



Iranian Research Organization
for Science and Technology
(IROST)



Sustainable plastics from renewable resources: A review on starch-based bioplastics

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ARTICLE INFO

Document Type:
Review Paper

Article history:
Received 18 July 2025
Received in revised form
11 November 2025
Accepted 14 November 2025

Keywords:

Starch-based bioplastic
Starch extraction
Solvent casting
Extrusion
Circular bioeconomy

ABSTRACT

The increasing environmental impact of petroleum-based plastics has accelerated the search for sustainable, biodegradable alternatives derived from renewable resources. Among various biopolymers, starch-based bioplastics have gained significant attention due to their abundance, low cost, biodegradability, and ease of processing. This review provides a comprehensive overview of starch-based bioplastics, focusing on their sources, extraction methods, structural characteristics, production techniques, additives, and diverse applications. Starch, primarily composed of amylose and amylopectin, can be converted into thermoplastic starch (TPS) through plasticization, enabling melt processing via extrusion, injection molding, or solvent casting. The addition of plasticizers, fillers, acids, and biodegradable polymer blends enhances mechanical strength, flexibility, and water resistance, although challenges remain in achieving optimal thermal stability and moisture tolerance. Characterization studies involving mechanical, thermal, and morphological analyses are discussed to elucidate structure-property relationships. The review also highlights emerging applications in packaging, agriculture, medical devices, 3D printing, consumer goods, automotive components, and textiles. Furthermore, it underscores the importance of optimizing formulations, utilizing agricultural residues, and performing life-cycle and biodegradation assessments to ensure sustainability. Overall, starch-based bioplastics represent a promising pathway toward reducing plastic pollution and advancing a circular, bio-based materials economy.

1. Introduction

The wide use of petroleum-based plastics has led to a significant and harmful environmental burden, primarily due to their non-biodegradable nature

and resistance to natural degradation processes. These conventional plastics, derived from fossil fuels, significantly contribute to land and marine pollution, generate substantial greenhouse gas emissions during their production and incineration,

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DOI: 10.22104/AET.2025.7748.2179

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and persist in natural ecosystems, thereby adversely impacting biodiversity and environmental health [1]. Despite their versatility, durability, and low production cost, petroleum-based plastics are unsustainable in the long term due to increasing challenges in plastic waste management and the need to reduce dependence on non-renewable energy sources. Research indicates that some bioplastics currently marketed as alternatives are not inherently biodegradable, thereby further complicating the challenge of sustainable plastic management [2]. As public awareness and environmental regulations strengthen, there is an increasing demand for sustainable materials that can provide the functional advantages of conventional plastics while minimizing their ecological impact.

In this context, recent advancements in biopolymers are gaining significant attention as viable alternatives owing to their renewable origin, biodegradability, and compatibility with various applications [3]. Biopolymers comprise a wide range of naturally occurring polymers that are increasingly being explored for applications in sustainable materials science. Among the most prominent are cellulose, chitosan, starch, proteins, and polylactic acid (PLA), each possessing unique structural and functional properties that make them suitable for diverse applications [4]. Collectively, these biopolymers provide diverse functionalities and represent sustainable alternatives to petroleum-based plastics. Factors such as environmental conditions, desired material properties, and economic viability influence the selection and application of these materials. With ongoing research and technological advancements, biopolymers are expected to play a pivotal role in the development of eco-friendly materials for industrial, agricultural, and biomedical applications, offering a promising pathway toward a more sustainable and circular materials economy. The global bio-based polymer market is projected to grow at an annual rate of approximately 13% through 2029, driven primarily by increasing demand in Asia and North America [5].

Among the various categories of bioplastics, starch-based plastics hold the second-largest share after polylactic acid (PLA), accounting for

roughly one-fifth of the total global bioplastic production capacity. Chemically, starch is a polysaccharide consisting of two primary constituents—amylose and amylopectin—whose molecular architecture and relative composition critically determine its film-forming capacity and thermoplastic behavior when subjected to heat and plasticizers [6]. Starch offers a distinct economic and environmental advantage over PLA, being a more affordable polysaccharide that requires substantially lower energy input during processing (around 25.4 MJ/kg compared to 57.0 MJ/kg for PLA). This makes starch a promising candidate for wider market adoption in the near future. The commercial success of starch-based plastics largely depends on blending modified or unmodified starch with other polymers to tailor mechanical strength, thermal stability, and degradability for specific end uses. Such blends may involve compostable polymers like PLA, polycaprolactone, and polyhydroxyalkanoates, or non-compostable polymers, including polyethylene, polypropylene, and polystyrene. These starch-based composite materials are extensively used in packaging applications across the food, cosmetic, and pharmaceutical sectors due to their non-toxicity, biocompatibility, and improved mechanical and degradation characteristics [7]. Recent advancements have focused on enhancing starch-based films through molecular modification and the addition of plasticizers, cross-linking agents, and natural fibers. Renewable agricultural sources, such as cassava, corn, and potatoes, serve as stable and accessible feedstocks for starch-based bioplastic production [8-10]. These innovations contribute to reducing plastic pollution and promoting a circular, bio-based economy.

Improved extraction and processing technologies now enable the use of underexploited sources, such as waste potato and tapioca starch, thereby expanding the renewable raw material base. Starch-based bioplastics are commonly produced using techniques such as solvent casting and thermomechanical methods, including extrusion or injection molding [11]. Their properties can be adjusted by compositional modification, plasticizer incorporation, or blending with other bio-based polymers. This review summarizes the current

progress in starch-based bioplastics, covering their sources, production methods, structural and functional features, biodegradability, and applications. It highlights key opportunities and challenges in advancing these materials as sustainable alternatives to conventional plastics.

2. Significance of starch as a biopolymer

Starch is the most abundant storage polysaccharide in plants and constitutes a primary source of carbohydrates in tuber crops and cereals such as cassava and corn. It is synthesized in plastids through enzyme-catalysed biochemical reactions and accumulated as semi-crystalline granules in storage tissues, including tubers, roots, and grains. These granules are water-insoluble and may occur as individual particles or as aggregated compound granules, with concentric or eccentric layers of varying density. As a non-structural carbohydrate composed of glucose polymers, starch serves as an osmotically inactive, biologically inert form of energy storage in plants

and algae, underscoring its essential role in plant metabolism and its potential as a renewable raw material [12]. Starch comprises of two types of glucose macromolecules—linear amylose and branched amylopectin—whose relative proportions vary across different feedstocks, making each starch source distinct (Figure 1). Amylose is a mostly linear polysaccharide, composed of $\sim 99\%$ α -1,4-linked D-glucose units with very minor ($\sim 0.5\%$) α -1,6 branching, whereas amylopectin is highly branched, containing $\sim 95\%$ α -1,4-linked and $\sim 5\%$ α -1,6-linked glucose units. The molecular weight of amylose ranges from 10^5 – 10^6 , with a degree of polymerization of 1,000–10,000 glucose units, while amylopectin has a molecular weight of 10^7 – 10^8 and a degree of polymerization typically between 10^4 – 10^6 glucose units. Despite both being composed of glucose polymers with α -1,4 linkages and α -1,6 branch points, their structural and functional properties differ across starch types [12]. The physicochemical properties of starch are largely determined by this compositional ratio [7].

