].

i. Esterification

Esterification significantly alters the gelatinization and aging characteristics of starch from various plant sources. This critical modification process involves combining an organic acid (RCOOH) with an alcohol (ROH) to form an ester (RCOOR) and water. To create esterified starch, the hydroxyl groups in starch are substituted with an organic acid or an anhydride. According to Tay et al. [37], these reactions are usually conducted at temperatures between 50 and 90°C and have a reaction time of one to six hours.

ii. Etherification

A common technique to change the characteristics of starch granules is the addition of substituents. Hydrophobic substituents like methyl, allyl, benzyl, and others are typically sought when the goal is to make starch more hydrophobic. But these enhancements frequently require intricate changes. Although not a current standard procedure, the benzylation of cellulose has been investigated in order to examine its possible application as a resin. Research findings reveal that, benzyl chloride treatment of starch results in a moderate level of substitution that is linked to a drop in the gelatinization temperature [16].

iii. Oxidation

Starch oxidation is a chemical reaction that occurs when starch reacts with an oxidizing agent, such as sodium hypochlorite, under precisely regulated conditions of temperature, pH, and time. When starches with primary or secondary hydroxyl groups are oxidized, aldehyde or carboxyl groups are produced.

iv. Schiff base

A modified version of starch called starch dialdehyde has several active aldehyde groups, which makes it easier for Schiff bases to develop. Moreover, the aldehyde group and the amino group on a compound's surface may interact chemically [38].

3 Production Methods for Starch-Based Bioplastics

In this section, details on the processing methods for bio-based polymers derived from renewable resources are discussed.

3.1 Extrusion Method

Extrusion is a process that creates a product by forcing a substance to flow through a specific shape orifice at a predetermined pace under a variety of conditions. The extrusion process is seen in Fig. 4. The material is subjected to shear and heat energies throughout the process. This results in changes to the nutritional, chemical, and structural composition, including lipid oxidation, protein denaturation, gelatinization and starch degradation [39,40].

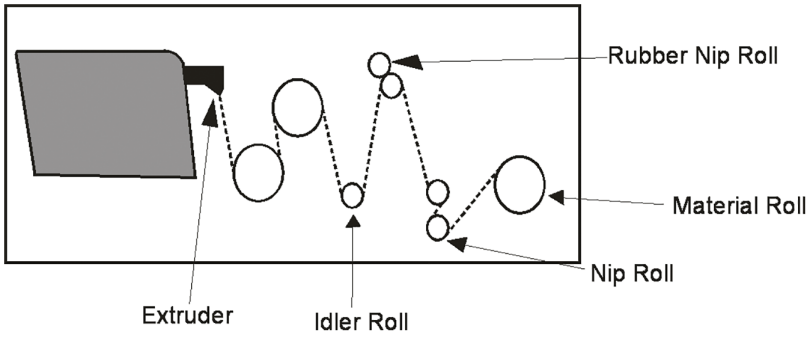

Figure 4: Extrusion technique for the production of starch-based biopolymers.

A popular technique in the polymer industry is extrusion. The food and pharmaceutical industries apply this technology in product processing, where it is used to alter the chemistry or microstructure of polymers. For instance, starch is the most often extruded food ingredient [24]. To facilitate digestion, the starch granule is split in this instance. Using this technique to encapsulate flavors, nutrients, and medications.

3.1.1 Injection Molding Method

Injection molding is a widely used technique for creating products using biopolymers. This technique consists of three steps [41] as demonstrated in Fig. 5.

The melting temperature employed in this process is far greater than the breakdown temperature of biopolymers like chitosan, which limits the utilization of biopolymers in this technology. Nonetheless, a polymeric matrix based on chitosan and thermoplastic starch was created and put through injection molding and molding compression [42]. Fig. 6 displays the injection molding technique.

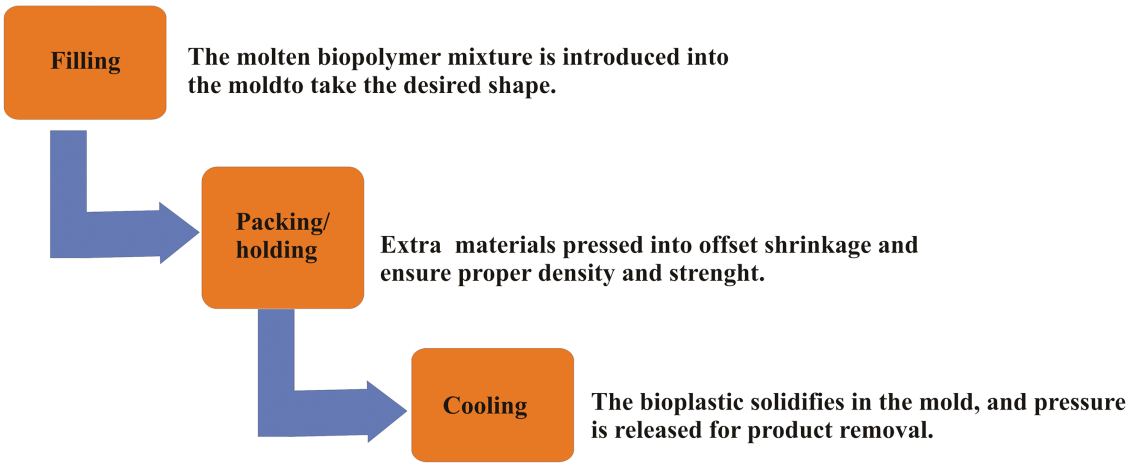

Figure 5: Injection molding steps for starch-based biopolymers.

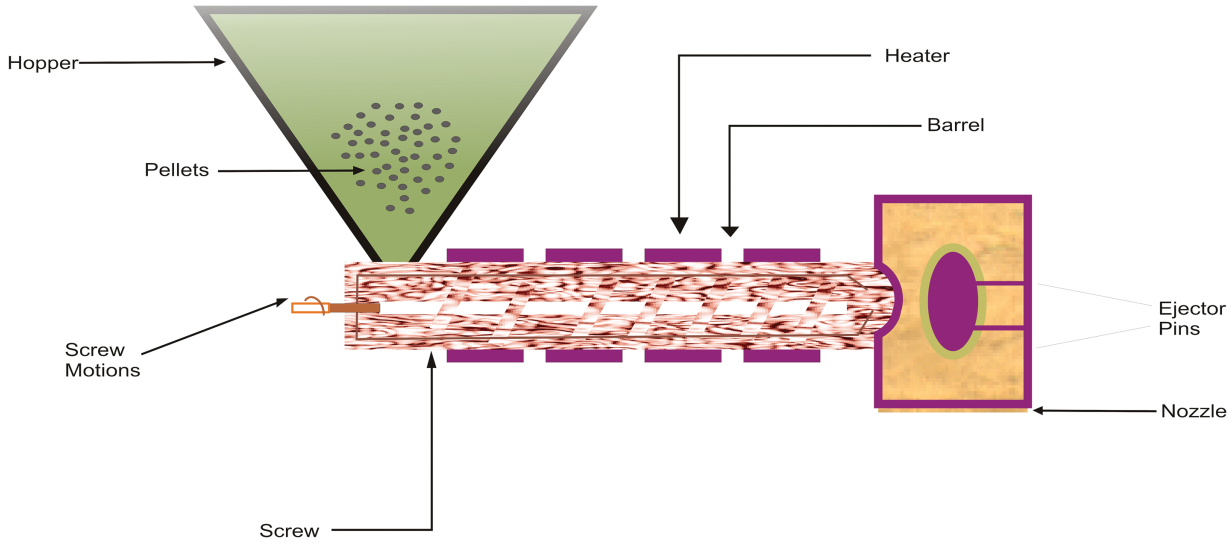

Figure 6: Schematic diagram of the injection molding technique.

3.1.2 Casting

Casting in bioplastic production is a method where a polymer solution (starch, plasticizer, fillers, etc.) is poured onto a flat surface and dried, leaving behind a thin solid bioplastic film.

When exposed to a solvent, the polymer matrix tends to swell as the solvent penetrates its structure. However, the extent to which a polymer dissolves depends greatly on the compatibility between the polymer and the solvent. This makes the careful selection of an appropriate solvent essential, as it directly influences the uniformity, stability, and overall performance of the resulting polymer solution. An unsuitable solvent may lead to incomplete dissolution, phase separation, or weak film formation, while a well-matched solvent ensures proper dispersion and enhances the quality of the final bioplastic [43]. Fig. 7 illustrates how casting is a straightforward technique.

