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Starch as a sustainable alternative for bioplastic packaging: A review

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Abstract:
The escalating environmental concerns associated with traditional plastic packaging materials have prompted a paradigm shift towards sustainable and eco-friendly alternatives. Starch, a naturally abundant and renewable polysaccharide, has emerged as a promising raw material source for the development of biodegradable plastic packaging films. This review aimed to provide a comprehensive overview of the current state of starch-based bioplastics, highlighting their potential as a sustainable alternative to conventional plastics.

A comprehensive search of peer-reviewed articles and reviews was conducted in the period of 2022–2024 using Google scholar. We examined the latest research on starch-based bioplastics focusing on the starch structure, extraction, modification, and processing, as well as applications, challenges, and future directions. The data were systematically gathered, evaluated, and organized into logical sections. We also discussed the processing methods employed to fabricate starch-based films, including casting, extrusion, and blown film extrusion.

We explored the structural and functional properties of starch, its modification techniques, and its blending with other biopolymers to enhance performance. Furthermore, we examined the physical, mechanical, and barrier properties of starch-based films, as well as their biodegradability and compostability. The challenges and limitations associated with starch-based packaging films include moisture sensitivity and poor mechanical properties. Finally, starch-based packaging films have potential applications in the food, pharmaceutical, and cosmetic industries.

By providing a comprehensive analysis of starch-based bioplastics, this review stimulates further research and development in this field, contributing to a more sustainable and environmentally friendly packaging industry.

Keywords: Starch, bioplastics, biofilms, sustainability, packaging, biodegradability, renewability

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INTRODUCTION

The packaging industry is a significant contributor to global plastic production, with millions of tons of plastic packaging materials being produced annually [1]. However, the environmental impact of these traditional materials has become a major concern, as they are primarily derived from non-renewable fossil fuels and contribute to plastic waste accumulation in landfills and oceans [2]. The urgent need for sustainable and eco-friendly packaging solutions has led to the exploration of alternative raw materials, such as starch, for the development of biodegradable plastic packaging films [3–5]. Starch, a naturally abundant and renewable polysaccharide, is the second most abundant biomass resource on Earth after cellulose. Its unique properties, such as biodegradability, non-toxicity, and renewability, make it an attractive raw material for the development of sustainable packaging films [5, 6]. Starch-based packaging films have the potential to replace traditional plastic packaging materials in various applications, including food, pharmaceutical, and cosmetic packaging [5, 7].

Recent studies have focused on improving the properties of starch-based packaging films through various modification techniques, such as chemical modification [8, 9], blending with other biopolymers [5, 10], and nanocomposite formation [11, 12]. These advancements have enhanced the mechanical, barrier, and thermal properties of starch-based packaging films, making them more competitive with traditional plastic packaging materials [9].

Despite these advancements, starch-based packaging films still face several challenges, including moisture sensitivity, poor mechanical properties, and limited scalability [9, 13]. Therefore, extensive research and

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development efforts are necessary to overcome these limitations and fully exploit the potential of starch as a sustainable raw material for plastic packaging films.

This review aimed to provide a comprehensive overview of the current state of starch-based packaging films, discussing their development, properties, and applications. We also examined the challenges and limitations associated with starch-based packaging films and explored future perspectives and potential solutions to overcome these challenges.

STUDY OBJECTS AND METHODS

We examined the latest research on starch-based bioplastics focusing on the starch structure, extraction, modification, and processing, as well as applications, challenges, and future directions. The data were systematically gathered, evaluated, and organized into logical sections.

Starch was defined as a natural polysaccharide consisting of amylose and amylopectin repeat units, which are linked together by α-1,4 and α-1,6 glycosidic bonds.

Bioplastic was defined as a type of plastic that is made from renewable biomass sources such as plants, animals, micro-organisms or agricultural waste rather than traditional fossil fuels. It has the advantage of being biodegradable unlike petroleum-based plastics.

Packaging was defined as a material used to enclose, protect, and prepare a product for distribution, storage, and safety.

A comprehensive search of peer-reviewed articles and reviews was conducted in the period of 2022–2024 using Google scholar. The following keywords were used in the search: starch, bioplastics, packaging. Our aim was to gather and evaluate relevant publications in the reputable journals.

RESULTS AND DISCUSSION

Recent studies on starch-based bioplastic packaging. Starch-based bioplastic packaging has gained significant attention in recent years due to its biodegradable and renewable nature. Researchers have focused on improving the properties of starch-based bioplastics through various modification techniques, blending with other biopolymers, and nanocomposite formation (Fig. 1).

Among the various modification techniques, chemical modification of starch has been widely explored to enhance its properties. For example, Altuna *et al.* [14] reported that modifying starch with octenyl succinic anhydride improves its paste properties such as viscosity, while lowering its gelatinization temperature for pharmaceutical applications. Similarly, Chen *et al.* [15] modified tapioca starch by crosslinking it with citric acid, which resulted in enhanced thermal stability and tensile mechanical properties. The crosslinking process created a network of starch molecules that are held more closely together, providing better resistance to thermal energy and tensile stretching. Furthermore, Choi *et al.* [16] developed sweet potato starch-based edible films through the chemical modification of starch for improved water solubility in vegetable and dairy products packaging.