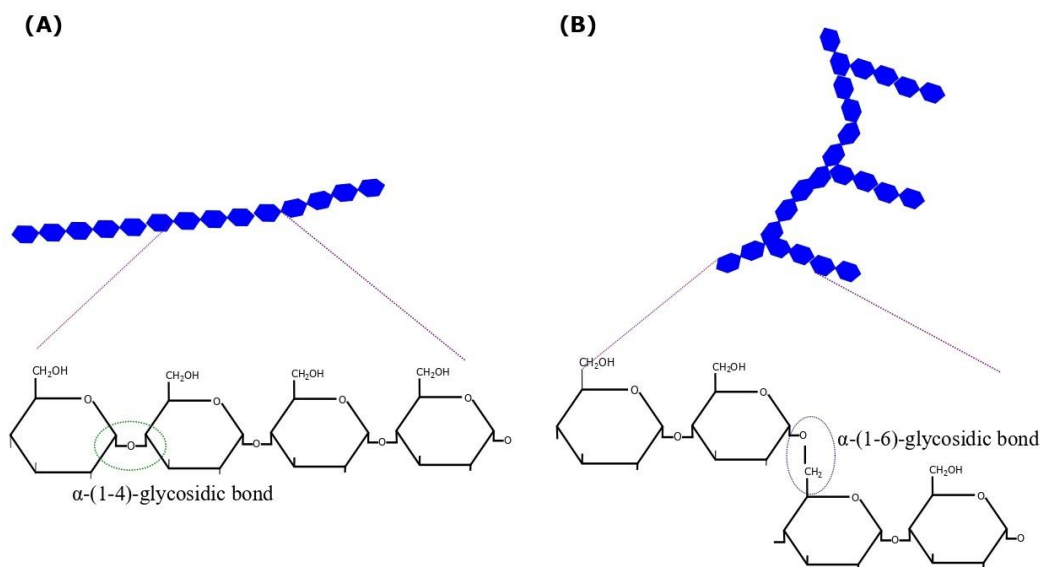


Fig. 1. Structural representation of starch components: (A) amylose containing $\alpha(1\rightarrow4)$ glycosidic linkages, and (B) amylopectin containing both $\alpha(1\rightarrow4)$ and $\alpha(1\rightarrow6)$ glycosidic linkages.

In its native form, dry starch has a melting point higher than its decomposition temperature, rendering it unsuitable for direct thermoplastic processing. However, when heated to elevated temperatures (90 – 180°C) in the presence of plasticizers such as glycerol, sorbitol, maleic anhydride, or citric acid, starch can be converted

into thermoplastic starch (TPS). During this process, starch absorbs water, swells, and forms a viscous slurry, while continued heating disrupts the crystalline structure of the granules by breaking the molecular order of amylose and amylopectin. Plasticizers are essential for this transformation, as they form new hydrogen bonds with starch

molecules, displacing the strong hydroxyl–hydroxyl interactions within the polymer. By interposing between polymer chains, plasticizers enhance chain mobility, facilitate starch gelatinization, and increase the fluidity and flexibility of the material. This disruption of polymer–polymer interactions prevents re-association and allows the formation of a homogeneous, processable thermoplastic material [7].

3. Sources of starch as bioplastic feedstock

Starch is a polysaccharide found in a wide variety of plant-based sources, and its availability makes it an ideal candidate for bioplastic production. Major starch sources include grains such as corn, wheat, and rice, as well as tuber and root crops like potato and cassava [13]. However, its inherent hydrophilicity and non-thermoplastic nature result in weak, water-sensitive bioplastic films. The hydrophobicity and mechanical properties can be enhanced through chemical, physical, enzymatic, or genetic modifications, which are discussed in detail elsewhere in this manuscript.

The linear structure of amylose contributes to higher crystallinity and tensile strength but often leads to brittleness, while the branched structure of amylopectin enhances flexibility and elongation.

Amylose-rich starches have been reported to serve as more efficient raw materials for bioplastic production compared to normal starches, as demonstrated by previous studies [14]. The amylose and amylopectin content of major starch feedstocks are listed in Table 1 [9].

Corn is a prominent source of starch, as it is commonly and abundantly found. Moreover, relatively high amylose content and thermal stability make it a suitable feedstock for bioplastic production. Although inherently sensitive to moisture, corn starch remains a sustainable and adaptable substrate for biodegradable film production when chemically or physically modified [9]. The incorporation of plasticizers, such as glycerol or sorbitol, has been shown to improve flexibility, elongation, and transparency in otherwise brittle cornstarch films. Further enhancements in mechanical strength and morphology have been achieved through the addition of natural fillers, confirming corn starch's compatibility with composite materials [28–30]. Cassava starch, abundant in tropical regions, possesses a high starch content, favorable physicochemical characteristics, and superior biodegradability, making it a promising raw material for bioplastic production [31].

Table 1. Percentage of starch, amylose, amylopectin and the starch granule size of major feedstocks of starch-based bioplastics.

Sl.no.	Source	Starch content (%)	Granule size (µm)	Amylose content (%)	Amylopectin content (%)	References
1	Corn	65 – 75	2 – 30	20 – 30	70 – 80	[15–17]
2	Cassava	70 – 85	5 – 35	15 – 25	75 – 85	[18–20]
3	Rice	70 – 80	2 – 9	15 – 35	65 – 85	[17, 21, 22]
4	Potato	60 – 80	5 – 100	20 – 30	70 – 80	[16, 22, 23]
5	Wheat	60 – 70	1 – 45	20 – 30	70 – 80	[17, 24]
6	Banana (Unripe)	70 – 85	5 – 70	20 – 40	60 – 80	[25–27]

Owing to its low cost and excellent film-forming capability, cassava starch has been widely investigated for applications in packaging and biomedical fields. Studies using cassava waste starch have shown its potential for producing antimicrobial bioplastics, while its inherent transparency and biodegradability further enhance its suitability.

However, its moderate mechanical strength can be improved through blending or reinforcement with

materials such as chitosan [32], gelatin [33], nanoclay [34], etc., which enhance tensile strength, water resistance, and overall structural integrity. Based on the study by Jareerat Ruamcharoen et al. (2022), blending cassava starch with natural rubber and nanoclays (MMT, KAO, and DKAO) significantly improved the mechanical strength, water resistance, and overall physical properties of the resulting bioplastic films [35].

Potato starch, characterized by its high amylopectin content, produces flexible and smooth films with lower tensile strength compared to amylose-rich starches. Optimization studies have shown that properly plasticized potato starch films can achieve tensile and barrier properties comparable to those of conventional plastics [36]. Plasticizer blends, particularly glycerol-sorbitol systems, enhance the thermal stability and durability of potato starch-based bioplastics, expanding their potential in packaging applications [37]. Further improvements in the performance of potato starch-based bioplastics can be achieved by incorporating fillers such as eggshells or chitosan [38]. In another study, potato starch-based bioplastics reinforced with inorganic materials, such as aluminum (AMP-F), exhibited enhanced tensile strength (29.91 MPa), improved thermal stability (melting point 169.15°C), and strong antimicrobial activity against bacteria and fungi, making them suitable for food packaging applications [39].

Rice starch, though less frequently utilized, offers advantages such as small granule size and high transparency, making it suitable for producing clear biodegradable films. Studies comparing rice, cassava, and corn starches have shown that rice starch films exhibit moderate tensile strength, which can be improved by incorporating gelatin [13]. Despite its limited water resistance, rice starch can be effectively used in blended formulations to exploit its clarity and biodegradability for applications such as food wraps and edible coatings [9].