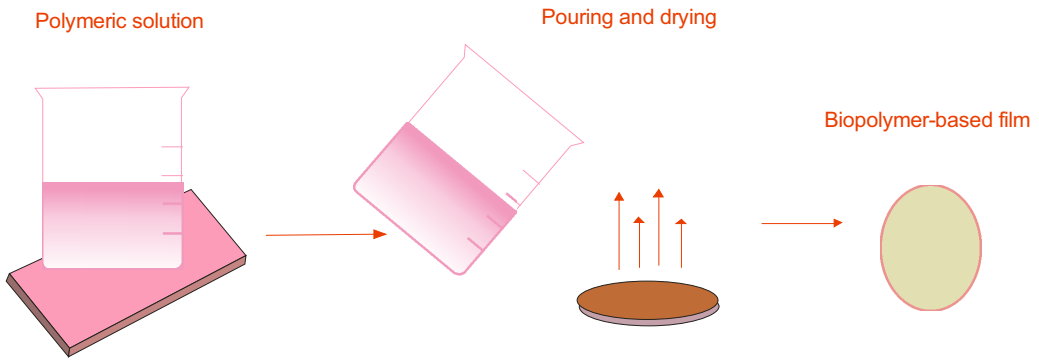

Figure 7: Casting method for starch-based biopolymers.

3.1.3 Additive Manufacturing (3D Printing)

Three-dimensional printing (Fig. 8) makes it possible to manufacture objects by layering a material with the help of a print head and a nozzle. According to Valino et al. [44], the chosen substance is applied to a substrate with a predetermined shape. Subsequently, the various layers of the chosen material are poured in throughout the construction process. The constructions are then taken off the support. The necessity of a curing phase may vary depending on the type of printing [45]. Other methodologies for starch-based biopolymers including their merits and demerits are presented in Table 1.

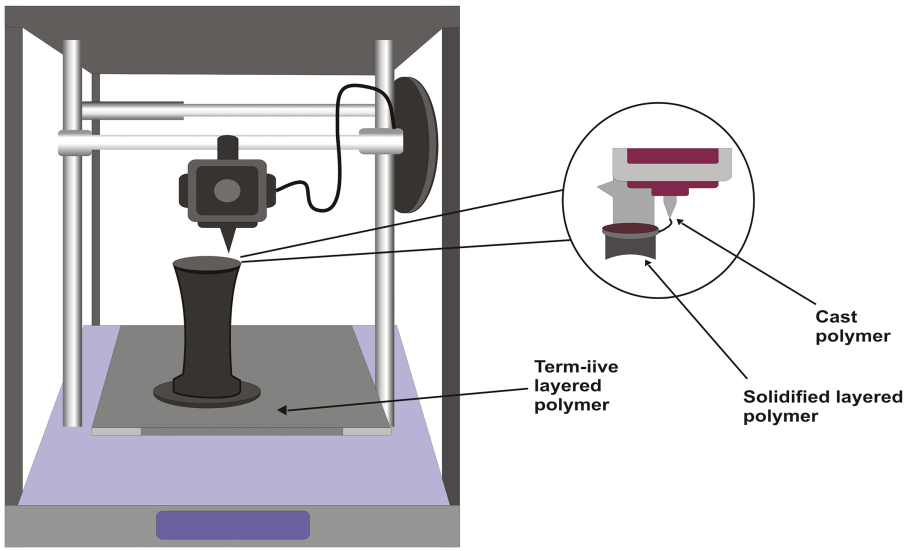

Figure 8: Schematic diagram of the 3D printing technique.

Table 1: Methods used to produce starch-based bioplastics, their pros and cons.

Method	Advantages	Disadvantages	Limitations	Comments	References
Thermoplastic processing (Film blowing extrusion)	Simple and cost-effective process. Easily scalable.	High energy consumption. Reduced mechanical properties.	Limited control over molecular structure.	Widely used method in industrial applications, especially for food packaging.	[3]

(Continued)

Table 1 (continued)

Method	Advantages	Disadvantages	Limitations	Comments	References
Solution casting	Good control over the film structure. Suitable for complex shapes.	Time-consuming. Limited to small-scale production.	Requires solvent removal step which may affect final properties. Lower mechanical resistance	Useful for producing thin films but not ideal for bulk production.	[46]
Blending with other biopolymers (e.g., PLA) (Injection molding)	Improved barrier and mechanical properties. Better processing performance	Potential for higher cost. Compromised biodegradability	Compatibility issues between biopolymers.	Blending with PLA or other biopolymers makes starch-based materials more versatile but may compromise sustainability.	[47]
Plasticization (e.g., glycerol)	Increases flexibility and processability Economical and simple.	Can lower mechanical strength. May increase water absorption.	Plasticizer migration over time.	Plasticizers are a cost-effective solution, but long-term performance issues such as plasticizer leaching could limit their use.	[48]
Film casting with nanoclay reinforcement	Enhanced mechanical and thermal properties. Increased barrier resistance.	Complex preparation process. Expensive materials.	Potential for reduced biodegradability with nanomaterials.	Nanoclay incorporation improves overall performance but may lead to environmental concerns due to the non-biodegradable nature of nanomaterials.	[49]
Acetylation (chemical modification)	Improved thermal stability. Better water resistance.	Involves hazardous chemicals. Reduces biodegradability	Chemical modification limits the natural properties of starch.	Effective for enhancing water resistance but may compromise biodegradability.	[16]
Compression molding (with plasticizers)	Simple process with minimal waste. Cost-effective.	Poor mechanical strength. Limited by the type of starch used.	May not be suitable for all applications.	Simple and cost-efficient but struggles with mechanical properties, limiting its broad applicability.	[4]
Reactive extrusion	Efficient process for large-scale production. Good material properties.	High energy consumption. Requires precise control over processing conditions.	Can lead to degradation if poorly controlled.	Allows for high-volume production but needs fine-tuning to avoid material degradation	[50]

4 Testing and Analysis of Starch-Based Bioplastics

The development and optimization of starch-based bioplastics rely heavily on rigorous testing and analysis to assess their performance across various applications. Given the inherent challenges posed by these materials, such as low mechanical strength, high brittleness, and moisture sensitivity, it is essential to evaluate their properties thoroughly before large-scale production. Testing and analysis help researchers pinpoint weaknesses in starch-based bioplastics, enabling the implementation of targeted improvements to make these materials more competitive with conventional plastics [51]. Such evaluations are critical for enhancing the material's robustness and functionality, facilitating their widespread adoption in industries like packaging, agriculture, and automotive. Recent studies have emphasized the importance of comprehensive testing to assess mechanical, physical, and barrier properties, as well as biodegradability and overall environmental impact [52]. This section explores the key testing methods used to evaluate these critical properties, while also discussing their implications for the future of starch-based bioplastics.

4.1 Mechanical Properties Testing

Mechanical properties are essential factors in determining the performance and applicability of starch-based bioplastics in various industries. Three key mechanical properties (tensile strength, elongation at break, and Young's modulus) are typically evaluated in these materials. These properties provide a detailed picture of the material's ability to withstand physical stresses, deform under load, and recover from strain.

4.1.1 Tensile Strength

Tensile strength is a measure of the maximum amount of tensile (pulling or stretching) stress that a material can endure before it breaks. It is one of the most critical properties for assessing a material's suitability for load-bearing applications, including packaging films, agricultural films, and structural components. In starch-based bioplastics, the tensile strength tends to be relatively low due to the crystalline nature of starch, which limits its ability to stretch without breaking. Starch molecules form hydrogen bonds, which provide structural integrity but also make the material more rigid and brittle. To improve the tensile strength of starch-based bioplastics, plasticizers such as glycerol, sorbitol, or even natural oils are often added. These additives reduce the inter-molecular bonding, increasing the material's flexibility, but they may not always significantly improve tensile strength. Furthermore, the type of starch used (e.g., corn, potato, tapioca, or rice starch) can impact the tensile strength, with variations observed depending on the source and preparation method. For example, studies have shown that starch-based films made with glycerol exhibit increased tensile strength compared to pure starch films [8], but still fall short compared to traditional plastic materials.