Blending starch with other biopolymers has also been investigated to improve its properties. In a recent study, Gao *et al.* [17] investigated the effect of blending on the physiochemical properties of polylactic acid (PLA)/modified starch blend. Their findings demonstrated that PLA/modified starch blend exhibited improved thermal and mechanical properties, as well as substantial biodegradability, when compared to native starch. In another study, Omoike *et al.* [5] developed a cassava starch/polyvinyl alcohol (PVA) blend with potential applications in food and pharmaceutical packaging. The focus was on determining the optimal blend ratio to achieve superior properties, including tensile mechanical strength, barrier properties, and thermal stability. The study revealed that the optimal blend ratio of 40% cassava starch and 60% PVA exhibited the best balance of properties. Furthermore, researchers have explored the potential of using crosslinking agents to enhance the properties of biopolymer blends. In a notable study, Wu *et al.* [18] utilized citric acid as a crosslinking agent in a potato starch-chitosan blend. This significantly improved the water resistance, mechanical properties, and antimicrobial activity of the blend,

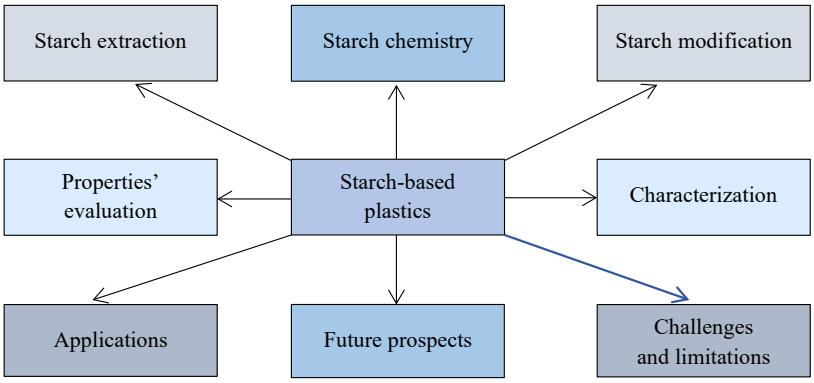

Figure 1 Graphical overview of starch as a source for bioplastics

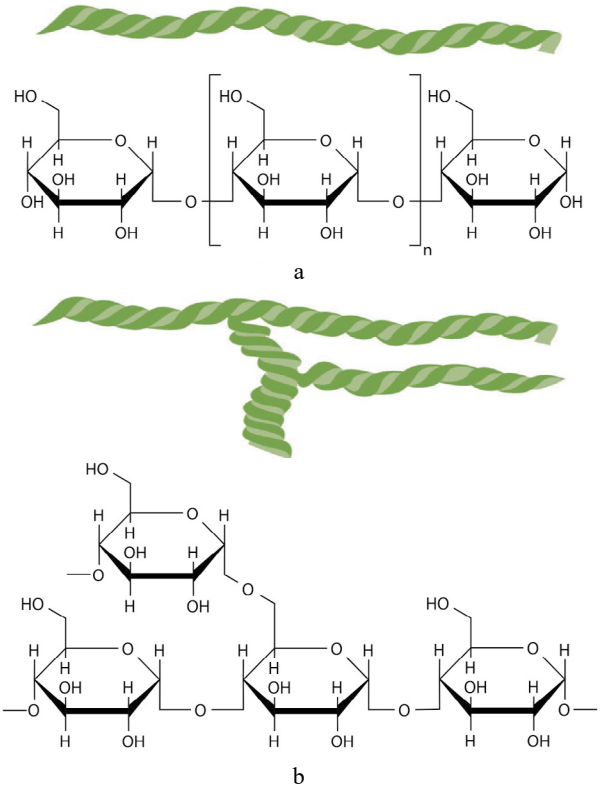

Figure 2 Structure of amylose (a) and amylopectin (b)[1]

demonstrating the effectiveness of crosslinking agents in optimizing biopolymer blend performance.

Nanocomposite formation has also been explored to enhance the properties of starch-based bioplastics. Coelho *et al.* [19] successfully developed starch-based nanocomposite films reinforced with cellulose nanocrystals extracted from grape pomace. The incorporation of cellulose nanocrystals increased the tensile strength and lowered the water vapor permeability of the starch-based nanocomposites, which are important parameters in packaging. Furthermore, Wang *et al.* [20] developed starch-based nanocomposites with graphene oxide to enhance their thermal stability and barrier properties.

Starch chemistry. Structurally, starch is a polysaccharide consisting of *α*-D-glucopyranose repeat units, which are linked together by α-1,4 and α-1,6 glycosidic bonds [21, 22]. These bonds are formed through the condensation reaction of neighboring *α*-D glucose molecules, resulting in the release of water molecules. The polymerization of glucose units leads to the formation of two main polysaccharide fractions: linear amylose and branched amylopectin. Amylose is primarily a linear fraction with few branches, consisting of long chains of *α*-D-glucopyranose residues connected by *α*-1,4-glycosidic bonds [23]. In contrast, amylopectin is a highly branched fraction with a complex molecular structure, comprising short and long chains [23]. The branched architecture of amylopectin with its intricate network of branching points enables the formation of a more extensive and complex branched structure. This significantly influences the rheological properties of starch solutions, particularly their viscosity and texture [15]. The branching points in amylopectin are classified into three types: A-chains (short, unbranched chains), B-chains (branched chains), and C-chains (long chains with branching points) [24]. The structure and properties of starch are influenced by various factors, including genetic conditions, plant species and varieties, cultivation conditions, and non-polysaccharide components [25]. These factors contribute to the diversity of starch grains and their physical and chemical properties (Fig. 2).

Native starch is insoluble in cold water and most organic solvents due to the presence of the amylose fraction, which is insoluble or sparingly soluble. However, starch grains can absorb water through reversible swelling, increasing their volume by up to 30% [26]. This swelling is an exothermic process where water molecules are absorbed into the amorphous zone and bonded to free hydroxyl groups of glucose units in polymer chains through hydrogen bonds [27].