4. Extraction of starch

Starch extraction is the process of isolating starch granules from plant based sources. The extraction aims to separate starch from non-starch components, such as proteins, lipids, and fibers, through mechanical, chemical, enzymatic, or physical means.

The specific extraction techniques can vary depending on the type of source material, such as cassava, potato, or corn, but the overall process tends to follow a similar pattern [25] each presenting a trade-off between yield, purity, and

functional properties (Figure 2). However, critical factors to consider include preventing amylolytic and mechanical damage to starch granules, ensuring efficient deproteinization, and minimizing the loss of small granules during extraction [40]. Initially, raw plant materials are thoroughly washed to remove any adhering dirt, fibers, or unwanted substances. In the case of tubers like potatoes or cassava, the process continues with peeling and cutting. For corn, the kernels are removed from the cob.

The procedure begins with the pulverization of the plant material to disrupt cell structures, followed by soaking in water to soften the tissues and facilitate the release of starch granules. The resulting suspension is then subjected to centrifugation or filtration to separate the starch from plant fibers and proteins. The crude starch is then subjected to a purification stage involving repeated washing and sedimentation to eliminate any remaining contaminants. After repeated washing, the starch is collected, decanted, and may be washed again for improved purity [27]. Lastly, the starch is dried using air-drying, oven-drying, or freeze-drying, and then milled into a fine powder, rendering it ready for use in various applications, like bioplastics [26, 28, 41].

In mechanical extraction, intense shear forces generated during grinding or milling can disrupt the granular architecture, leading to changes in granule size distribution and potential damage to granule integrity.

Such physical disruption may also modify the amylose-to-amylopectin ratio, thereby affecting the gelatinization behavior and overall functional properties of the starch.

Certain starch extraction methods employ alkaline solutions to solubilize proteins, thereby facilitating the recovery of purified starch from flours. Various alkaline agents, including detergents, and sodium hydroxide can serve as extraction solvents. Apart from this, sodium hydrogen sulphite has been employed in steep water to accelerate water diffusion into seeds, promote the breakdown of the protein-starch matrix, and suppress microbial growth [42].

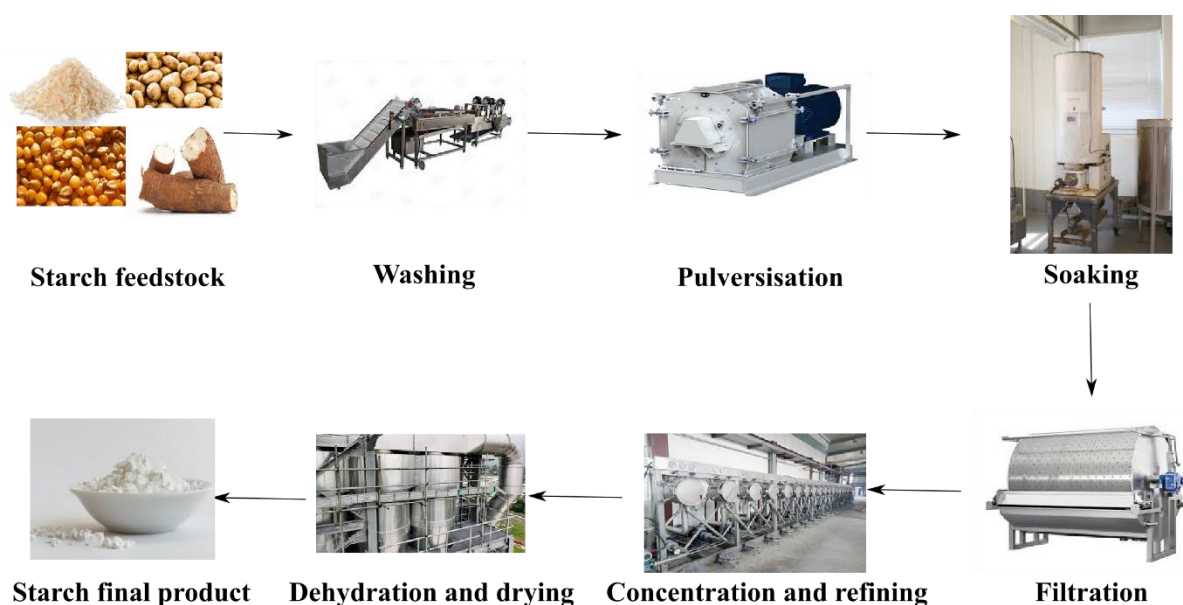


Fig. 2. Schematic representation of starch extraction from plant-based feedstocks. The raw material is first washed to remove impurities and then pulverized into a fine powder. The resulting mass is subjected to steeping with water, chemicals, or enzymes, followed by filtration and refining to obtain purified starch, which is subsequently dehydrated and dried to yield the final product.

In a study, the use of an oxalic acid/ammonium oxalate solution for chemical starch extraction was found to be highly effective, as it reduced slurry viscosity and enhanced starch separation efficiency. This method yielded 18 g of starch per 100 g of *Dioscorea alata*, representing the highest recovery among the tested approaches. Additionally, it produced a wide range of granule sizes, varying from 1.94 μm to 67.7 μm , indicating the influence of the extraction medium on starch granule morphology [43]. However, the use of such chemicals raises environmental concerns related to effluent disposal, and prolonged exposure to alkaline conditions may lead to deterioration in the quality of the isolated starch [44].

Enzymes, such as proteases, are occasionally employed for deproteinization, often following chemical treatment. For instance, Zhao et al. extracted rice starch by soaking rice powder in 0.45% sodium metabisulfite at 4 °C for 18 h, followed by overnight protease treatment. They observed the highest amylopectin molecular weight, indicating that protease had minimal impact on the starch [45]. A similar enzymatic approach has also been applied to extract starch from quinoa seeds. Compared with wet-milling and alkali methods, enzymatic extraction more effectively preserves the native structure of starch

granules, yielding larger aggregates, higher protein content, increased crystallinity, enhanced helical structures, and greater molecular weight, along with improved textural properties. In contrast, wet-milling and alkali treatments reduce these structural and functional qualities. These results highlight that enzyme treatment is the most effective strategy for maintaining intact starch architecture, whereas the alkali method prioritizes extraction efficiency at the expense of structural integrity [46]. Ultrasonic technology, combined with alkali treatment [47] and enzymes [48], has been used to prepare modified starch.

Ultrasound disrupts starch macromolecules via mechanical and radical-mediated effects, causing partial chain fragmentation, reduced entanglement, and crystalline structure disruption. It also enhances molecular mobility through mechanical, cavitation, and thermal effects, while altering hydrogen bonds and the double-helix structure, ultimately affecting the starch's morphology, physicochemical properties, and digestibility [49].

5. Production of bioplastics

The conversion of starch into bioplastic materials can be achieved through two primary approaches:

the wet method and the dry method (Figure 3). In the wet method, starch undergoes gelatinization by heating with water and plasticizers such as glycerol or sorbitol. The resulting viscous solution is then cast onto a flat surface and dried to form thin bioplastic films. This technique allows the incorporation of fillers and additives to enhance the film's mechanical strength and barrier properties [7].

The wet method, employing the solvent casting technique, has been successfully utilized for the preparation of starch-based bioplastics from several sources, including corn [50], rice [51], cassava [52], bananas [53], and yams [54]. Moreover, this approach provides flexibility for studying the influence of various components on the physicochemical properties of the resulting bioplastics. The specific effects of additives on bioplastic properties are discussed elsewhere in this manuscript. In contrast, the dry method involves thermomechanical processing techniques such as extrusion, hot pressing, and injection molding.