4.1.2 Elongation at Break

Elongation at break measures how much a material can stretch before it breaks, providing insight into its flexibility and ductility. This property is vital for applications where flexibility and resistance to cracking are necessary. Starch-based bioplastics, especially those with high amylose content, tend to have poor elongation at break because of their rigid crystalline structure. The addition of plasticizers like glycerol can improve elongation by reducing the stiffness of the starch chains and increasing the free volume between them, allowing the material to stretch without breaking. However, while plasticizers improve flexibility, they often lead to a trade-off with tensile strength. Therefore, the balance between flexibility (elongation) and strength must be carefully managed to meet specific application requirements. For example, starch-based films with higher glycerol content have been shown to exhibit higher elongation at break but also a reduction in tensile strength [13].

4.1.3 Young's Modulus

Young's modulus, or the elastic modulus, refers to a material's stiffness. It is defined as the ratio of stress to strain in the elastic region of the material's deformation. Materials with a high Young's modulus is stiff and resist deformation under load, while those with a low Young's modulus are more flexible. In the case of starch-based bioplastics, Young's modulus typically correlates with the crystallinity and molecular structure of the starch. Pure starch, being rigid and crystalline, typically exhibits a high Young's modulus, meaning it resists deformation. However, this high stiffness is often undesirable in applications where flexibility is essential, such as in packaging films. The addition of plasticizers can reduce the Young's modulus, increasing the material's flexibility while sacrificing stiffness. This trade-off is another important consideration in designing starch-based bioplastics for specific end-use applications [13].

Table 2 compares tensile strength, elongation at break, and Young's modulus for various starch-based bioplastics, considering different starch sources and plasticizers as observed, the tensile strength for starch-based bioplastics generally ranges from 1.2 to 40.3 MPa, with some variations depending on the starch source and plasticizer used. Corn starch, for instance, shows a higher tensile strength of up to 10.66 MPa when combined with glycerol and fructose compared to lower tensile strength values of 2.24 MPa for the same corn starch with glycerol [53]. In terms of elongation at break, the values range from 33.30% to 70.7%, indicating the flexibility and ductility of the material. The best value of Elongation at Break is as large of 122.80% ZnO concentration of 0.6% and plasticizer concentration of 30% [54], while wheat starch with sorbitol tends to be more rigid with elongation at 3.3% [55]. The addition of plasticizers like glycerol and formamide increases the material's elongation by disrupting the crystalline structure of the starch, making the polymer more flexible. Regarding Young's modulus, starch-based bioplastics typically have a range of values from 14.67 to 997 MPa, suggesting variability in stiffness. The stiffness is relatively similar across many types of starch but can be adjusted through formulation. For example, glycerol and sorbitol plasticized corn starch exhibits a modulus of 47 MPa when compared with only sorbitol with modulus of 495.97 MPa [56], while glycerol-based wheat starch has a slightly higher modulus of 997 MPa [57]. This suggests that although plasticizers reduce tensile strength, they have a relatively smaller effect on Young's modulus, which is more influenced by the crystallinity of the starch. The mechanical properties of starch-based bioplastics, including tensile strength, elongation at break, and Young's modulus, are highly dependent on the starch type and the plasticizers used. In addition, Table 2 highlights how different starch sources and additives contribute to the final properties of the bioplastic. Researchers and manufacturers must consider these properties carefully to tailor starch-based bioplastics for specific applications, balancing strength, flexibility, and stiffness to meet desired performance standards. The table provides a comprehensive comparison of recent studies, offering valuable insights into the ongoing development and optimization of starch-based bioplastics for a variety of uses.

Table 2: Mechanical properties of starch-based bioplastic.

Starch Type	Plasticizer	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (MPa)	References
Corn starch	Glycerol	1.28	12.69	14.67	[8]
Wheat starch	Glycerol	40.3	NA	997	[57]
Corn starch	Glycerol/White vinegar	3.55	88.1	NA	[13]
Corn starch	Fructose	7.44	70.7	32.97	[53]

(Continued)

Table 2 (continued)

Starch Type	Plasticizer	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (MPa)	References
Corn starch	Glycerol	2.24	33.30	28.8	[53]
Corn starch	Glycerol & Fructose	10.66	57.67	66.4	[53]
Corn starch	Sorbitol	13.62	NA	475.97	[56]
Corn starch	Sorbitol & Glycerol	5.74	NA	47.17	[56]
Wheat starch	Sorbitol	25.3	3.3	1230	[55]
Cassava starch	Glycerol	13.5	NA	47.0	[58]
Cassava starch	Glycerol	22.3	220	NA	[54]
Durian seed starch	Sorbitol	10.63	8.21	129.57	[59]
Avocado seed starch	Glycerol	5.10	14.03	36.36	[59]
Corn starch	Formamide	3.40	105.21	NA	[60]
Corn starch	Ethylene glycol	3.8	98.22	NA	[60]
Jackfruit seed starch	Glycerol	3.13	4.5	120	[61]

5 Barrier Properties Testing

Starch-based bioplastics are increasingly being explored for use in food packaging and other applications, however, one of the significant challenges they face is their poor barrier properties, especially in terms of moisture and gas permeability. These properties are essential in determining the material's effectiveness, particularly in applications where moisture control, freshness, and shelf life are crucial. Moisture and oxygen barrier properties are some of the primary metrics that dictate the performance of bioplastics in packaging, making their optimization an area of intensive research. Water Vapor Transmission Rate (WVTR) and Oxygen Permeability (OP) are the two most critical tests used to assess the barrier performance of starch-based bioplastics.

5.1 Water Vapor Transmission Rate (WVTR)

The WVTR test measures the rate at which water vapor passes through a material under controlled conditions. This test is crucial because high water vapor transmission can lead to issues like material degradation, food spoilage, and structural failure when used in packaging. The WVTR is typically measured in grams per square meter per day ($g/m^2 \cdot day$). The lower the WVTR, the better the material's ability to act as a moisture barrier. This property is especially significant for packaging applications involving moisture-sensitive foods, pharmaceuticals, and agricultural products. The MOCON (Modern Controls Inc.) test or permeability chambers are commonly used to measure WVTR. The standard testing involves exposing the bioplastic to a controlled environment where humidity is regulated, and the rate at which moisture passes through the material is measured.

5.1.1 Water Vapor Permeability (WVP)

A crucial characteristic of food packaging materials is water vapor permeability (WVP), which establishes how quickly moisture can permeate the material. Maintaining the shelf life and quality of packaged

food items depends on this feature. It is essential for food packaging materials because it prevents mold growth, regulates moisture transmission, and keeps products fresh by preventing texture changes [19].

5.1.2 Oxygen Permeability (OP)

The OP test evaluates the material's ability to block oxygen from passing through, which is vital for applications such as food packaging, where oxygen can cause oxidation and spoilage. Oxygen permeability is typically expressed in cubic centimetres per square meter per day ($cc/m^2 \cdot day$). A lower OP value indicates better barrier properties against oxygen and greater potential for preserving the freshness of food products. Oxygen permeability testing is often conducted using specialized equipment, such as a permeability chamber or MOCON tester, where the material is exposed to a controlled environment with oxygen concentration on one side. The rate at which oxygen passes through the material is then quantified.

5.2 Strategies for Improving Barrier Properties

Starch-based bioplastics inherently suffer from high moisture absorption and gas permeability, but researchers are actively exploring methods to improve these properties (Table 3). Some common strategies include:

1. Plasticizers and Cross-Linking Agents: The addition of plasticizers, such as glycerol and sorbitol, can enhance flexibility but often worsen the barrier properties due to increased water uptake. Conversely, cross-linking agents can help form a stronger, more rigid network that reduces permeability. For instance, the use of glycerol or glutaraldehyde as cross-linking agents has shown promise in improving the barrier properties of starch-based bioplastics [62]. However, while these agents improve barrier resistance, they may also affect mechanical properties and biodegradability
2. Composite Formation: Another approach is to combine starch with other materials, such as polylactic acid (PLA), cellulose, or nano clays, to create composites that have improved barrier resistance. For example, starch-PLA composites have shown significantly lower WVTR and OP compared to pure starch films [63]. The incorporation of nano clays into starch matrices has been reported to reduce the water vapor permeability by forming a tortuous path that hinders moisture migration [64].
3. Surface Coating and Modifications: Surface treatments, such as the application of wax coatings or silicone-based polymers, have been investigated as a means to enhance moisture barrier properties. These coatings can significantly reduce the material's hydrophilicity, improving its resistance to water vapor. Additionally, chemical modifications such as esterification or acetylation of starch have been shown to improve both the hydrophobicity and the barrier properties of the resulting films [16,65].