Starch gelatinization. When starch is heated above a certain temperature, its granules undergo gelatinization, a thermal transition characterized by spherical swelling and amorphization leading to the formation of a more viscous structure [28]. The gelatinization temperature varies depending on the botanical starch type and is a range rather than a single value, as it depends on the grain size. For example, potato starch gelatinizes

[1]Structure and Function of Carbohydrates. Biology for Majors I. [cited 2024 Sept 10]. Available from: https://courses.lumenlearning.com/wm-biology1/chapter/reading-types-of-carbohydrates/

at 50–70°C [29]. Gelatinization is accompanied by loss of birefringence, which is the ability of starch granules to split light into two beams with different polarizations and velocities [30]. This property is due to the ordered arrangement of starch molecules in the granule. When starch granules are heated during gelatinization, the ordered arrangement of molecules is disrupted, leading to a loss of birefringence [30]. During starch gelatinization, the viscosity of the starch suspension increases significantly due to the following factors: starch granule swelling, breakdown of crystalline structure leading to more disordered and random arrangement of starch molecules, uncoiling of starch molecules, and increased molecular interactions via new hydrogen bonding [31, 32].

Furthermore, gelatinization increases the electrical conductivity of starch due to the hydration of starch molecules, formation of more conductive pathways, and increased ionic mobility. Gelatinization increases the mobility of ions within the starch matrix enabling them to carry electrical charge more efficiently [33].

Starch retrogradation. Starch retrogradation is a process where gelatinized starch molecules re-associate and re-crystallize, leading to a more ordered and rigid structure [32]. This process occurs over time, often resulting in a loss of flexibility and an increase in brittleness. During retrogradation, the starch molecules that were previously uncoiled and hydrated during gelatinization start to re-form their crystalline structure. This re-association is driven by hydrogen bonding between the starch molecules, leading to a more rigid and inflexible network [32].

Starch extraction. Starch extraction is a process of isolating starch from plant sources, such as corn, potatoes, and cassava [34]. This process is crucial for various industries, including food, pharmaceuticals, and paper production, as starch is a versatile ingredient with numerous applications.

The first step in starch extraction is harvesting, where the plant material is collected from its source and washed to remove dirt, soil, and other impurities. It is then pulverized into a milky mash and suspended in water to soften the tissues and remove the starch granules. This pulverization process is typically done using a mill or grinder, and the resulting mash is mixed with water to create a starch suspension. The starch suspension is then centrifuged or sieved to separate the starch from the other plant components. The centrifuge spins the mixture at high speeds, causing the starch to settle at the bottom of the centrifuge, while the supernatant is removed. The starch is then washed with water to remove any remaining impurities and dried to remove excess moisture [34–36].

There are different methods of starch extraction, including wet milling (Fig. 3), dry milling, enzymatic extraction, and alkaline extraction. Wet milling is the most common method, which involves grinding the plant material in water. Dry milling, on the other hand, involves grinding the plant material without water and is used for plants with a low moisture content. Wet milling generally yields higher purity starch compared to dry milling due to its superior ability to separate starch from proteins, lipids, and fibers. This is because wet milling uses water to hydrate and swell the starch granules, making them more easily separable from the other components. In contrast, dry milling relies solely on the mechanical force to break down the starch granules, which can lead to a higher likelihood of contamination with proteins, lipids, and fibers [37]. Enzymatic extraction uses enzymes to break down the plant cell walls and release the starch, while alkaline extraction uses an alkaline solution to achieve the same result.

The efficiency of starch extraction depends on various factors, including plant variety, moisture content, grinding method, water quality, and temperature. Different plant varieties have different starch contents and properties, which affect the extraction process. The moisture content in the plant material also plays a crucial role, as excessive moisture can lead to poor starch yields. The grinding method can also impact the release of starch from the plant cells, and the quality of water can affect the purity of the extracted starch.

Starch extraction has numerous applications in various industries. In the food industry, starch is used as a thickening agent, stabilizer, and emulsifier in food products

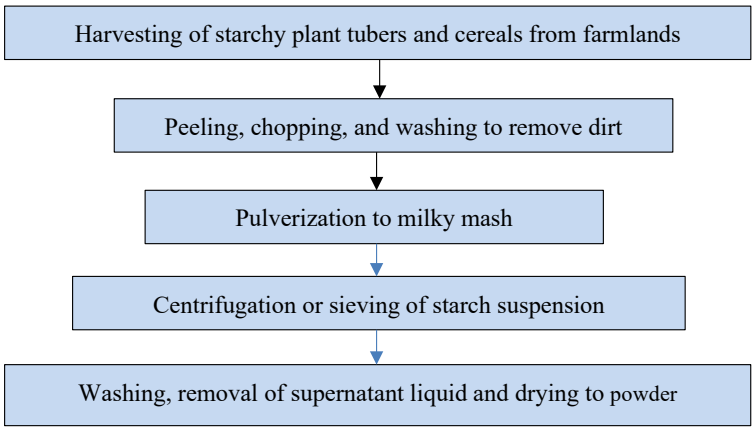

Figure 3 Flowchart for the extraction of starch from plant sources (wet method)

such as soups, sauces, and baked goods. In the pharmaceutical industry, starch is employed as an excipient in tablets, capsules, and ointments. In the paper industry, starch is used as a sizing agent to improve the strength and durability of paper. It is also used as a sizing agent in the textile industry and as a sustainable alternative to synthetic polymers in biodegradable packaging [9].

Starch modification. Starch modification is a process of altering the properties of starch to enhance its functionality and performance in various applications [38]. Starch is a versatile carbohydrate that can be modified in various ways to suit specific requirements.

Chemical modification. One common method of starch modification is chemical modification, which involves treating starch with chemicals to alter its structure and properties. This can include reactions such as etherification, esterification, and cross-linking, which can improve starch stability, solubility, and resistance to degradation. Chemical modification can also be used to introduce new functional groups, such as hydroxyl or carboxyl groups, which can enhance starch reactivity and versatility [39, 40].