For industrial-scale applications, extrusion is preferred due to its reliability, efficiency, and capability for continuous operation. During extrusion, the polymer melt is forced through a die of defined geometry to produce profiles such as sheets, tubes, or films. This method offers high productivity and precise process control, making it a robust and widely adopted technology for the fabrication of thermoplastic starch (TPS)-based materials intended for commercial use [55].

Native starch can be converted into thermoplastic starch (TPS), a translucent, amorphous polymer exhibiting properties comparable to those of conventional synthetic polymers. This transformation is achieved by combining starch with suitable plasticizers at its gelatinization temperature, during which the hydrogen bonds within the starch granules are disrupted, resulting in a fully amorphous material. The obtained product, referred to as plasticized starch, destructured starch, or thermoplastic starch (TPS), may exist in either a fully amorphous (TPSA) or semi-crystalline (TPSC) form, depending on the processing conditions [55]. Thermoplastic starch can be fed into an extruder, where it is subjected to external heating and shear forces generated by screw-barrel interactions. Under these conditions,

TPS softens and can be molded into various plastic products. Due to its thermoplastic nature, it can be repeatedly melted and solidified, enabling its processing through conventional plastic manufacturing techniques, such as extrusion and injection molding [55]. Furthermore, the incorporation of biodegradable polymers (e.g., PLA, PCL, PBAT) or nanofillers (e.g., cellulose nanocrystals, layered clays) can further enhance the thermal stability, mechanical strength, and structural integrity of TPS-based materials [56, 57]. Post-processing steps such as drying, annealing, or surface modification are often employed to optimize the material's properties for targeted applications in packaging, agriculture, and disposable products. Overall, starch-based bioplastic production through both wet and dry processing routes represents an environmentally sustainable approach, utilizing renewable raw materials and yielding fully biodegradable products under suitable conditions [58].

6. Characterization studies

The characterization of starch-based bioplastics is crucial for understanding their structure, properties, and suitability as alternatives to conventional plastics. These methods generally fall into categories that assess mechanical, physicochemical/ barrier, structural/ morphological, and thermal properties.

6.1. Mechanical testing

Mechanical characterization of starch-based bioplastics typically involves evaluating tensile strength (TS), elongation at break (EAB), and Young's modulus. TS and EAB are measured using a Universal Testing Machine (UTM) in accordance with standards such as ASTM D882-02. Tensile strength reflects the material's resistance to breaking under tension, while elongation at break indicates the extent to which the material can stretch before rupture. Young's modulus, derived from the stress-strain curve, quantifies the material's stiffness or rigidity, providing insight into its structural integrity under mechanical stress.

According to Kowser, M. A. et al. (2025), natural materials like tea waste have improved the mechanical properties of corn starch-based

bioplastics. Based on their findings, green tea-infused bioplastics have a tensile strength of roughly 2.7 MPa and an elongation at break of 42.5%, demonstrating moderate strength and excellent flexibility that are appropriate for packaging use. Bioplastics from different treatments displayed a broad range of tensile

strength and elongation values [59]. Glycerol, the most commonly used plasticizer, interacts effectively with diverse starch types, while fillers like chitosan, clay, and ZnO tend to enhance strength but reduce flexibility, thereby counteracting the plasticizer's effects [60].

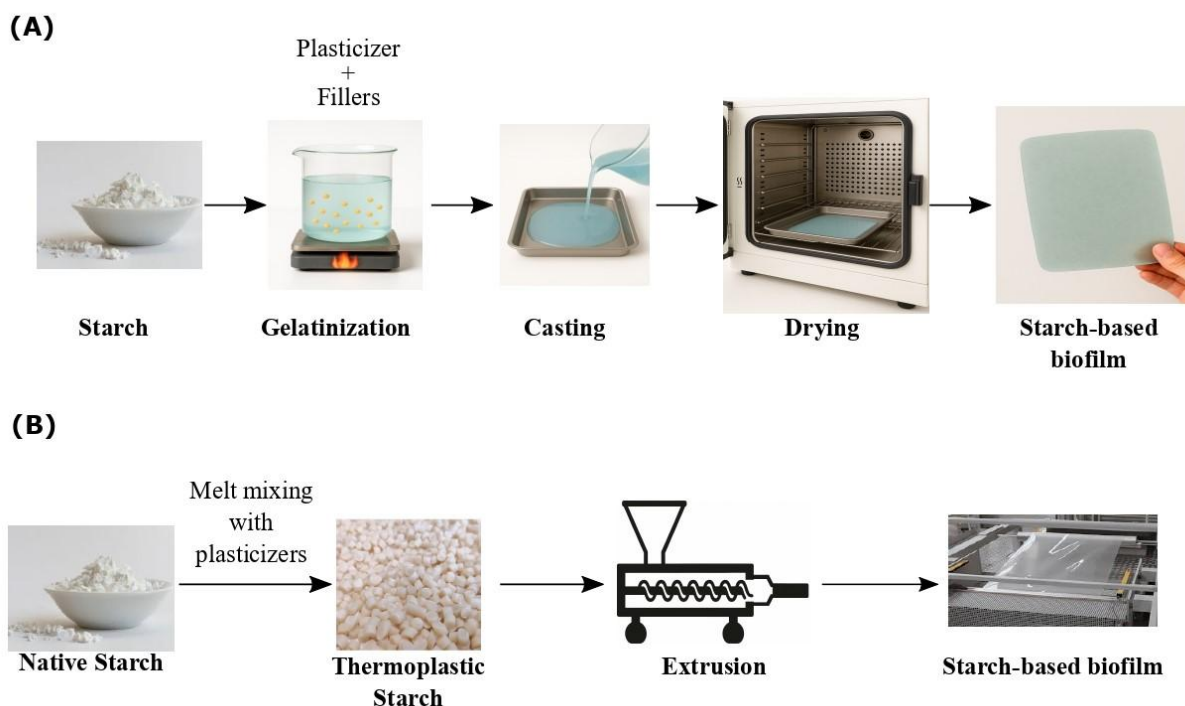


Fig. 3. Schematic representation of the production of starch-based biofilms. (A) Wet method via solvent casting: starch is gelatinized with the addition of plasticizers and fillers at elevated temperature, followed by casting into a mold and subsequent drying to remove residual solvent. (B) Dry method via thermomechanical processing: thermoplastic starch is extruded into films under the combined action of heat and shear forces.

6.2. Physicochemical and barrier properties

Physicochemical and barrier properties are important, especially for packaging applications, as starch is inherently hydrophilic. The water absorption test is also known as water uptake, which determines the percentage of moisture a bioplastic film may absorb when exposed to a humid or wet environment. This test is necessary for determining the moisture resistance and dimensional stability of the film. Starch-based bioplastics frequently display great water absorption because of the hydroxyl groups in the starch backbone, which readily form hydrogen

bonds with water molecules. It was discovered that films of cassava starch with more glycerol content absorbed more moisture, making them more flexible but weaker mechanically [61]. Reduce water absorption and enhance the film's performance under wet conditions by incorporating plasticizers, crosslinking agents, and hydrophobic fillers.