Barrier properties, particularly water vapor transmission rate (WVTR) and oxygen permeability (OP), are crucial in determining the suitability of starch-based bioplastics for applications like food packaging. The WVTR test measures the material's moisture barrier, and the OP test measures its resistance to oxygen penetration. Both properties can be significantly improved through the use of plasticizers, cross-linking agents, and composite materials, making starch-based bioplastics more competitive with petroleum-based counterparts. The studies summarized in Table 3 provide insight into ongoing efforts to optimize the barrier properties of starch-based films, paving the way for more sustainable and functional alternatives to traditional packaging materials.

Table 3: Comparison of barrier properties of starch-based bioplastics from various studies.

Starch Type	Plasticizer/Cross-Linker	WVTR (g/m^2·day)	OP (cc/m^2·day)	References
Corn starch	Glycerol & Glutaraldehyde	100	40	[62]
Cassava starch	Glycerol & PLA	60	20	[63]
Rice starch	Glycerol	120	45	[33]
Potato starch	Sorbitol & Nanoclay	55	25	[64]
Wheat starch	Glycerol & Acetylation	85	30	[65]
Tapioca starch	Sorbitol	150	50	[66]
Maize starch	Glycerol & PEG	110	35	[53]
Corn starch	Sorbitol & Cross-Linking Agent	95	28	[67]
Rice starch	Glycerol & Cross-Linker	105	40	[52]
Tapioca starch	Glycerol & Cross-Linker	90	32	[68]

5.3 Physicochemical Properties Testing

5.3.1 Thermal Properties

Thermal properties are fundamental in determining the performance and stability of starch-based bioplastics, which are often subject to various environmental conditions during processing and end-use. The inherent thermal behaviour of starch, including its glass transition temperature (Tg), melting temperature (Tm), and thermal degradation profile, plays a critical role in defining its suitability for diverse applications. Understanding these properties is essential not only for enhancing the performance of these materials but also for making starch-based bioplastics competitive with traditional, petroleum-based plastics.

Enhancement of Thermal Properties through Additives

The challenges associated with the thermal properties of starch-based bioplastics are not insurmountable. Researchers have been exploring a variety of additives to improve the thermal stability, flexibility, and processability of these materials. The addition of plasticizers like glycerol, sorbitol, and polyethylene glycol (PEG) helps to enhance flexibility but can lower the material's melting and degradation temperatures. The addition of cross-linking agents, such as genipin and glutaraldehyde, significantly increases thermal stability by creating stronger intermolecular bonds that prevent degradation at higher temperatures [63]. Similarly, the inclusion of nano clay or poly lactic acid (PLA) in starch blends has been shown to improve thermal properties by reinforcing the material's polymeric network. Nanoclays, for example, act as a barrier to heat transfer, which delays thermal degradation and enhances degradation temperature (Tdec) [54,69]. Biopolymer blending, especially with PLA, results in a more thermally stable composite, making starch-based bioplastics more viable for applications that require higher heat resistance. Moreover, recent efforts have focused on modifying starch through chemical treatments such as acetylation and etherification to improve its thermal behaviour. Acetylation of starch reduces its crystallinity and enhances both its melting temperature (Tm) and Tdec, thus improving its suitability for high-temperature processing and use in diverse applications [70,71]. These modifications can substantially enhance the performance of starch-based bioplastics without compromising their biodegradability. Table 4 compares the thermal properties of starch-based bioplastics from several recent studies. It provides key data on Tm, glass transition temperature (Tg), and Tdec, along with the starch type used and any additives incorporated. The Tm for starch-based bioplastics still ranges between 220°C to 245°C, with variations depending on the starch type and additives. For example, cassava starch composites with PLA exhibited a higher Tm (239°C) than corn starch bioplastics with glycerol (232°C) [72]. The presence of cross-linking agents or biopolymer blends (such as PLA and nano clay) often

results in slight increases in Tm, suggesting improved crystalline order and better processing capabilities. The Tg values for these bioplastics remain negative, indicating that starch-based materials typically retain flexibility at lower temperatures but lose this property at higher temperatures. The addition of plasticizers such as glycerol and sorbitol lower the Tg, improving the flexibility of the material. For example, glycerol-based corn starch has a Tg of around −15°C, while acetylated maize starch has a Tg closer to −28°C, indicating a more flexible material at ambient temperatures [31,71]. The Tdec values for starch-based bioplastics generally fall in the range of 310°C to 350°C. The Tdec of rice starch/nano clay composites was the highest in the table, reaching 350°C, which suggests a significant enhancement in thermal stability with the inclusion of nano clay. Conversely, bioplastics with glycerol (such as maize starch) exhibited lower Tdec values around 315°C, which can be attributed to the inherent moisture sensitivity of glycerol [52]. The addition of plasticizers like glycerol, sorbitol, and polyethylene glycol (PEG) helps to improve the flexibility and ease of processing of starch-based bioplastics but often results in a reduction of both Tm and Tdec. In contrast, cross-linking agents such as genipin and acetylation typically improve both Tm and Tdec, making these bioplastics more suitable for high-temperature applications. Biopolymer blends, especially those with PLA and nanoclay, have emerged as a promising way to improve the thermal stability of starch-based bioplastics. The incorporation of PLA increases the Tm and Tdec while maintaining the biodegradability of the material, making it more competitive with petroleum-based plastics for packaging and other high-performance applications. Ref. [52] demonstrates that the inclusion of nanoclay improves thermal properties significantly by enhancing the polymer's structural integrity and heat resistance. Similarly, sorbitol used in combination with acetylation results in more thermally stable starch composites with improved processing capabilities.

Table 4: Thermal properties of starch-based bioplastics.

Starch Type	Plasticizer/Cross-Linker	Tm (°C)	Tg (°C)	Tdec (°C)	References
Corn Starch	Glycerol	232	−21	320	[72]
Cassava Starch	PLA	239	1	340	[73]
Rice Starch	Sorbitol & Cross-Linker	235	−25	310	[74]
Tapioca Starch	Genipin	230	−20	325	[75]
Maize Starch	Glycerol	220	−15	315	[31]
Rice Starch	Nanoclay	245	−12	350	[52]
Corn Starch	PEG	225	−5	325	[76]
Potato Starch	Glycerol & PEG	231	−17	338	[33]
Maize Starch	Cross-Linker & Nanoclay	237	−18	335	[53]
Cassava Starch	Sorbitol & Acetylation	240	−10	345	[70]
Tapioca Starch	Glycerol & PLA	232	−12	330	[35]
Rice Starch	PEG & Cross-Linking Agent	245	−15	320	[77]
Corn Starch	Genipin & Acetylation	225	−28	325	[71]
Potato Starch	Sorbitol & Nanoclay	233	−20	340	[69]
Maize Starch	PEG & Glycerol	240	−10	330	[78]

Note: Melting Temperature (Tm), Glass Transition Temperature (Tg), Thermal Degradation Temperature (Tdec).

5.3.2 Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) is one of the most widely used techniques for assessing the thermal properties of starch-based bioplastics. It provides critical insights into the material's Tm, Tg, and crystallization behaviour [79]. The Tm indicates the temperature at which a polymer transitions from a crystalline to an amorphous phase, which directly impacts the material's processability during production. In starch-based bioplastics, Tm values are typically lower than those of synthetic plastics, which is one of the challenges faced when attempting to process these materials at high temperatures. For example, starches from corn, potato, and cassava all exhibit Tm values that are generally in the range of 220°C to 245°C, depending on the starch type and the presence of any additives like plasticizers or cross-linkers. The Tg of starch-based bioplastics is another crucial metric, as it indicates the transition of the material from a rigid, glassy state to a more flexible, rubbery one. Many starch-based materials exhibit negative Tg values (e.g., −30°C), indicating that they remain flexible under normal conditions but may lose this flexibility at higher temperatures [76]. This is an advantage in certain applications such as food packaging, where flexibility is essential, but it can also be a limitation for high-temperature applications. The addition of plasticizers, such as glycerol and sorbitol, typically lowers the Tg by reducing the intermolecular forces in the starch structure, making it more flexible and easier to process [70]. Furthermore, the crystallization behaviour of starch-based materials is highly dependent on the source of starch and the specific modifications made to the polymer. Starch is a semi-crystalline polymer by nature, but the incorporation of plasticizers and cross-linking agents reduces its crystallinity, enhancing its flexibility and processability. However, reducing the crystallinity of starch can also lower its Tm, making the material more susceptible to thermal deformation during processing.

