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REVIEW

Functionalized Starch Polymers in Packaging: Advances in Bioengineering and Material Science

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ABSTRACT

Background: Conventional plastics pose significant environmental challenges, prompting research into biodegradable alternatives. Starch-based packaging materials represent a promising eco-friendly solution derived from renewable sources.

Scope and Approach: This review examines recent developments in starch-based polymers for packaging applications, focusing on modification techniques, property enhancements, and environmental performance.

Key Findings and Conclusions: Chemical modifications and physical blending have successfully improved the mechanical strength and barrier properties of starch-based materials. Integration of nanotechnology has yielded starch nanocomposites with superior tensile strength and enhanced moisture and gas barrier properties. Life cycle analyses demonstrate significant reductions in environmental impact compared to traditional plastics, confirming advantages in biodegradability and carbon footprint. Despite progress, challenges in scalability and cost-effectiveness remain. Future directions include bio-based hybrid materials and smart packaging solutions, suggesting continued innovation in this field.

Significance and Novelty: This comprehensive review synthesizes technical advancements and environmental benefits of starch-based packaging materials, providing valuable insights for researchers and industry stakeholders seeking sustainable alternatives to conventional plastics.

1 | Introduction

Food packaging plays a crucial role in preserving the quality, safety, and shelf-life of food products. Enhanced versatility and convenience of plastics have played a significant role in shaping modern society [1]. However, the extensive use of petroleum-based plastics and nonbiodegradable plastic materials in packaging has led to environmental issues such as plastic pollution and long degradation times [2]. In response, researchers and industries have turned their attention towards more sustainable alternatives, with starch-based materials emerging as a promising solution. In recent years, the global push for more sustainable and eco-friendly packaging solutions has led to significant advancements in the field of starch-based packaging [3]. Starch, a carbohydrate polymer composed of glucose units, is abundant, renewable, and biodegradable [4]. It is a complex carbohydrate made up of two main forms: amylose (a linear chain of glucose units) and amylopectin (a branched chain). The molecules are organized into granules, which are commonly found in plants and serve as a storage form of energy [5]. The production of starch-based pack-

TABLE 1 | Differences in Amylose and Amylopectin characteristics for development of packaging material.

Characteristic	Amylose	Amylopectin
Structure	Linear Polymer	Branched polymer
Chain arrangement	$\alpha(1\rightarrow4)$ glycosidic bonds	$\alpha(1\rightarrow4)$ glycosidic bonds with $\alpha(1\rightarrow6)$ branches
Degree of Branching	Minimal	High
Helical Structure	Forms a helical structure in solution	Limited helical structure in solution
Solubility	Lower	Higher
Digestibility	Slower digestion	Faster digestion
Function	Storage of energy in plants	Rapid energy release
Gel formation	Forms less stable gels	Forms more stable gels
Starch types	Common in waxy starches	Common in regular starches
Barrier properties	Higher oxygen barrier	Lower oxygen barrier
Film formation	More difficult to form films	Easier to form films
Mechanical strength	Lower mechanical strength	Higher mechanical strength
Transparency	Less transparent	More transparent
Water sensitivity	More sensitive to water	Less sensitive to water
Shelf life	Provides longer shelf life	May lead to shorter shelf life
Compatibility	Limited compatibility with other polymers	Better compatibility with other polymers
Applications	Used in coatings, adhesives, and as additives	Used in biodegradable packaging and coatings

aging typically requires lower energy consumption and generates fewer greenhouse gas emissions compared to the production of conventional plastic packaging. This contributes to a reduced carbon footprint and supports more sustainable manufacturing practices. Starch-based packaging aligns with the principles of a circular economy by providing a renewable and compostable alternative to single-use plastics. When disposed of properly, starch-based packaging can be composted, returning valuable nutrients to the soil and completing the nutrient cycle [6].

2 | Starch: Structure, Properties, and Sources

Starch consists of two major components: amylopectin and amylose (Table 1 & Figure 1). Amylopectin, the branched polymer, is composed of glucose molecules linked together by alpha-1,4 and alpha-1,6 glycosidic bonds. Its branching pattern sets it apart from amylose, the other major component of starch. Amylopectin exhibits a highly branched structure unlike the linear amylose due to the presence of frequent alpha-1,6 glycosidic bonds [7]. These branching points give rise to a tree-like arrangement, resulting in a complex and three-dimensional molecule. The glucose units within amylopectin are organized into clusters. Each cluster contains a central core of interconnected glucose residues linked by alpha-1,4 glycosidic bonds, analogous to the structure of amylose. Extending from this core are numerous linear chains of glucose molecules connected through alpha-1,6 glycosidic bonds [8]. These branches radiate outwards, creating a highly branched molecule.