The water solubility test measures the amount of bioplastic material that dissolves in water over a specified time frame. Particularly for applications including food packaging, sanitation products, and agricultural films where water contact is frequent,

this test is crucial. Due to its hydrophilic polysaccharide nature, starch exhibits great water solubility. The type and concentration of plasticizers used, nevertheless, have a big effect on the degree of solubility. For instance, the common plasticizer glycerol interacts with starch chains by hydrogen bonding, therefore lowering their crystallinity and increasing the material's solubility [62]. Higher solubility generally results from more plasticizer concentration as a result of superior free volume and chain mobility in the film matrix.

6.3. Structural and morphological analysis

These techniques look at the internal structure and surface characteristics. Fourier-Transform Infrared (FTIR) Spectroscopy is used to identify the functional groups (hydroxyl (-OH), carboxyl (C=O), and ether (C-O-C)) present and confirm chemical interactions (like hydrogen bonding) between the starch and any added plasticizers or fillers [30]. Shifts in peak positions can indicate successful mixing or reaction [59]. Oluwasina, O. O. et al. (2019) observed new peaks around 1720 cm^{-1} in oxidized starch-based films, suggesting esterification and enhanced thermal and mechanical properties [63].

Scanning electron microscope (SEM) provides useful information about the morphological makeup of starch-based bioplastics. Cracks, pores, and phase separation, which indicate poor filler matrix interaction or inadequate miscibility, are observed in the analysis. A starch's smoother appearance typically suggests consistent blending with any fillers or additives. Recent research indicates that adding corn starch with a small amount of plasticizer produces a relatively smooth and compact structure, suggesting good dispersion and plasticization [61]. In contrast, the researcher observed a rougher surface topology when natural reinforcements, such as lignocellulosic biomass, were utilized, indicating enhanced interfacial adhesion between the filler and starch matrix. The degradation rate and mechanical strength are greatly influenced by these morphological alterations [64].

X-ray diffraction (XRD) is useful for determining the amount of crystalline and amorphous phases in bioplastics made from starch. A film's strength, flexibility, and barrier characteristics are

influenced by its crystalline composition. Native starch usually has a semicrystalline structure; however, its crystallinity is lowered by processing methods like gelatinization, plasticization, and blending. The peak intensity in the XRD spectra decreased with the inclusion of food grade additives to potato starch, indicating a reduction in crystallinity caused by molecular disruption [65]. The oxidation of starch changed the molecular packing and produced a more amorphous structure, which improved flexibility and degradation behaviour [63]. These changes in crystallinity are directly related to the film's characteristics, like solubility and tensile strength.

6.4. Thermal analysis

Thermal analysis evaluates the stability and phase transition temperatures of biopolymeric composites used in the production of bioplastics. The thermal degradation profile of bioplastics is determined by Thermogravimetric Analysis (TGA), which monitors weight loss as temperature increases. This technique provides insights into decomposition phases, thermal stability, and moisture content. Water evaporation typically occurs during the initial phase of weight loss, followed by the breakdown of plastic components and starch. According to a study [64], the addition of lignocellulosic fillers increased the onset degradation temperature, indicating enhanced thermal resistance due to reduced volatility and stronger molecular bonding. Similarly, oxidized starch films exhibited delayed thermal decomposition, suggesting improved heat resistance suitable for thermal packaging applications in [65].

Differential scanning calorimetry (DSC) assesses thermal transitions like the glass transition temperature (T_g) and melting temperature (T_m), which evaluate a film's heat flexibility and stability. A lower T_g typically indicates increased chain mobility and thus greater flexibility and workability, often caused by the addition of plasticizers, like tea-based reinforcement [59]. Furthermore, a narrower endothermic peak in the DSC curve suggests effective plasticizer-starch interaction and consistent thermal behaviour [63]. These characteristics are vital for setting the

bioplastic's processing window and predicting end-use performance.

6.5. Biodegradation testing

One of the most appealing characteristics of starch-based bioplastics is their biodegradability, which sets them apart from traditional petroleum-based plastics.

As a natural polysaccharide, starch readily degrades due to its susceptibility to microbial and enzymatic action. Under composting or natural environmental conditions, starch-based bioplastics can rapidly break down into water, carbon dioxide, and biomass [66]. Plasticizers, such as glycerol and sorbitol, are commonly used to increase the flexibility and processability of starch-based films, influencing their biodegradability. By increasing water absorption, these agents facilitate microbial access to the polymer matrix. For instance, glycerol-plasticized cassava starch films exhibited improved biodegradability and water sorption [61]. However, achieving an optimal balance between mechanical strength and biodegradability remains a key challenge. Although biodegradable and edible films offer environmental benefits, their mechanical properties and water sensitivity limit broader commercial use [67]. Structural modifications, such as blending starch with other biodegradable polymers or adding natural fillers and crosslinking agents, have improved stability without significantly compromising biodegradability.

The degradation test evaluates the biodegradability of starch-based bioplastics under various environmental conditions, including soil (soil burial test), compost, and aqueous media. Typically, it measures mass loss or observable structural breakdown over time. Due to their hydrophilic nature and natural origin, starch-based bioplastics are highly susceptible to microbial degradation. Depending on temperature, moisture, and microbial activity in composting environments, they can fully decompose within a few weeks. Bioplastics derived from starch degrade significantly faster than conventional polymers, making them ecologically superior.

The incorporation of additives, crosslinkers, or blending starch with other biodegradable polymers

can influence the degradation rate [68]. As a result, starch-based bioplastics offer both practicality and environmental sustainability, making them a viable alternative to conventional plastics.

7. Additives used in bioplastics

The mechanical, thermal, and processing properties of starch-based bioplastics can be greatly improved through the addition of suitable additives. Plasticizers, such as glycerol, sorbitol, and polyethylene glycol (PEG), increase flexibility and reduce brittleness. Fillers, both synthetic and natural, enhance mechanical strength and lower production costs. Acids, such as citric or acetic acid, act as chemical modifiers or processing aids, improving compatibility and processability of the polymer matrix. The various additives and their corresponding effects on the properties of starch-based bioplastics are summarized in Table 2.

7.1. Plasticizers

Plasticizers are crucial for improving the mechanical and functional qualities of starch-based bioplastics. These bioplastics tend to be brittle and stiff due to strong hydrogen bonding between starch molecules. This results in materials with higher elongation at break (more stretchiness) and improved processability, as the material flows more easily during extrusion or moulding. Plasticizers help reduce the glass transition temperature and enhance the movement of polymer chains. This leads to more flexible films, better processing, and less cracking during shaping or drying. Among the various plasticizers, glycerol is the most widely used because it mixes well with starch and forms strong hydrogen bonds. Glycerol is a highly hygroscopic molecule generally added to bioplastic formulations to prevent film brittleness.

Table 2. Summary of various additives used to enhance the physicochemical and mechanical properties of starch-based bioplastics.