5.3.3 Thermogravimetric Analysis (TGA)

Another critical method for evaluating the thermal properties of starch-based bioplastics is Thermogravimetric Analysis (TGA). TGA measures the material's thermal stability by monitoring weight loss as a function of temperature. The onset of thermal degradation provides vital information about how the material will behave when exposed to heat. Starch-based bioplastics are known to be highly susceptible to degradation at elevated temperatures due to their high moisture content, which often results in weight loss at relatively low temperatures [16]. The Tdec for starch-based bioplastics generally falls between 250°C and 350°C, depending on the type of starch and any additives used. For example, corn starch bioplastics typically begin to degrade around 320°C, while starch blends with cross-linking agents, such as genipin or glutaraldehyde, exhibit a higher Tdec, typically around 325°C to 340°C [71]. This enhancement in thermal stability is crucial for improving the material's usability in real-world applications where heat resistance is a critical factor. The incorporation of plasticizers also influences the TGA profile of starch-based bioplastics. For instance, glycerol and sorbitol reduce the Tdec of starch, primarily because these agents disrupt the intermolecular forces in the starch, making it more prone to early-stage degradation. On the other hand, cross-linking agents and the addition of biopolymer blends such as polylactic acid or nano clays improve the thermal stability of the material by creating a more robust, interlinked polymer network. This is evident in the improved Tdec of cassava starch/PLA composites, which exhibit a significantly higher thermal stability compared to neat starch-based bioplastics [53]. For wild cocoyam starch-based systems, processing windows should be aligned with the inherent thermal transitions of the starch and the effects of plasticisers and fillers on thermal behaviour. Gelatinisation of wild cocoyam starch has been reported around **≈70°C–90°C** depending on source and composition, indicating the lower bound for effective plastification during thermal processing [80]. Accordingly, **extrusion** of thermoplastic formulations (e.g., with glycerol and small amounts of gelatin/vegetable oil) can be conducted at **~110°C–150 °C**, ensuring sufficient flow without excessive degradation, while formulations with higher filler content may tolerate somewhat elevated temperatures due

to improved thermal stability. For **injection moulding**, a range of **~150°C–190°C** balances melt viscosity and thermal integrity, with shorter residence times recommended to suppress degradation. **Film casting and drying** are best carried out below gelatinisation and retrogradation thresholds, typically **25°C–60°C** for solvent film spreading and up to **70°C** for controlled drying/annealing, avoiding thermal history that could weaken the material. These windows offer practical guidance for industry and reflect how plasticisation lowers transition temperatures yet requires careful thermal management to prevent decomposition [81]

5.4 Biodegradability Testing

Soil Burial Tests

One of the common techniques used to evaluate the biodegradability of polymers is the soil burial test. In this method, samples are exposed to soil-dwelling microorganisms such as bacteria and fungi that act as their food supply by being buried in the soil for a predetermined amount of time. These microorganisms utilize the polymer as a food source, which accelerates the degradation process. Because of this, the soil burial test can be considered a genuine method of examining how the natural environment deteriorates [82]. Thus, the film's susceptibility to biodegradation can be assessed over time by monitoring changes in its physical properties and the extent of weight loss across several days. Cross-linked starch films were said to break down more slowly than non-cross-linked ones over the course of burial [82].

5.5 Microstructural and Morphological Analysis

5.5.1 Scanning Electron Microscopy (SEM)

The proportion of weight loss, the presence of microorganisms, and the eroded surface on starch films are all frequently assessed using scanning electron microscopy (SEM) [82]. SEM images display the surface roughness, homogeneity, and shape of bioplastics [83]. Understanding the molecular arrangement and interactions within bioplastics can influence their mechanical, degradation and barrier properties. Morphological analysis reveals the topography, texture and roughness of bioplastics which affects their interaction with other materials and the environment. Particle size and distribution are key parameters of bioplastics determined using SEM to assess their impact on the properties and performance [66].

Importance of Microstructure and Morphological (MM) Analysis

- Material optimization: MM analysis enables optimization of bioplastics properties for specific application such as biomedical devices, textiles and packaging materials.
- Degradation behavioral pattern: Understanding the MM of bioplastic helps in predicting their degradation patterns, essential for designing sustainable materials.
- Performance prediction: MM analysis can be utilized to predict the performance of bioplastics in different environment and applications.
- Comparison with conventional plastics: MM analysis is used to examine and highlight the merits and limitations of bioplastics in comparison to the conventional plastics.

5.5.2 X-Ray Diffraction (XRD) Analysis of Starch-Based Bioplastics

X-Ray Diffraction (XRD) is a powerful analytical technique used to investigate the crystalline structure of bioplastics, particularly starch-based polymers. XRD provides insights into the degree of crystallinity, polymorphic transitions, and molecular arrangements of starch molecules when blended with plasticizers, reinforcing agents, or biodegradable synthetic polymers. Starch, as a semi-crystalline polymer, exhibits distinct XRD patterns based on its botanical source and processing conditions. The native starch structure typically exists in A-type, B-type, or C-type polymorphs, characterized by specific diffraction peaks. The

incorporation of plasticizers such as glycerol, sorbitol, or polyethylene glycol (PEG) significantly influences these crystalline regions by disrupting intermolecular hydrogen bonding, thus increasing the amorphous phase [84]. According to Abotbina et al. [53], XRD analysis of starch-based bioplastics containing glycerol showed characteristic diffraction peaks at approximately 16.8° and 19.8°, indicating the presence of a partially disrupted crystalline region. The reduction in peak intensity suggested the transformation from a native starch crystalline structure to a more amorphous bioplastic matrix. Similar findings were reported by Patel et al. [84], where an increase in glycerol concentration led to a decline in crystallinity index, enhancing the flexibility but reducing the mechanical strength of the bioplastics. Plasticization plays a crucial role in modifying the XRD patterns of starch-based bioplastics. Studies by Jiang et al. [3] indicated that the addition of glycerol at 30% weight reduced the crystallinity index from 42.5% to 28.6%, confirming the disruption of starch's ordered structure. Furthermore, when nano-fillers such as cellulose nanofibers or montmorillonite clay were incorporated, a partial recovery of the crystalline structure was observed, improving mechanical stability [85].

XRD data is essential in determining the structural stability and processing suitability of starch-based bioplastics. A lower degree of crystallinity generally correlates with higher flexibility and elongation, making the bioplastic more suitable for applications requiring enhanced ductility, such as packaging films [86]. However, highly amorphous bioplastics often exhibit poor barrier properties and mechanical performance, necessitating reinforcement with biopolymers like polylactic acid (PLA) or nano-additives. Moreover, XRD analysis also helps in monitoring aging effects in starch-based bioplastics. Studies by Srinivasa Rao et al. [87] showed that over time, retrogradation leads to an increase in crystallinity due to molecular rearrangement, affecting flexibility and shelf life. Understanding these transitions allows for the optimization of formulation parameters to enhance long-term performance. XRD serves as an essential technique for assessing the crystallographic behaviour of starch-based bioplastics. The variation in peak intensities and crystallinity index reflects the impact of plasticizers, reinforcements, and processing conditions on the material properties. Future research should focus on developing novel starch modifications and hybrid biopolymer blends that can enhance the balance between crystallinity, mechanical properties, and biodegradability, ensuring wider industrial applicability of starch-based bioplastics. The crystallinity of starch-based bioplastics is influenced by plasticizers, reinforcements, and starch type. The XRD analysis provides essential data (Table 5) on material structure, stability, and processability, helping researchers optimize formulations for specific applications.

Table 5: XRD crystallinity data of starch-based bioplastics with various additive.