Physical modification. Physical modification involves treating starch with physical agents such as heat, light, or radiation to alter its structure and properties [41]. This can include processes such as heat treatment, mechanical treatment, high pressure application, moisture treatment, and electrical treatment. These methods can improve starch solubility, gelatinization, viscosity, crystallinity, and stability for various industrial applications. Physical modification can also be used to create new starch-based materials, such as nanocrystals and nanoparticles, which have unique properties and applications [42].

Enzymatic modification. Enzymatic modification is another method of starch modification, which involves using enzymes to break down or modify starch molecules. This can include processes such as hydrolysis, which can break down starch into simpler sugars, and transglycosylation, which can create new glycosidic bonds and modify the starch structure and properties. Enzymatic modification can be used to improve digestibility, solubility, and stability of starch, as well as to create new starch-based products with specific properties and applications.

Genetic modification. Genetic modification of starch refers to the use of biotechnology techniques to alter the genetic code of plants to produce starch with desired properties [43]. This is achieved through the introduction of specific genes or changes to existing genes that regulate starch biosynthesis, structure, and functionality [44]. One approach is to enhance the starch content and yield in plants, allowing for increased production and efficiency. This can be done by introducing genes that regulate starch biosynthesis, such as those involved in the production of the enzymes ADP-glucose pyrophosphorylase or starch synthase. Alternatively, genes that limit starch production can be suppressed to increase yields [45].

Another strategy is to modify the starch structure and properties (e.g., increase its amylose content) to improve its suitability for specific applications. This can be achieved by introducing genes that encode enzymes involved in starch biosynthesis, such as granule-bound starch synthase, or by modifying the existing genes to alter their activity [46, 47]. For example, RNA interference technology can be used to silence the genes responsible for amylose degradation, resulting in a higher amylose content. Genetic modification can also be used to introduce new functional properties into starch, such as improved thermal stability, biodegradability, or resistance to degradation [43]. This can be achieved by introducing genes from other organisms, such as bacteria or fungi that encode enzymes with desired activities. For example, introducing a gene that encodes a heat-stable enzyme can improve the thermal stability of starch.

Starch-based bioplastic processing techniques. Starch-based bioplastics are a sustainable alternative to traditional plastics and are made from renewable resources such as corn starch, potato starch, or tapioca starch. Their processing involves various methods to convert starch into a plastic-like material.

One common technique is extrusion, where starch is mixed with other biodegradable polymers and additives, and then fed into an extruder. The extruder converts the mixture to a flowable viscous melt by heating. The viscous melt is then homogenized and forced through a die by means of a rotating screw where it is shaped into a desired form [47]. This process can produce a wide range of products, including packaging materials, disposable cutlery, and bags (Fig. 4).

Another technique is injection molding, which involves melting starch-based pellets in an extruder and injecting the molten plastic into a mold cavity of specific shapes and designs. As the molten plastic cools and solidifies in the mold, it takes the shape of the mold cavity. The final solidified product is ejected from the mold [49]. This process is often used for producing high-precision items with fast production rates and quality.

Blown film extrusion is another method used to produce starch-based bioplastics, particularly for packaging materials like bags and wraps. This process involves extruding starch-based pellets through a die to create a tube, which is then blown up like a balloon and cooled to form a thin film [50]. Thermoforming is also used to process starch-based bioplastics, where a sheet of starch-based material is heated to a pliable and flexible form and molded into a specific shape by cooling in a mold [49]. This process is often used for producing trays, containers, and other packaging materials.

Solvent casting is a technique used to produce starch-based bioplastics with specific properties, such as transparency and flexibility. This process involves dissolving starch and other additives in a solvent (usually water), heating, and stirring for the viscous solution to gelatinize and homogenize. This is followed by casting it into a thin film, and then evaporating the solvent to create a solid material (Fig. 5) [5, 51].

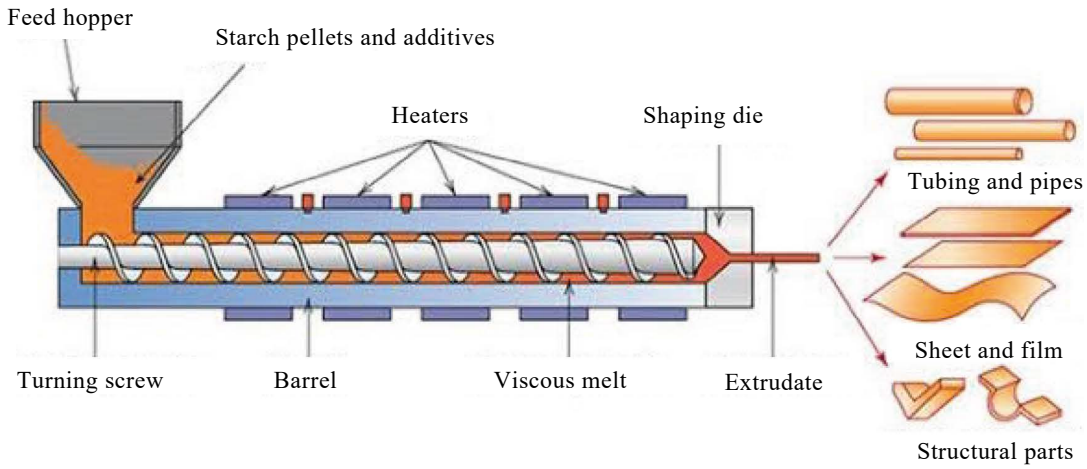

Figure 4 Extrusion of starch-based bioplastics using a single screw extruder (adapted from Bacalhau *et al.* [48])