The branching structure of amylopectin has led to the formation of granules within plant cells. Starch granules are made up of both amylose and amylopectin, with amylopectin constituting the granule's outer layers. This arrangement facilitates the packing of glucose molecules, making starch an efficient energy storage form for plants [9]. Amylopectin granules exhibit a larger surface area due to their three-dimensional structure that allows for efficient interactions with enzymes during digestion [10]. The branching pattern of amylopectin makes it less soluble in water compared to amylose, which hinders water penetration [11]. This property contributes to the ability of starch granules to form gels when heated in the presence of water, a characteristic often utilized in food processing and culinary applications [12].

Amylopectin's gel-forming property in starch makes it valuable in the production of biodegradable packaging materials and adhesives. The structural integrity, flexibility, and water-resistant properties of starch-based packaging are attributed to amylopectin. The branched structure allows for intermolecular interactions, including hydrogen bonding, which leads to the formation of a dense and cohesive network within the packaging material [13]. The presence of amylopectin imparts resilience and toughness to the packaging material, enabling it to withstand stresses encountered during storage, transportation, and handling. In addition, amylopectin plays a crucial role in influencing the water resistance of starch-based packaging. The branched structure and hydrogen bonding capacity contribute to the formation of a hydrophobic barrier. Amylopectin-rich starch films exhibit reduced water vapor permeability, which is advantageous for protecting perishable goods and maintaining a stable microenvironment within the package [14]. Unlike linear polymers such as polyethylene, the branched structure of amylopectin provides sites for enzymatic attack by various microorganism-derived enzymes. This renders starch-based packaging materials susceptible to degradation by amylolytic enzymes, ultimately leading to the breakdown of the material into simpler carbohydrate components [15]. As a result, starch-based packaging offers a more sustainable end-of-life option, as it can be

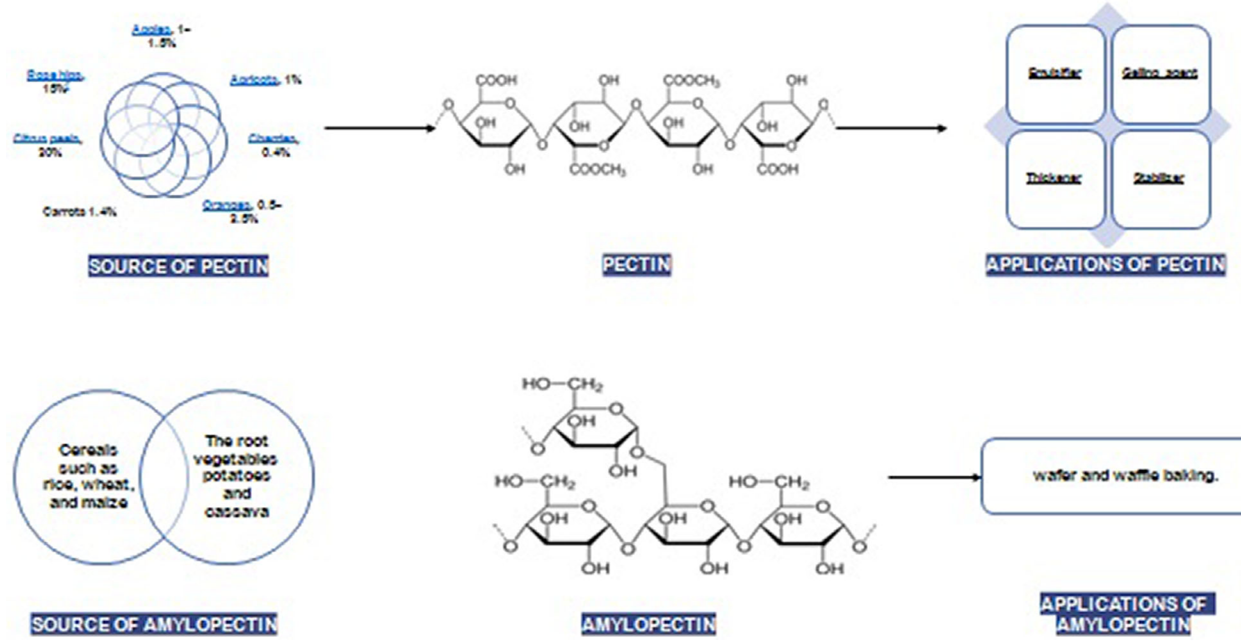

FIGURE 1 | Amylose and amylopectin molecules.

broken down by natural processes into environmentally benign products.