Starch Type	Plasticizer	Reinforcement	Crystallinity (%)	Key XRD Peaks (°)	Key Observations	References
Corn Starch	Glycerol (30%)	None	35.20%	16.8°, 19.8°	Glycerol disrupted crystallinity, increased flexibility	[53]
Tapioca Starch	Sorbitol (25%)	None	38.70%	17.1°, 22.3°	Higher crystallinity than glycerol-based plasticization	[86]
Potato Starch	Glycerol (30%)	None	28.60%	16.5°, 19.5°	Significant reduction in crystallinity, increased amorphous phase	[84]

(Continued)

Table 5 (continued)

Starch Type	Plasticizer	Reinforcement	Crystallinity (%)	Key XRD Peaks (°)	Key Observations	References
Corn Starch	Glycerol (20%)	Nano-clay	41.80%	17.2°, 22.1°	Nano-clay reinforcement improved structural stability	[62]
Rice Starch	PEG (15%)	Cellulose fibers	46.50%	16.9°, 21.5°	Reinforcement enhanced crystallinity and mechanical strength	[52]
Wheat Starch	Glycerol (30%)	PLA (30%)	42.30%	17.0°, 22.0°	PLA blend improved rigidity and processability	[87]
Cassava Starch	Sorbitol (20%)	Montmorillonite	48.10%	17.4°, 22.7°	Nanoclay increased crystallinity, enhanced thermal stability	[85]
Blended Starch (Corn + Potato)	Glycerol (25%)	None	33.90%	16.6°, 19.9°	Blended starch had lower crystallinity than single-source starch	[88]
Sweet Potato Starch	Urea (10%)	Chitosan	50.20%	17.8°, 22.5°	Chitosan reinforcement improved crystallinity and water resistance	[89]
Corn Starch	Glycerol (20%)	Kaolin	39.50%	17.3°, 21.9°	Kaolin improved moisture barrier properties	[13]

5.6 Applications of Bioplastics in Various Industries

5.6.1 Packaging

One important aspect of the food sector is the use of bioplastics in food packaging. They prolong the product's shelf life, keep the nutritional value intact, facilitate transportation, and stop food from decomposing [90]. They are typically utilized in food products with low oxygen and water requirements as well as in the packaging of goods with both short and lengthy shelf lives. Inventory films made from bioplastics are utilized in harsher packaging settings, such as modified environment packing, and for commercial applications.

5.6.2 Medical and Pharmaceutical Applications

It is important for biomaterials to break down within the body without interfering with medical procedures or causing physical discomfort to patients [91]. According to Jain and Tiwari [92], polyhydroxyalkanoate (PHA) is a reliable bio-based polymer because of its biocompatibility, it is utilized in the creation of various medical devices, including those for nerve, tendon, and hernia repair. When in contact with bodily fluids, poly(3-hydroxybutyrate) breaks down into its monomer D, L-β-hydroxybutyrate, which stops cell death in a dense culture. The invention of surgical instruments like stitches, pins, and staples uses it. It is also used in a number of tissue and cell engineering procedures, such as drug administration, replacement of blood vessels, nerve cuffs, cardiovascular patches, and plate and bone replacement. Cell proliferation

treatments use flax bandages made from plants that produce bioplastic. When mixed with either organic or inorganic nanoparticles, bioplastics represent a remarkable advancement in the domains of nanotechnology, biomedical engineering, and life sciences [93].

5.6.3 Agriculture and Horticulture

In horticulture and agriculture, bioplastics and biopolymers are utilized to make mulches and seeding tapes. Mulch films supply moisture, regulate soil temperature, and inhibit the growth of undesirable weeds, while the tapes are biodegradable [94]. Bioplastic-derived nets and foils are used on mushroom fields to enhance their quality and offer the essential conditions for growth. In a similar manner, slopes are covered with threads derived from bioplastics to stop soil erosion until the plant's roots are completely established. According to Kong et al. [90], solaplast mulching films are used in horticulture for banana bushes and vineyards. Biodegradable burial pods are utilized in cemeteries and offer enormous potential for both financial and environmental advantages. Since PLA golf tees are completely biodegradable and harmless, they are recommended [95]

6 Environmental Impact and Sustainability

6.1 Biodegradability and End-of-Life Analysis

Biodegradable plastics can be disposed of in a variety of ways, including landfilling, chemical recycling, incineration with energy recovery, recycling (including reprocessing), and biological waste treatment (such as composting and anaerobic digestion). Nevertheless, the majority of bio-based plastics wind up in landfills and incinerators as a result of improper sorting and littering, a lack of infrastructure for composting, and rejection at composting facilities because they resemble conventional plastics, have expensive infrastructure, a slower rate of degradation than other compostable wastes, and lack consumer knowledge [51]. Based on this fact in addition to their slow rate of breaking down in the natural environment, bio-based plastics are just as potentially harmful to the environment as their conventional counterparts, in containing chemical additives such as plasticizers or stabilizers which slows down biodegradation. The best end-of-life solutions for fiber and bio-based packaging materials are recycling, organic recovery, and energy recovery since they prevent landfilling [96]. Life cycle assessments validating bio-based nonwovens' sustainability (e.g., 30% energy reduction vs. synthetics) and alignment with circular economy initiatives are critically analyzed.

6.2 Life Cycle Analysis (LCA)

LCA, is a valuable tool for evaluating the environmental impacts of bioplastics throughout their life cycle. While bioplastics offer several benefits, which includes; renewable resources and biodegradability, they also pose several challenges in land use, water consumption and waste management. The most prevalent impact categories in most articles for life cycle analysis of bioplastics reported lower greenhouse gas emissions, ozone depletion, photochemical oxidant generation, global warming potential due to carbon sequestration in biomass. However, the reverse is the case in acidification potential, eutrophication potential, particulate matter generation, energy, land use, and water consumption. With an emphasis on savings and trade-offs across impact categories, a growing number of research are assessing the environmental effects of bioplastics and contrasting them with their petrochemical counterparts [97,98]. The energy consumption and potential for global warming of bioplastics in comparison to petrochemical plastics are the main topics of the literature. While our life cycle assessment emphasizes global warming potential (GWP) reductions for starch-based bioplastics relative to conventional plastics, it is important to contextualize this within a broader set of environmental impact categories. Several LCA studies indicate that although incorporating starch into bioplastic formulations can lead to significant reductions in greenhouse gas

emissions and non-renewable energy use, it may also be associated with higher eutrophication potential, land occupation, and water use compared to petrochemical counterparts, largely due to agricultural inputs and crop cultivation demands [99]. For example, the use of starch in biodegradable plastics has been shown to increase eutrophication potential by up to 400% and require greater land use per kilogram of bioplastic, with nutrient run-off and feedstock production driving these impacts [100]. However, these trade-offs can be mitigated through strategies such as blending with residual starch residues, utilizing agricultural residues, and adopting improved agronomic practices, which have been found to reduce land use, eutrophication potential, and water footprint while still retaining benefits in GWP and energy use [101]. By acknowledging these multidimensional impacts, our conclusions about environmental preference are framed as conditional on feedstock choice, agricultural practice, and impact mitigation strategies rather than as universally superior.

Table 6 summarizes the results of life cycle assessments on bioplastics based on starch.

Table 6: Summary of LCA on starch-based bioplastics.

Author	Polymer	LCA Findings
Brizga J [102]	Fossil-based and bio-based polymers	From petrochemical and bioplastics: The production of petrochemical polymer packaging films results in higher greenhouse gas emissions than in the production of bioplastics.
Walker S [103]	Polybutylene Succinate (PBS), Polylactic Acid (PLA), and Polyethylene Terephthalate (PET)	The data ranges for fossil-based and bio-based polymers were found to be quite similar in the categories of energy use and climate change. PET and biobased PBS have drawbacks in acidification. According to research, biobased PLA has significant negative effects on the environment in terms of eutrophication, ecotoxicity, and biobased PET.
Koch D [104]	Bioplastics and conventional plastics	It was discovered that the potential for acidification and eutrophication increased with bioplastics while the potential for global warming decreased.
Dunn JB [105]	Bioproducts and Their fossil-based counterparts	In comparison to bioproducts, fossil-based alternatives increased greenhouse gas emissions from 27% to 86% from birth to death.
Ingrao C [106]	Polystyrene (PS) and Polylactic Acid (PLA)	The global warming potential of PLA (4826 kg CO_2) was lower than that of PS (5.11 kg CO_2) in the life cycle comparison.

6.3 Circular Economy Potential

According to Lazarevic et al. [107], the circular economy is founded on a life cycle model that measures the environmental, financial, social, and cultural effects of a product or process from the time raw materials are harvested until the end of its existence. LCA is the process of assessing a product's whole life, from the extraction of raw materials to the different phases of manufacture, distribution, usage, and material processing [108]. The LCA approach is determined by the worldwide ISO 14000 standard. Lifecycle impact review (ISO 14043); lifecycle interpretation (ISO 14044); needs and directives (ISO 14040); principles and

framework (ISO 14041); purpose, scope, and inventory analysis (ISO 14042). By embracing circular economy principles, bioplastics can help reduce plastic pollution, promote sustainable resource management and support a more regenerative economy.