Sl. No	Types of starch	Additives	Properties	References
1	Corn starch	30% glycerol and 5% acetic acid	Tensile strength 0.59 MPa and Young's modulus 5.02 MPa	[28]
2	Banana peel and corn starch	Banana peel film with 4% corn starch	Tensile strength of 34.72 N/m ²	[29]
3	Corn starch	Titanium dioxide nanoparticles (7%) as reinforcing filler, vinegar (7%), glycerol (5.5%)	Tensile strength 3.95 MPa, Elongation at break 62%	[30]
4	Corn starch	0.5% Silica powder from sugarcane waste ash	Elongation at break increased from 59.2% to 78.9%; inhibited growth of fungi	[69]
5	Corn Starch	Sorbitol (30% w/w), Multi-scale Kenaf Fibre (6% wt)	Tensile Strength of 17.74 MPa, Young's Modulus of 1324.74 MPa, elongation at break of 48.79%, Decreased water absorption of 114.68% and solubility of 25.17%.	[70]
6	Cassava peel starch	Chitosan	Tensile strength of 49.93 MPa, elongation of 3.068% and Young modulus of 1627.63 MPa.	[32]
7	Cassava starch	Gelatin (30%)	Tensile strength ~8 N/m ²	[33]
8	Cassava starch	Glycerol, Coir Fibers (Green Coconut Fiber) (up to 30%)	Tensile strength of 10-11 MPa and Young modulus of 373.5 MPa. Water uptake and moisture absorption decreased with increasing fiber content.	[71]
9	Cassava starch	Glycerol, Poly-vinyl alcohol (10-40%), Banana Pseudostem Powder (30%) from sour and ash plantain	Tensile Strength of 2.5 MPa, elongation at break of 11%, and Water absorption of 50%.	[72]
10	Cassava Starch (CS)	Brown Seaweed (RO), Glycerol (Gly) (50/50 biomass/Gly ratio)	At optimal ratio of CS and RO (30/70): Tensile Strength of 580 kPa, elongation at break of 25.2%, Increased CS decreased Elastic Moduli 23.72 to 5.69 MPa) and smoothed microstructure.	[73]
11	Potato starch	Egg shells	↑ Tensile strength (4.94%), ↓ Water absorption (10.95%), ↑ Biodegradability (21.06% weight loss in 20 days)	[38]
		Chitosan	↑ Tensile strength (1.28%), ↓ Water absorption (27.59%), ↑ Biodegradability (7.9% weight loss in 20 days)	
12	Potato starch	Aluminium	↑ Tensile strength (29.91 MPa), ↑ Thermal stability (melting point 169.15°C), strong antimicrobial activity, slower biodegradability (>105 days)	[39]
13	Potato Peel Starch (from rotten peels)	Glycerol (20% v/w), HCl (23.33 % v/w), Sorbitol (tested for biodegradability)	Tensile Strength of 6.649 MPa, elongation at break of 19.87%, biodegradability was high (83.92%), Water absorption (59.94%) and Optimal drying temperature of 48°C	[74]
14	Corn Starch (CS) & Potato Starch (PS)	9 g corn starch, 9 mL Glycerol (plasticizer) and 2.5 g Calcium Carbonate (Filler)	↑ Tensile strength of 22.5% (6.08 MPa) and ↑ Young's modulus of 31.7% (0.103 GPa)	[75]

A study [76] found that the addition of arrowroot fibre to biopolymer film improved water vapor permeability and the linear burning rate of bio-composite films. However, too much glycerol

reduced tensile strength and increased water sensitivity, highlighting the need to determine the right concentration levels. Other plasticizers like sorbitol, polyethylene PEG, and citric acid have also

been studied. Sorbitol has a larger molecular structure and lower hygroscopicity, which provides better dimensional stability and moisture resistance. PEG improves flexibility and thermal properties depending on its molecular weight. Citric acid will act as both a plasticizer and a cross-linking agent, enhancing elasticity and strength. Furthermore, bio-plasticizers from renewable sources are gaining popularity due to their environmental friendliness and their contribution to the complete biodegradability of the final product. According to a report [77], the compounds include polyols, organic acids, and their esters, which are expected to replace traditional petroleum-based additives. Plasticizers also significantly influence other characteristics such as transparency, thermal properties, and water solubility, especially in food packaging. For instance, sorbitol offers better water barrier properties and thermal stability compared to glycerol, making it more suitable for edible films and coatings. Therefore, selecting and measuring plasticizers is essential for tailoring starch-based bioplastics to meet specific functional and environmental performance needs.

7.2. Fillers

Fillers are added to starch-based bioplastics mainly to improve mechanical properties, thermal stability, and dimensional integrity, as well as to lower production costs. These fillers, both organic (natural, biodegradable) and inorganic (synthetic), strengthen the starch matrix by improving adhesion and reducing the natural brittleness of starch films. Synthetic fillers, such as calcium carbonate, Talc, and silica, are commonly used to enhance mechanical strength by increasing tensile strength and Young's Modulus for various packaging applications, including stretchable films, wrappers, and rigid packaging. Recent findings have shown a significant improvement in tensile strength and Young's modulus when optimized plasticizer-to-filler ratios are used with multiple starch sources [75]. Natural cellulose-based fillers, like sugarcane bagasse, rice husks, coffee husks, and green coir fibers, are popular because they are derived from renewable sources, possess a high strength-to-weight ratio, and are biodegradable. A researcher showed that cellulose fibers from sugarcane bagasse significantly

improved the tensile and thermal properties of acetylated starch films, especially when processed with the right compounding methods [78]. A previous study found that cellulose fibers from rice and coffee husks increased the tensile strength and flexibility of thermoplastic starch films without affecting biodegradability [79]. Likewise, the study reported that adding green coir fibers to cassava starch composites improved mechanical strength and water resistance, making them suitable for sustainable packaging [80].

Besides organic fillers, researchers are also looking at inorganic fillers like bentonite nano clay for their ability to enhance barrier properties and thermal resistance. A work [81] showed that adding bentonite nano clay to sago starch bioplastics improved water resistance, dimensional stability, and stiffness, broadening their use in food contact materials. These nano clays created intercalated or exfoliated structures within the starch matrix, forming complex paths that slow down the transmission of water vapor and gas. The effectiveness of these fillers often depends on their size, dispersion, surface treatment, and interaction with the starch matrix. Using chemically modified fillers, such as treated oil palm mesocarp fibers, further enhances compatibility with hydrophilic starch chains. Better tensile and thermal properties were observed with modified fibers compared to raw ones [82].

The reinforcement of starch-based bioplastics with various natural fibre fillers sourced from bamboo, pineapple leaf fibre (PALF), kenaf, flax, and hemp stalk significantly modifies the material's properties, primarily through enhanced filler-matrix interactions at the molecular level. These lignocellulosic fillers, often treated to increase surface roughness and expose reactive functional groups, serve as a reinforcing scaffold within the more ductile starch matrix derived from tapioca, corn, wheat, or potato. The improvement in mechanical properties, such as increased stiffness, tensile strength, and modulus, is driven by the formation of strong interfacial bonds, particularly hydrogen bonds between the hydroxyl groups of the fibers and the starch chains. These bonds facilitate efficient load transfer under mechanical stress [83-85].

Beyond mechanical enhancement, the incorporation of fillers like walnut shell powder or coconut shell ash contributes to additional functional benefits. Their rigid structures reduce moisture absorption and improve hardness and dimensional stability [86]. Certain fillers, such as arrowroot fibre, enhance flame resistance and impart antimicrobial properties, while others, like hemp fibre, accelerate biodegradation [87]. Overall, these natural fillers transform the physical behaviour of the composite by establishing a more cohesive and robust network than what pure starch alone can achieve. In summary, including both natural and synthetic fillers in starch-based bioplastics greatly improves their physical properties, extends the shelf life of packaging, and preserves the environmental integrity of the material. This contributes to the development of high-performance, eco-friendly alternatives to petroleum-based plastics.