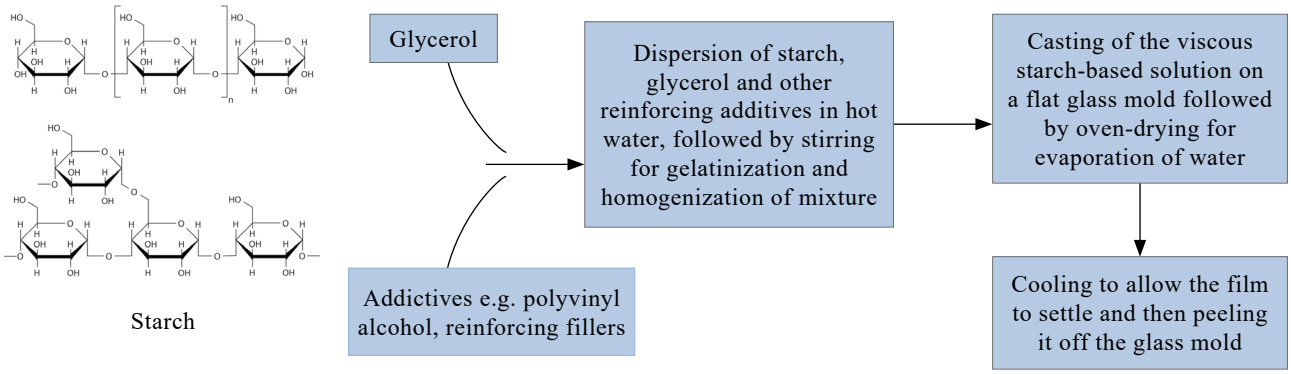

Figure 5 Preparation of starch-based plastics using solvent casting techniques

Three-dimensional printing is also being explored as a processing technique for starch-based bioplastics, allowing for the creation of complex shapes and designs with high precision and accuracy [52]. It involves layer-by-layer deposition of starch-based filaments to create a physical object. Here, a starch-based plastic filament is fed through a heated extruder, which melts and deposits the material on a build platform or substrate. The deposited material is then cooled and solidified thereby bonding to the previous layer. This process is repeated until the entire object is printed (Fig. 6) [52].

The advantages of starch-based bioplastic processing techniques include the use of renewable resources, biodegradability, and reduced greenhouse gas emissions. However, challenges still exist, such as high production costs, limited scalability, and the need for improved material properties. Research and development is ongoing to overcome these challenges and improve the processing techniques for starch-based bioplastics. This includes the development of new starch-based materials with improved properties, the optimization of processing conditions, and the scale-up of production processes.

Scanning electron microscopy characterization of starch-based bioplastics. Scanning Electron Microscopy (SEM) characterization of starch-based bioplastic packaging provides valuable insights into the material's

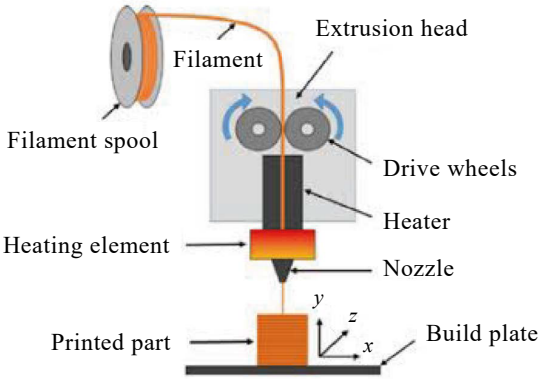

Figure 6 Three-dimensional printing of bioplastic coating on objects (adapted from Andanje *et al.* [53])

surface morphology, structure, and properties. The SEM analysis reveals the texture, porosity, and topography of the bioplastic surface, which is essential for understanding its performance and functionality [5, 54].

The SEM images of starch-based bioplastic packaging typically show a smooth and continuous surface with no visible pores or cracks. This morphology is attributed to the well gelatinization of starch granules and good compatibility with other biopolymers and suitable

additives [5, 55–57]. The surface morphology can affect the bioplastic's barrier properties, mechanical strength, and biodegradability.

The SEM analysis also reveals the presence of starch granules, their size and distribution, and the extent of gelatinization. The degree of gelatinization affects the bioplastic's properties, such as its solubility, swelling behavior, and enzymatic digestibility. In addition, SEM can detect the presence of additives, such as plasticizers, fillers, or reinforcing materials, and their distribution within the bioplastic matrix.

The SEM characterization of starch-based bioplastic packaging can be used to study the effect of processing conditions on the bioplastic's microstructure and properties. It can also analyze the bioplastic's degradation behavior under different environmental conditions, as well as compare the properties of starch-based bioplastics with those of conventional plastics. In summary, SEM is a powerful tool for understanding the microstructure and properties of starch-based bioplastic packaging, enabling the development of high-performance, sustainable packaging materials.

X-ray diffraction. X-ray diffraction (XRD) analysis reveals the crystal structure, degree of crystallinity, molecular arrangement, and lattice spacing, which are essential for understanding the bioplastic's properties and behavior [58]. The XRD patterns of starch-based bioplastic packaging typically show a semi-crystalline structure, with both amorphous and crystalline regions [5, 57, 59]. The crystalline regions are attributed to the ordered arrangement of starch molecules, while the amorphous regions are due to the disordered structure. The degree of crystallinity affects the bioplastic's mechanical strength, thermal stability, and barrier properties [5].

The XRD analysis can also detect the presence of different polymorphs, such as A, B, or C, which are related to the starch source and processing conditions. The polymorphs have different crystal structures and properties that influence the bioplastic's behavior [60]. Furthermore, XRD can monitor changes in the crystal structure and crystallinity during processing, aging, or degradation, providing valuable information on the bioplastic's stability and durability [58].

Thermogravimetric analysis. Thermogravimetric analysis (TGA) is a powerful analytical technique used to characterize the thermal properties of starch-based bioplastic packaging. The TGA instrument measures the weight loss of the bioplastic as a function of temperature, providing valuable insights into its thermal stability, decomposition behavior, and moisture content [61]. The TGA curves of starch-based bioplastic packaging typically exhibit a multi-step decomposition process. The first step involves the loss of moisture, which occurs at temperatures below 150°C [5, 62]. The second step corresponds to the decomposition of starch molecules, which takes place between 200 and 300°C [63]. The final step involves the degradation of the bioplastic matrix, which occurs at temperatures above 300°C [5, 57].