7 Key Challenges and Limitations in Producing Bio-Plastics from Starch-Based Materials

The development of bioplastics derived from starch-based materials has emerged as a promising solution to the growing environmental concerns associated with conventional petroleum-based plastics. Starch, a naturally abundant and renewable resource, offers the potential for producing biodegradable plastics that can reduce the environmental impact of plastic waste. As global attention shifts toward sustainability, starch-based bioplastics have gained considerable interest due to their biodegradability, carbon neutrality, and lower environmental footprint. Despite these advantages, the large-scale production and commercialization of starch-based bioplastics face several significant challenges and limitations that must be addressed to make them a viable alternative to traditional plastics. These challenges range from issues related to their mechanical properties, such as low tensile strength and brittleness, to the hydrophilic nature of starch, which makes the material highly susceptible to moisture absorption. Furthermore, the production processes, cost competitiveness, and the overall performance of these bioplastics in real-world applications continue to pose barriers to their widespread adoption. This section delves into these key challenges and explores the limitations that need to be overcome to unlock the full potential of starch-based bioplastics.

Despite these advancements, critical challenges hinder widespread adoption. Production costs, scalability, and performance limitations (e.g., PLA's brittleness, PHAs' slow degradation in non-industrial environments) remain barriers [20]. Additionally, inconsistent regulatory frameworks and a lack of standardized biodegradability certifications complicate market entry [20].

7.1 Mechanical and Barrier Properties

One of the major challenges in bioplastics development is their poor mechanical properties, specifically their low tensile strength and high brittleness [109]. Starch is naturally a polysaccharide that exhibits a highly crystalline structure, which, while beneficial for its functional properties in food and other applications, limits its flexibility and strength when used in plastic form. The intermolecular forces between the starch molecules tend to form rigid networks, making it prone to cracking and breaking under stress. These mechanical limitations significantly hinder the commercialization of starch-based plastics in many industries where robustness and durability are key, such as packaging and automotive applications. The hydrophilic nature of starch further compounds these challenges. Starch molecules have a strong affinity for water, leading to high water absorption and making the material susceptible to degradation and dimensional instability in humid or wet conditions. This characteristic of starch-based bioplastics limits their utility in environments that require moisture resistance, such as food packaging or agricultural films [110]. The interaction of water with starch can cause it to swell, soften, and lose its mechanical integrity, undermining its long-term performance. As a result, moisture sensitivity is a critical limitation that restricts the applications of starch-based materials in certain sectors. To address these shortcomings, various modifications have been explored to improve the properties of starch-based bioplastics, including the incorporation of plasticizers like glycerol and sorbitol. Plasticizers reduce the intermolecular forces between the starch molecules, enhancing flexibility and workability. By increasing the free volume in the polymer matrix, plasticizers make it easier for the chains to slide past each other, improving the material's ductility. However, while the use of plasticizers results in enhanced flexibility and reduced brittleness, it often comes at the expense of the material's tensile strength. The addition of plasticizers can lead to a decrease in the structural integrity of the plastic, making it more prone to tearing under load. Additionally, the presence of plasticizers can affect the material's barrier

properties, as the plasticized matrix may allow for higher permeability to gases and moisture, counteracting the very properties needed for certain applications. Recent research has focused on blending starch with other natural polymers or reinforcing it with nanomaterials to enhance both mechanical and barrier properties. For example, the combination of starch with biodegradable polyesters such as polylactic acid (PLA) or polyhydroxyalkanoates (PHA) has shown promise in improving the tensile strength, flexibility, and moisture resistance of starch-based plastics [88]. Similarly, the incorporation of nanocellulose or clay nanoparticles has demonstrated significant improvements in the mechanical strength and barrier properties of starch-based films [111]. These nanomaterials act as reinforcing agents that enhance the overall structural integrity of the plastic while also improving its resistance to water and gases. Moreover, these hybrid materials have the potential to retain biodegradability, making them an attractive alternative to conventional plastics in applications where environmental sustainability is a priority. Another promising approach to improving the barrier properties of starch-based bioplastics is the use of surface modifications or coatings. Studies have explored the application of hydrophobic coatings or cross-linking agents to reduce the material's water absorption and increase its moisture resistance [33]. Cross-linking agents such as glutaraldehyde have been found to enhance the molecular network of starch, making it less susceptible to water uptake and improving its mechanical properties. Furthermore, the development of composite materials, where starch is combined with other biodegradable polymers, has been shown to improve both the mechanical and barrier properties, thereby expanding the range of potential applications for starch-based bioplastics. In conclusion, while starch-based bioplastics offer significant environmental benefits, their widespread use is limited by their poor mechanical properties and moisture sensitivity. Advances in material modification, including the use of plasticizers, reinforcement with nanomaterials, and the application of surface treatments, show promising potential for overcoming these limitations. As research progresses, these innovations may enable the development of starch-based bioplastics with enhanced performance characteristics, making them more viable alternatives to traditional petroleum-based plastics in a variety of applications.

7.2 Thermal Stability Issues

Thermal stability is a critical limitation of starch-based bio-plastics, significantly affecting their processing and application in high-temperature environments. Starch exhibits a low degradation threshold, with gelatinization occurring between 60°C and 80°C, followed by thermal decomposition above 250°C. This behaviour makes conventional plastic processing techniques, such as extrusion, injection molding, and thermoforming, challenging for starch-based bio-plastics [112]. Unlike petroleum-based plastics, which can withstand a broad range of temperatures, starch-based materials tend to break down or lose mechanical integrity when subjected to elevated temperatures. The low thermal stability of starch is attributed to its complex macromolecular structure and strong intermolecular hydrogen bonding, which limits its thermal flow properties [3]. To enhance the thermal resistance of starch-based bio-plastics, researchers have investigated various modification strategies, including blending with thermally stable biodegradable polymers such as polylactic acid (PLA) and polycaprolactone (PCL) [113]. However, these blends often require compatibilizers to achieve homogeneity and avoid phase separation, which can increase production costs and affect biodegradability [88]. Recent advancements in nanotechnology have shown promising results in improving the thermal performance of starch-based bio-plastics. The incorporation of nano-fillers such as cellulose nanofibers, montmorillonite, and graphene oxide has been reported to enhance the heat resistance of these materials by reinforcing the polymer matrix and restricting molecular mobility [3]. These nano-fillers form strong interfacial interactions with the starch molecules, leading to improved thermal stability and mechanical properties [114]. Additionally, the crosslinking of starch molecules using chemical agents such as citric acid and maleic anhydride has been explored as a method to enhance its thermal

resistance without compromising biodegradability [88]. Despite these advancements, large-scale industrial adoption of thermally stable starch-based bio-plastics remains a challenge. The cost implications of nano-filler incorporation and polymer blending must be addressed to make these materials commercially viable. Future research should focus on optimizing these enhancement techniques while ensuring sustainability and economic feasibility.

7.3 Poor Processability and Compatibility with Other Polymers

The processability of starch-based bioplastics is a significant challenge due to their inherent rheological properties. Starch exhibits high viscosity and shear sensitivity, which complicates its processing in conventional plastic manufacturing techniques such as extrusion, injection molding, and thermoforming [114]. Unlike petroleum-based plastics, which possess well-defined and consistent flow properties, starch undergoes significant changes in viscosity and thermal degradation when subjected to high processing temperatures, leading to difficulties in achieving uniform melt flow [115]. Additionally, starch's hydrophilic nature increases its sensitivity to moisture, affecting its thermal stability and mechanical properties during processing [88]. To enhance the processability of starch-based bioplastics, researchers have attempted to blend starch with biodegradable synthetic polymers such as polylactic acid (PLA) and polybutylene adipate terephthalate (PBAT) [116]. These polymers offer better mechanical strength and processability; however, achieving homogeneity in the blend remains a challenge due to differences in polarity and molecular structure [106,117]. The lack of compatibility between starch and these polymers often results in phase separation, leading to poor mechanical performance and reduced biodegradability of the final product [118]. To address these challenges, compatibilizers and plasticizers such as glycerol, citric acid, and maleic anhydride are introduced to improve the interfacial adhesion between starch and other polymers [88]. These additives modify the polymer matrix by reducing phase separation and enhancing the blend's mechanical properties. In conclusion, the poor processability and compatibility of starch-based bioplastics with other polymers remain significant obstacles to their widespread application. Ongoing research efforts focusing on material modifications, innovative blending techniques, and advanced compatibilizers are crucial to improving their performance and making them a viable alternative to conventional plastics. Future studies should explore cost-effective and environmentally friendly methods to enhance the processability of starch-based bioplastics without compromising their biodegradability and sustainability.