7.3. Acids

Native starch often exhibits poor compatibility with hydrophobic fillers or other synthetic polymers, leading to weak interfaces within the composite. Acids can chemically react with the hydroxyl groups on starch, sometimes forming slight cross-links or acting as coupling agents during processing. This improves the intermolecular adhesion between the starch matrix and the reinforcing filler. They enhance mechanical strength, thermal stability, water resistance, and biodegradability. Among various acids, citric acid is commonly used because it acts as a non-toxic, biodegradable crosslinking agent. Citric acid reacts with hydroxyl groups in starch to form ester bonds. This reaction improves the structural integrity and reduces the water solubility of the bioplastic films [88].

Crosslinking reduces the availability of free hydroxyl groups, making the film more hydrophobic. It also improves thermal properties and resistance to retrogradation. Additionally, organic acids like acetic acid and lactic acid are often used to modify starch during thermoplastic processing. These acids lower the pH, which helps starch gelatinize and improves its film-forming ability. They also affect the plasticization process, making the resulting bioplastics more flexible and easier to process [6]. Moreover, banana peel starch

has been successfully combined with natural acid-based cross linkers to create biodegradable films with better mechanical and barrier properties [89]. This shows the potential of using fruit waste starch in conjunction with acids to develop sustainable materials. Recent research also suggests that acid treatment, when paired with fillers or blends, will enhance composite properties. For example, blending starch with biodegradable polymers and using acid modification allows for better phase compatibility and controlled degradation behaviour [11]. Thus, acids serve a dual purpose as modifying agents and functional enhancers in forming starch-based bioplastics. This makes them more suitable for real-world applications.

8. Applications of starch-based bioplastics

Bioplastics offer a wide range of sustainable solutions, making them suitable for diverse applications from everyday packaging to advanced medical uses. Starch-derived bioplastics are extensively used in industrial sectors due to their economic viability, widespread availability, and intrinsic thermoplastic properties, which facilitate superior film-forming and processability characteristics. The inherent physicochemical properties of starch-derived bioplastics, namely biodegradability, renewability, and structural adaptability, render them highly applicable across a broad spectrum of industries, including packaging, agriculture, 3D printing, consumer goods, food processing, automotive, healthcare, and textiles as depicted in Figure 4. The use of these materials offers a sustainable and environmentally responsible alternative, serving as a foundation for implementing regenerative and waste-minimizing industrial practices.

8.1. Packaging industry

In the packaging sector, starch-based bioplastics are consistently engineered into biodegradable formats such as films, bags, and rigid articles. The primary application for bioplastics is food packaging, accounting for approximately 43% of the 2.18 MT produced in 2023 [90]. Despite the current market dominance of conventional plastics (such as PE, PP, PS, and nylon), bioplastics frequently exhibit comparable or superior mechanical properties. This strength allows them

to directly substitute in rigid food packaging applications, including cutlery, containers, blown films, and straws. Their intrinsic physico-chemical attributes, such as film-forming capability, biocompatibility, and complete biodegradability, make them a sustainable and high-performing alternative to petrochemical plastics, particularly

for disposable applications, thereby promoting waste diversion and minimizing environmental impact. Currently, the commercial exploitation of bio-based packaging materials is primarily driven by their suitability for short- and long-shelf-life products that do not require superior O₂ or water barrier performance.

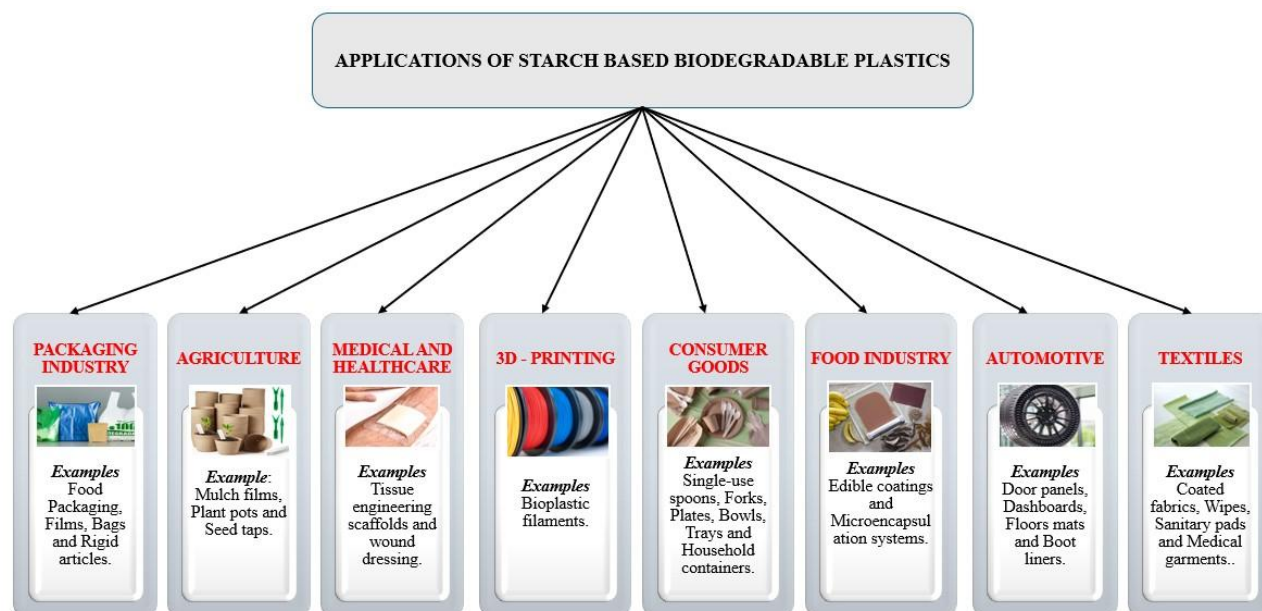


Fig. 4. Overview of major industrial and emerging applications of starch-based bioplastics across sectors.

However, recent material advancements have expanded their applicability into more demanding fields, including Modified Atmosphere Packaging [91].

An optimized plasticizer-filler ratio is essential for achieving optimal mechanical performance in starch-based bioplastics for packaging. Fillers increase stiffness and load-bearing capacity, making the material suitable for rigid applications. Plasticizers provide the necessary flexibility for film applications while maintaining structural integrity. This synergistic formulation results in bioplastics with enhanced mechanical robustness, improved moisture resistance, and efficient biodegradability, positioning them as a functional and sustainable alternative for conventional packaging materials [75].

8.2. Agriculture

Starch-based bioplastics offer significant advantages in agricultural applications, primarily utilized for manufacturing mulch films, plant pots, and seed tapes. These products are highly valued

for their key technical properties of biodegradability and compostability. Specifically, mulch films made from these materials help improve soil moisture retention, reduce weed growth, and ultimately enhance crop yields. These biodegradable films can be directly mixed into the soil after use, removing the need for costly and time-consuming collection and disposal. This not only lowers labour expenses but also helps reduce plastic pollution, supporting more sustainable and eco-friendly farming practices. The growing shift towards biodegradable mulches eliminates the environmental and labour challenges associated with removing conventional plastic films, thereby promoting a sustainable approach to boosting crop yields and contributing to global food security. Key benefits include significantly increasing soil water availability, reducing soil erosion, improving nutrient cycling, and managing soil temperature for optimal growth [92].