TGA provides important information on the bioplastic's thermal stability, which is essential for its processing and application. The decomposition temperature and weight loss associated with each step provide insights into the bioplastic's degradation mechanism and volatile content, which can affect its performance and shelf life. Additionally, TGA can detect the presence of additives, such as plasticizers or fillers, which can affect the bioplastic's thermal behavior.

Tensile mechanical properties of starch-based bioplastics. Starch-based bioplastics are biodegradable polymers derived from renewable resources such as corn starch, potato starch, or tapioca starch. The mechanical properties of starch-based bioplastics are crucial in determining their suitability for various applications. Their tensile mechanical properties, such as tensile strength, percentage elongation at break, and tensile modulus, can be evaluated using tensile testing machines.

The tensile strength is the maximum stress a material can withstand when subjected to tensile force. For starch-based bioplastics, the tensile strength ranges from 1 to 100 MPa, depending on the type of starch and processing conditions [64]. This is lower than the tensile strength of traditional plastics such as polyethylene (20–30 MPa) and polypropylene (30–40 MPa) [65]. Studies have shown that the greater the strength of molecular interaction between polymer constituents, the higher the tensile strength [5, 57]. The tensile strength of starch-based bioplastics can be improved through incorporation of biopolymers such as PVA or chitosan [5], as well as through reinforcement with nanofillers such as clay, carbon black, and fibers [9].

The percentage elongation at break is a measure of the flexibility and extensibility of a polymer material, indicating its ability to stretch and deform without rupturing. In starch-based bioplastics, while high tensile strength is desirable, a substantial level of flexibility is equally important to meet packaging requirements. In particular, flexibility ensures that the material can withstand handling, storage, and transportation without cracking or breaking. The incorporation of plasticizers into starch film matrices can provide higher molecular mobility and increased flexibility, allowing the bioplastic film to become more pliable and less brittle [66, 67]. The elongation at break for starch-based bioplastics ranges from 10 to 50%, depending on the type of starch and processing conditions. This is lower than the range for traditional plastics such as polyethylene (50–100%) or polypropylene (100–200%) [68].

The tensile modulus is defined as a ratio of stress to strain within the proportionality limit of a material, indicating its stiffness and resistance to deformation. For starch-based bioplastics, the tensile modulus ranges from 100 to 500 MPa, which is lower than the range for traditional plastics such as polyethylene (1000–1500 MPa) or polypropylene (1,500–2,000 MPa) [69].

Water vapor barrier properties. Starch-based bioplastics have barrier properties that are essential for various applications, including packaging and dispos-

able products. The barrier properties of starch-based bioplastics refer to their ability to prevent the passage of gases, vapors, and liquids through the material [6].

One of the critical barrier properties of starch-based bioplastics is their water vapor transmission rate. Starch-based bioplastics have a higher water vapor transmission rate compared to that of traditional plastics, which can be a limitation for applications requiring high moisture barrier properties [5, 51, 70].

Starch-based bioplastics also have a relatively high oxygen transmission rate, which can affect their ability to protect products from oxidation [71]. This can be a concern for applications such as food packaging, where oxygen can cause spoilage or degradation. However, some starch-based bioplastics have been developed with improved oxygen transmission rate properties, making them suitable for specific applications.

The carbon dioxide transmission rate (CO_2TR) of starch-based bioplastics is another essential barrier property. Starch-based bioplastics have a higher CO_2TR compared to traditional plastics, which can affect their ability to maintain pressure and prevent carbonation loss in applications such as beverage packaging.

The barrier properties of starch-based bioplastics can be improved through various techniques, such as adding barrier coatings or layers, using nanoclay or other reinforcing materials, optimizing processing conditions, and blending with other biodegradable polymers [9]. Some starch-based bioplastics have been developed with improved barrier properties, making them suitable for food packaging, pharmaceutical packaging, and cosmetic packaging.

Biodegradability assessment. Starch-based bioplastics are biodegradable, meaning they can break down naturally in the environment through microbial action, enzymatic degradation, or chemical hydrolysis. The biodegradability of these bioplastics is influenced by various factors, including the type of starch used, processing conditions, and the presence of additives or coatings [57, 72].

The biodegradability of starch-based bioplastics can be assessed through various tests, such as ASTM D6400, ASTM D6868, and ISO 14855 [73]. These tests evaluate the biodegradability of plastics in different environments, including composting, soil, and water. The biodegradability of starch-based bioplastics is affected by several factors including crystallinity, molecular weight, and hydrophilicity [57, 74]. Bioplastics with lower crystallinity, molecular weight, and higher hydrophilicity are more biodegradable. Additionally, the presence of additives or coatings can also impact the biodegradability of starch-based bioplastics. Biodegradability offers several benefits, including reduced plastic waste, lower carbon footprint, and improved sustainability.

Applications of starch-based bioplastics. Starch-based bioplastics have a wide range of applications across various industries, including packaging, disposable cutlery and tableware, agricultural films, medical devices, and three-dimensional printing.

Food packaging. Starch-based bioplastics are used in food packaging as a biodegradable and renewable alternative to traditional plastics. They are applied in various forms, such as flexible packaging films, rigid containers, disposable cutlery, and edible packaging materials. Starch-based bioplastics have been successfully utilized in packaging various food products, including baked goods, fresh produce, dairy products, and beverages [75]. These bioplastics can enhance food safety, quality, and shelf life, as well as improve packaging performance, by providing a barrier against moisture, oxygen, and other external factors [76]. Furthermore, several studies have shown that starch-based bioplastics can be engineered to possess antimicrobial and antioxidant properties to further extend the shelf life of packaged food products [57, 77, 78]. Additionally, starch-based bioplastics are compostable and therefore they reduce food waste and environmental impact. They can also be customized to meet specific packaging requirements, making them an attractive solution for sustainable food packaging.