7.4 High Production Costs and Limited Scalability

Despite the environmental benefits of starch-based bioplastics, their widespread adoption is significantly hindered by high production costs and limited scalability. Unlike petroleum-based plastics, which benefit from well-established production infrastructure and economies of scale, starch-based alternatives require complex processing methods, high-purity raw materials, and additional modifications to enhance mechanical and barrier properties [116]. The cost disparity primarily stems from the need for extensive refining, drying, and plasticization processes, as native starch lacks the structural and functional robustness needed for many commercial applications [6]. Additionally, the incorporation of plasticizers, cross-linking agents, and reinforcements to improve performance further adds to production expenses. A key economic challenge is the cost of raw materials. Starch is predominantly sourced from food crops such as corn, cassava, and potatoes, which are subject to market fluctuations, seasonal availability, and competition with the food industry [110]. The rising global demand for starch-based materials may drive up prices, making bioplastics less economically viable than their petroleum-based counterparts. To address this, researchers are exploring non-food starch sources and agricultural residues such as banana peels, rice husks, and sorghum husks as potential feedstocks [119]. While these alternatives show promise in reducing raw

material costs, efficient extraction and processing techniques must be developed to ensure their feasibility in large-scale production. The scalability of starch-based bioplastics is further constrained by the need for advanced processing technologies. Unlike conventional plastics, which can be mass-produced using well-established extrusion and injection molding techniques, starch-based bioplastics require specialized processing conditions to control moisture content, enhance durability, and ensure compatibility with existing manufacturing systems [33]. The absence of large-scale production facilities and high initial investment costs for equipment upgrades hinder the expansion of bioplastic manufacturing industries, especially in developing economies [9]. Policy support and financial incentives play a crucial role in overcoming cost-related barriers. Government subsidies, tax incentives for bioplastic manufacturers, and research funding for alternative processing methods can help bridge the economic gap between starch-based and petroleum-based plastics [119]. Advances in raw material sourcing, process optimization, and policy interventions are essential to making these bioplastics commercially viable. Future research should focus on developing cost-effective processing techniques and exploring underutilized starch sources to enhance economic sustainability. Economic feasibility remains a significant challenge for starch-based bioplastics due to higher production costs and limited economies of scale. While conventional petrochemical plastics such as polyethylene and polypropylene typically cost around **$1.00–$1.80 per kg**, bioplastics including starch-derived systems often range from roughly **$2.50–$4.00 per kg**, making them **~2–3 times more expensive** in mainstream markets without subsidies or regulatory incentives [120]. The elevated costs reflect energy-intensive processing, specialized compounding, and smaller production capacity, in contrast to mature fossil plastic industries with vast scale advantages [121]. Other biodegradable polymers such as polylactic acid (PLA) exhibit similar pricing (approximately **$2.00–$3.50 per kg**) relative to petroleum-based plastics, further illustrating the broader biopolymer cost premium [122]. These relative cost positions underscore the economic trade-offs of starch-based materials and suggest that cost competitiveness will depend on scale-up, feedstock optimization, and policy support rather than intrinsic parity with conventional plastics.

7.5 Environmental and Biodegradability Concerns

Although starch-based bioplastics are widely recognized for their biodegradability, their degradation rate is highly dependent on environmental conditions. Factors such as microbial activity, humidity, temperature, and soil composition play crucial roles in determining how efficiently these materials break down in natural environments [11]. In controlled composting environments, starch-based bioplastics can degrade within weeks; however, in less favourable conditions, such as marine ecosystems or landfills, degradation may take significantly longer, raising concerns about their long-term environmental impact [123]. The accumulation of partially degraded starch-based materials in certain environments can also lead to potential ecological issues, including the formation of microplastics if the breakdown process is incomplete [3]. To improve the functional properties of starch-based bioplastics, manufacturers often incorporate plasticizers, cross-linking agents, and synthetic polymers. While these additives enhance flexibility, water resistance, and mechanical strength, they can also introduce new challenges in biodegradation. Some additives slow down the decomposition process or leave behind residues that may persist in the environment for extended periods [5]. Additionally, chemically modified starch derivatives such as acetylated starch or grafted starch-polymer composites may not be fully assimilated by microbial communities, reducing their eco-friendliness compared to native starch [124]. Addressing the environmental challenges of starch-based bioplastics requires a multifaceted approach involving material innovation, policy support, and waste management strategies. Improved composting infrastructure, the development of biodegradable additives, and stricter regulations on bioplastic formulations can help minimize their unintended environmental consequences. Moreover, increased public awareness and responsible disposal practices will play a vital role in ensuring

that starch-based bioplastics truly contribute to global sustainability efforts rather than becoming another source of pollution [7]. Biodegradability of starch-based materials varies substantially with environmental conditions, and quantitative benchmarks are critical for contextualizing claims of "biodegradable" behaviour. Under soil burial conditions at ambient temperatures (≈20°C–25°C), thermoplastic starch alone has been reported to achieve significant mass loss often exceeding ~60% within 28–136 days and approaching complete biodegradation over several months driven by microbial activity and moisture availability [125]. In composting environments with elevated temperatures and controlled humidity, certified compostable materials (e.g., under ASTM D6400/ISO 17088 standards) can reach ≥70%–90% mineralization within ~45–180 days [126]. However, aquatic systems tend to be much less conducive to rapid biodegradation: reports for starch-based films show high variability, with minimal breakdown in some freshwater or marine tests over 90 days, and in other cases modest mass loss over several months. Moreover, additives, blends, and fillers can either enhance or retard enzymatic accessibility and biodegradation, meaning that some formulations may fragment without full mineralization, raising concerns about incomplete degradation and transient microplastic formation in less active environments [127]. These divergent time scales and environmental dependencies underscore the need to interpret biodegradability claims in light of specific disposal pathways and ecosystems rather than assume uniform breakdown across all settings.

8 Future Directions and Perspectives

Recently, a number of successful methods have been used to create increasingly high-performance starch-based blends and composites, including the creation of self-reinforced composites, coatings with decreased moisture sensitivity, and antimicrobial properties. However, a number of obstacles and limitations still need to be overcome for a variety of potential uses. Antimicrobial resistance needs to be expanded further because it is still insufficient. To attain longer longevity, the natural moisture sensitivity must be further decreased and the UV/aging resistance of polysaccharides increased.

Furthermore, there is still room for diversity in the *in vivo* uses of starch-based mixes and composites. In order to create biocompatible, high-performing, yet affordable blends and composites that can be used for scaffold construction, drug delivery, and tissue engineering, scientists are now working on various alternative approaches. In a variety of medical and nonmedical applications, the current extremely popular nonbiodegradable synthetic polymeric materials may soon be significantly replaced by relatively inexpensive, adaptable green materials. Future studies should also concentrate on improving these materials' mechanical strength, flexibility, and thermal stability in order to meet or surpass those of conventional plastics. The creation of composites and polymer mixes that include natural fibers or nanoparticles may be one way to achieve this. Additionally, for applications in food packaging and other delicate uses, renewable polymers' gas and moisture barrier qualities must be improved. Future directions emphasize machine learning for biodegradation, supportive policies (e.g., USDA BioPreferred), industrial scaling of cost-effective PLA, nanocellulose advancements, novel functionalization, and production optimization for economic and environmental gains, providing a roadmap for mainstreaming these materials toward a sustainable, circular economy.

Key priorities include enhancing mechanical strength through controlled filler incorporation, optimizing barrier properties to reduce water vapor and oxygen permeability, improving thermal stability for scalable processing, and quantifying biodegradation rates in soil, compost, and aquatic environments while minimizing microplastic formation. Additionally, efforts should address economic feasibility by exploring feedstock selection, formulation, and processing strategies to reduce production costs relative to conventional plastics. These focused objectives provide a clear roadmap for advancing both the performance and sustainability of starch-based materials.

9 Conclusion

Starch-based bioplastics offer a viable and sustainable alternative to conventional plastics, aligning with global initiatives for reducing environmental pollution and promoting a circular economy. Their biodegradability, renewable origins, and compatibility with existing processing methods make them highly attractive for use in food packaging, medical applications, and agriculture. Inherent limitations such as poor mechanical strength, thermal instability, and high sensitivity to moisture hinder their broader adoption. Recent advancements in chemical modification, polymer blending, and nanocomposite reinforcement have significantly improved the performance characteristics of starch-based bioplastics, although challenges in scalability and cost remain. Comprehensive analytical evaluations, including thermal, mechanical, and structural testing, are essential to optimizing formulations and guiding further research. Future progress depends on interdisciplinary collaboration, policy incentives, and technological innovation to overcome production barriers and enhance the material's commercial viability. Addressing these challenges can enable starch-based bioplastics to play a transformative role in reducing plastic pollution and advancing sustainable development.

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