In Mediterranean eggplant farming, starch-based biodegradable mulches, especially starch co-polyester blends, are proving to be effective, eco-

friendly substitutes for polyethylene films. They raise soil temperature by up to 9.7 °C and maintain fruit quality, offering a sustainable solution that reduces plastic waste without compromising crop performance [21]. Additionally, starch is used in agricultural nets for shading and crop protection, as well as in seed coatings and controlled-release fertilizer systems, enabling efficient delivery of nutrients and also supporting soil health.

8.3. Medical and healthcare

The medical sector's dependence on disposable, non-recyclable petroleum-based plastics poses a significant environmental challenge. Advancing biodegradable alternatives, such as starch-based bioplastics, polycaprolactone (PCL), poly (lactic-co-glycolic acid) (PLGA), and polybutylene succinate (PBS), is therefore imperative. These materials exhibit promising attributes, including biocompatibility, safety, and functional efficacy. Ongoing research aims to ensure that such bio-based substitutes can meet the stringent performance requirements of medical applications, particularly in terms of mechanical strength, flexibility, and antimicrobial properties, thereby enabling a reduction in the environmental impact of medical waste without compromising patient care [93].

In wound healing, starch-based films and membranes function as biodegradable dressings that facilitate tissue repair while reducing environmental waste. Additionally, starch composites are being investigated as tissue engineering scaffolds that naturally degrade after supporting cell proliferation and tissue regeneration. These bioplastics are also under consideration for use in absorbable surgical sutures and meshes, although further optimization of their mechanical properties remains necessary [94]. Overall, starch-based materials support safer and more sustainable healthcare by reducing long-term plastic pollution from disposable medical products.

8.4. 3-D Printing

Potato starch-based bioplastic filaments are being developed for 3D printing by optimizing the extrusion process using glycerin as a plasticizer and distilled water as a solvent. Successful printing

requires careful formulation, as a high glycerin content causes brittleness and slippage issues in the printer motor. Thermal analysis (DSC) confirms the characteristic starch gelatinization peak, necessary for filament preparation.

While the resulting mechanical properties (tensile strength and modulus) are generally modest compared to conventional polymers, they are considered adequate for flexible and biodegradable applications. The optimal printing conditions identified (e.g., 105 °C extrusion temperature) confirm the feasibility of using potato starch bioplastics for functional 3D printed components [95, 96].

8.5. Consumer goods

Bioplastics derived from starch are increasingly used in the production of environmentally friendly consumer goods, offering a biodegradable alternative to petroleum-based plastic in household products. One common application is the production of single-use items such as spoons, forks, knives, plates, bowls, trays, and household containers, where starch blends possess sufficient strength, moldability, and compostability for these applications [75]. Although native starch is hydrophilic and crystalline—limiting its barrier and thermomechanical properties—these drawbacks are addressed through plasticization (using agents like glycerol and organic acids), fiber reinforcement, and compatibilizers such as maleic anhydride-grafted polymers. Antimicrobial functionality is often added via bioactive compounds or essential oils. Emerging innovations focus on agro-waste starch sources and multilayer films with hydrophobic coatings to enhance durability and barrier strength, aligning performance with industrial plastic standards [97].

8.6. Food industry

Starch-based bioplastics are gaining attention in the food industry not only for packaging but also for a variety of functional, biodegradable, and edible applications. One major use is in edible coatings for fresh produce, which help reduce moisture loss, slow down respiration, and extend shelf life. These coatings will also carry bioactive compounds, such as essential oils or plant

phenolics, to provide added antimicrobial and antioxidant activity [68].

Starch derivatives are also used in microencapsulation systems to protect and control the release of sensitive food ingredients, such as probiotics, flavors, and vitamins. These systems help enhance nutritional delivery and stability of nutrients during storage and digestion [98]. Hazardous UV radiation in sunlight can penetrate food packaging, causing adverse physicochemical changes in the contents. Recent research proves that incorporating metal-organic framework (MOF) nanoparticles into starch-based polymeric biofilms creates effective UV-blocking capability. More critically for food packaging, this inclusion significantly enhanced film performance by increasing tensile strength, improving UV protection, and boosting water stability, leading to greater robustness in humid environments [99].

8.7. Automotive

Starch-based bioplastics have emerged as the best substitute in the automotive industry, offering eco-friendly alternatives to petroleum-derived plastics. It is used to produce lightweight and biodegradable components. These include door panels, dashboards, seat backs, floor mats, and boot liners, which help reduce vehicle weight and improve environmental performance. Other examples, such as cargo area floors and package trays, demonstrate how bio-based materials are replacing conventional plastics in interior vehicle parts. These developments align with broader trends in automotive manufacturing, where major companies are adopting starch- and fibre-reinforced bioplastics to meet sustainability goals [100]. Further developments include stampable sheets formed from starch and jute fabric, which are used for moulded parts, and biodegradable foams made from thermoplastic starch, which are employed in packaging automotive components.

8.8. Textiles

Starch-derived bioplastics are being applied in the textile sector for the development of coated fabrics, serving as eco-friendly alternatives to synthetic water-resistant layers. These coatings improve properties such as breathability, moisture resistance, and antibacterial performance, making them suitable for sportswear and protective

clothing. Starch-based bioplastics reinforced with natural fibers are being explored in the development of biodegradable nonwoven fabrics in hygiene products, such as wipes, sanitary pads, and absorbent liners. They have also been used for medical garments and disposable linens, where compost ability and skin safety are essential [101]. Thermoplastic starch (TPS) is created by plasticizing native starch under heat and shear to overcome its inherent low mechanical strength, making it deformable. Further improving performance, natural fibers are incorporated as reinforcement, significantly enhancing the composite's overall properties. This enhanced fibre-reinforced starch composite is now showing promise as a biodegradable alternative in the textile sector due to its better mechanical characteristics [102].

9. Conclusion

Starch-based bioplastics have emerged as a highly promising biodegradable polymer class because of their renewability, abundance, and cost-effectiveness. When suitably plasticized and processed through solvent casting or thermomechanical techniques, such as extrusion and injection molding, starch can be transformed into functional films and molded products suitable for diverse applications, including packaging, agriculture, healthcare, 3D printing, automotive, and textiles. The incorporation of additives, such as plasticizers, fillers, crosslinkers, and biodegradable polymer blends, significantly enhances mechanical, thermal, and barrier properties. However, challenges related to moisture sensitivity, processability, and mechanical stability remain. Future research should emphasize optimizing formulation strategies to strike a balance between performance and biodegradability, improving compatibility between starch and reinforcing components, and developing scalable, energy-efficient processing routes. Additionally, the utilization of agro-industrial residues as starch sources and the integration of life-cycle and biodegradation assessments will be crucial to validate environmental sustainability. With continued advancements in material design, processing, and eco-performance evaluation, starch-based

bioplastics are poised to play a vital role in replacing conventional plastics and driving the transition toward a circular, bio-based materials economy.

Acknowledgment

The authors thank the lab facilities provided by the Kalaigarkarananidhi Institute Of Technology.

Author's contribution

All authors contributed equally to the conception, design, analysis, and manuscript preparation.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

Not Applicable.

Funding

Self-funded.

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How to cite this paper:



Thangavelu, C. D., Harish, B. S., Abinaya, R., Dhanvadhini, S. & Sivakumar, R. (2025). Sustainable plastics from renewable resources: A review on starch-based bioplastics. *Advances in Environmental Technology*, 11(4), 476-499. DOI: 10.22104/AET.2025.7748.2179