The development of starch-based bioplastics has also led to the creation of innovative, smart packaging materials that can monitor food freshness and quality. For instance, starch-based bioplastics infused with natural extracts, such as anthocyanins, can change color in response to changes in pH levels, indicating spoilage or contamination [79]. Additionally, starch-based bioplastics can be designed to release preservatives or nutrients in a controlled manner, enhancing food quality and safety [5]. With ongoing advancements in nanotechnology, electrospinning, and three-dimensional printing, the potential applications of starch-based bioplastics in food packaging are vast and promising, offering a sustainable and environmentally-friendly alternative to traditional plastic packaging materials.

Medicine and pharmaceutical industry. In medicine, starch-based bioplastics offer useful applications as biodegradable and biocompatible medical implants, such as bone screws and plates that can dissolve over time, eliminating the need for surgical removal [75]. The breakthroughs in biodegradable starch materials have paved the way for innovative biomedical applications, including the creation of advanced drug delivery systems such as capsules and tablets, which can release medication in a controlled manner [80]. Starch-based bioplastics are also used in wound dressing materials, surgical meshes, and tissue engineering scaffolds that promote tissue growth and regeneration [80]. For instance, the study by Kiran *et al.* [81] shows the potential of starch-based bioplastics obtained from banana peel to be used as material for intravenous tubes for medical operations, thereby reducing the application of single use plastics which could constitute environmental waste. Furthermore, starch-based bioplastics are used in pharmaceutical packaging, such as compostable blister packs and containers, also reducing environmental waste. In a recent study, Omoike *et al.* [5] developed a starch/PVA blend to be used as a coating in food and

pharmaceuticals applications. This innovative blend combines the biodegradable and renewable properties of starch with the flexibility and strength of PVA, making it a viable material in sustainable drug packaging.

Agriculture and agro-allied industry. Agricultural films made from starch-based bioplastics are used as mulch films, greenhouse covers, and soil conditioning materials [82]. These bioplastics improve soil health and reduce water consumption. They are also used in controlled-release fertilizer coatings, seed coatings, and plant growth promoters that enhance crop yields and reduce environmental impact [83]. Additionally, they are applied in biodegradable planting pots, trays, and containers, which eliminates the need for plastic waste disposal. Furthermore, starch-based bioplastics are used in animal feed packaging, agricultural packaging materials, and bio-based composites for agricultural equipment. Overall, starch-based bioplastics offer a versatile and biodegradable solution for various agricultural and agro-allied applications, reducing plastic waste and promoting sustainability.

Cosmetological industry. Starch-based bioplastic are used in the cosmetological industry as a biodegradable and renewable material for various applications. They are used to create edible skin-care, hair products, and edible packaging for cosmetics and personal care products, thereby enhancing human well-being and sustainability [84]. Starch-based bioplastics offer a sustainable alternative in the production of disposable makeup remover wipes, facial masks, and exfoliating scrubs that are gentle on the skin and the environment. Additionally, they find promising application in biodegradable microbeads for skin care products, replacing traditional plastic microbeads that harm the environment [85]. Overall, starch-based bioplastics provide a sustainable and eco-friendly solution for the cosmetological industry, reducing plastic waste and promoting environmental responsibility.

Future prospects of starch-based bioplastics. Starch-based bioplastics have promising prospects, with potential growth and expansion in various industries.

Increasing demand. The demand for starch-based bioplastics is expected to rise significantly due to the growing concerns about plastic pollution, climate change, and sustainability [86]. Governments, consumers, and businesses are increasingly seeking eco-friendly alternatives to traditional plastics, driving the demand for biodegradable plastics. This trend is expected to continue, with starch-based bioplastics playing a crucial role in reducing plastic waste and promoting sustainable practices.

Technological advancements. Ongoing research and development in the field of starch-based bioplastics is expected to improve their performance, scalability, and cost-effectiveness. New technologies will enhance their mechanical properties, barrier properties, and processing capabilities, making them more competitive with traditional plastics [87]. These advancements will also enable the production of starch-based bioplastics with tailored properties for specific applications.

Expanded applications. Starch-based bioplastics will find new applications in various industries, including textiles, automotive, and construction. They will be used in a wider range of products, such as biodegradable fibers, composites, and building materials [49]. This expansion will be driven by the growing demand for sustainable materials and the need to reduce plastic waste.

Sustainable agriculture. Starch-based bioplastics will promote sustainable agriculture practices by utilizing waste biomass and reducing synthetic fertilizer use. This will contribute to a circular economy and reduce environmental impacts [88]. The use of starch-based bioplastics will also provide new revenue streams for farmers and rural communities.

Biodegradable plastics. Starch-based bioplastics will play a crucial role in replacing traditional plastics in packaging, disposable products, and single-use items [89]. They will help reduce plastic waste and marine pollution, which are major environmental concerns. The use of biodegradable plastics will also reduce greenhouse gas emissions and mitigate climate change.

Global market growth. The global starch-based bioplastic market is expected to grow significantly, driven by the increasing demand, technological advancements, and expanding applications [90]. The market growth will also be fueled by government policies, regulations, and incentives that promote the use of biodegradable plastics. This will also create new business opportunities and jobs in the sustainable materials sector.

Current challenges and limitations of starch-based bioplastics. While starch-based bioplastics offer tremendous potential for driving eco-friendly innovations, their adoption is hindered by several key challenges and limitations. Recognizing and addressing these constraints is essential for successfully harnessing their benefits.

Lower strength and durability. One of the significant challenges hindering the widespread adoption of starch-based bioplastics is their lower strength and durability [72]. The incorporation of starch, a natural component, can compromise the structural integrity and mechanical properties of the resulting polymer blend. This can make it unsuitable for applications that require robustness and long-term durability, such as packaging and durable goods manufacturing. This limitation underscores the need for further research and development to enhance the mechanical strength and durability of starch-based bioplastics, thereby expanding their potential applications and promoting their adoption as a sustainable alternative to traditional plastics.

Moisture sensitivity. High moisture sensitivity poses a significant challenge to the use of starch-based bioplastics. These materials are prone to water absorption, which can trigger degradation and compromise their performance and shelf life [72]. This sensitivity to environmental moisture can be particularly problematic in humid climates or in applications where exposure to water is unavoidable, such as packaging for food or beverages. As a result, moisture sensitivity of starch-based

bioplastics can limit their utility and reliability, emphasizing the need for further research and development to enhance their water resistance and durability.

Limited shelf life. The limited shelf life of starch-based bioplastics is a significant concern, as these materials tend to degrade more rapidly than traditional plastics. Their shorter shelf life can lead to a decline in their mechanical properties, such as strength and flexibility, ultimately affecting their performance and integrity over time [91]. As a result, starch-based bioplastics may become brittle, crack, or break down, which renders them unsuitable for long-term applications. Moreover, the degradation process can also lead to the release of volatile compounds, potentially impacting the quality and safety of packaged products. This highlights the need for improved formulations and preservation methods to extend the shelf life of these biodegradable materials.

Limited scalability. The limited scalability of starch-based bioplastics is a significant hurdle to their widespread adoption, primarily due to their higher production costs compared to traditional plastics. The expense of starch-based bioplastics can be attributed to various factors, including the cost of raw materials, processing, and manufacturing. Consequently, large-scale production of starch-based bioplastics becomes challenging, making it difficult for manufacturers to achieve economies of scale and reduce costs. This scalability limitation can hinder the ability of starch-based bioplastics to compete with traditional plastics in terms of price. This can restrict their market penetration and adoption in various industries, such as packaging, textiles, and automotive.

Limited availability of raw materials. Starch-rich crops such as corn, potatoes, and tapioca are the primary feedstocks for starch-based bioplastics, but their availability can be regionally constrained. This limited availability can lead to fluctuations in raw material prices, affecting the overall cost of production and making it difficult for manufacturers to maintain a stable supply chain [50]. Furthermore, reliance on specific geographic regions for raw material sourcing can also create logistical challenges and increase transportation costs. This can exacerbate the environmental impact of production, ultimately hindering the growth and development of the starch-based bioplastics industry.

Lack of standardization. There is a lack of standardization in the production and processing of starch-based bioplastics, which can affect their quality, performance, and overall reliability.

Without standardized manufacturing protocols, the resulting bioplastics can exhibit varying levels of mechanical strength, thermal stability, and biodegradability, making it difficult for manufacturers to ensure consistency and predictability in their products. This lack of standardization can also hinder regulatory frameworks and industry-wide quality control measures.

Limited compatibility with existing infrastructure. The limited compatibility of starch-based bioplastics with the existing packaging infrastructure poses a significant barrier to their widespread adoption. Many conventional packaging facilities and equipment designed to handle traditional plastics may not be suitable for processing starch-based bioplastics, which can have different melting points, viscosity, and other physical properties. This incompatibility can lead to difficulties in manufacturing, filling, and sealing, ultimately increasing costs and reducing efficiency. This highlights the need for specialized infrastructure and equipment to support the production and use of starch-based bioplastics.

Public perception and awareness. Limited public awareness and understanding of starch-based bioplastics can hinder their adoption and use. Consumers may be skeptical or uninformed about the benefits and characteristics of these biodegradable materials. Without adequate education and awareness, consumers may not recognize the environmental advantages of starch-based bioplastics, such as their renewable sourcing, biodegradability, and reduced carbon footprint. There is therefore a need for targeted educational campaigns and outreach initiatives to promote awareness and acceptance of these sustainable materials.

CONCLUSION

This review provided an exhaustive examination of the production process, properties, applications, challenges, and future directions of starch-based bioplastic packaging, demonstrating its potential to transform the packaging industry. The merits of starch-based bioplastics are multifaceted, including biodegradability, compostability, renewability, and reduced greenhouse gas emissions. These benefits make them an attractive solution to the environmental and sustainability concerns associated with traditional plastics. The versatility of starch-based bioplastics has been demonstrated through their successful application in various packaging sectors, including food, beverage, and cosmetic packaging.

While challenges persist, ongoing research and development is addressing the limitations of starch-based bioplastics, such as high production costs, limited scalability, and inferior mechanical properties. The future directions for starch-based bioplastics are promising, with potential applications in edible, smart, and nanotechnology-enhanced packaging. Policy support and public awareness are crucial in promoting the adoption of starch-based bioplastic packaging, so encouraging regulations and education will drive the growth of the bioplastic industry. The development of starch-based bioplastics has the potential to revolutionize the packaging industry, mitigating plastic waste and reducing environmental pollution.

In summary, this review comprehensively demonstrated that starch-based bioplastic packaging is a sustainable alternative to conventional plastics, offering improved environmental and sustainability benefits. Our findings have significant implications for the packaging industry, policymakers, and consumers, highlighting the need for a shift towards sustainable and biodegradable

packaging solutions. Overall, this review lays a foundation for further research and development in starch-based bioplastic packaging, driving innovation and sustainability in packaging technologies.

CONTRIBUTION

All the authors contributed equally and substantially to this research work. Each author was involved in the conception, design, implementation, and interpretation of the research findings, as well as in the writing of this manuscript.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest, financial or personal, that could bias the work reported in this paper.

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