Recent advances in understanding amylopectin's structure-function relationship have revealed its critical role in next-generation packaging materials. Conventional understanding of amylopectin as merely a branched polymer has evolved with emerging research using atomic force microscopy (AFM) and small-angle X-ray scattering (SAXS), which has revealed nanoscale structural features that directly influence material properties.

Distinct structural domains within amylopectin molecules that significantly impact gelatinization behavior was identified using enzymatic fingerprinting techniques. The length of internal chains between branch points (rather than simply the degree of branching) dictates the material's response to thermal processing, with longer internal chains (>25 glucose units) leading to more thermally stable films [16]. Recent work by Zhu et al. [17] has further differentiated amylopectin's role in different botanical sources, showing that rice and potato amylopectin, despite similar branching degrees, exhibit markedly different film-forming properties due to variations in branch clustering patterns. This research has enabled the strategic selection of starch sources for specific packaging applications, with potato amylopectin's widely spaced branch clusters yielding films with superior oxygen barrier properties (40-50% improvement over maize-based films).

Amylose, on the other hand, is a polysaccharide composed of glucose molecules linked together by alpha-1,4 glycosidic bonds. The linear nature of amylose gives it a distinct molecular structure and unique properties [18]. Due to the geometry of the glycosidic bonds, the linear chain of amylose can fold into a helical structure [19]. The intramolecular hydrogen bonding of glucose units stabilizes the helical structure formed [20]. The characteristic rigidity of amylose is due to the helical arrangement, and it also contributes to its unique properties like water insolubility [21]. Unlike amylopectin, the helical structure of amylose prevents water molecules from readily interacting with the glucose units, reducing its solubility [22]. Another notable property of amylose is its ability to form complexes with various molecules such as iodine, resulting in the blue coloration observed when amylose-iodine complexes are formed. The intensity of this color change is used as an indicator in assays to quantify amylose content in starch samples [23]. Amylose is also a critical component in the development of resistant starches, which are not fully digested in the small intestine [24]. Films based on amylose create an effective barrier that minimizes the transfer of moisture, gases, and light, thus helping to maintain the freshness and quality of packaged goods [25]. Food preservation can be improved by the release of active compounds or additives from the films in addition to its barrier properties [26]. This incorporation can actively contribute to extending the shelf life of products and maintaining their quality [27].

Starch is derived from various sources in nature (Table 2). The most significant sources of dietary starch are cereals and grains, which form the staple food in many cultures. They are rich in starch and provide a sustainable amount of energy. Common examples include rice, wheat, corn, oats, and barley. This starch is mainly stored in the endosperm of cereals and grains that makes up the majority of the kernel [28]. The worldwide consumed starchy tubers and roots like potatoes, sweet potatoes, yam, and cassava are another important source of dietary starch. The starch granules are stacked within the underground storage organs that act as a reserve energy source for the plant. These versatile ingredients can be prepared in various ways. The bulky nature and high moisture content (60–90%) of these roots and tuber crops often restrict them from getting connected with markets. This low market access is also associated with low shelf life and high shipping costs margin in developing nations [29].

Protein and starch-rich legumes such as beans, lentils, chickpeas, and peas are also important sources. The starch content in

TABLE 2 | Various sources of starch with their properties, extraction method and morphology.

Botanical source	Properties	Extraction Method	Morphology
Corn Starch	High amylose content, string and flexible films, good moisture barrier	Wet milling, Centrifugation	Granular, oval shape
Potato Starch	Good film forming properties, transparent films, moderate moisture barrier	Water extraction, filtration	Round and Elliptical granules
Cassava Starch	Strong films, high transparency, excellent moisture barrier	Grating, Centrifugation	Oval and spherical granules
Rice Starch	Good film forming ability, high amylopectin content, moderate moisture barrier	Wet milling, Sedimentation	Polygonal and oval granules
Wheat Starch	Moderate film forming ability, suitable for blends, relatively low moisture barrier	Wet milling, Centrifugation	Polygonal and irregular granules
Sweet potato Starch	Strong films, high transparency, good barrier against water vapour and gases	Grinding and sieving	Irregular granules
Quinoa Starch	High amylose content, good film forming ability, Low gelatinization temperature, Strong moisture barrier	Washing, grinding, drying, alkaline treatment, centrifugation, filtration	Granular structure, Ellipsoidal or irregular shape
Yam Starch	High viscosity, film forming and adhesive, gelatinization temperature varies, good resistance to heat and shear	Peeling, washing, grinding, sieving, drying, centrifugation and filtration	Granular structure, oval to round shape,
Jackfruit seed Starch	High viscosity, good film forming ability, Resistance to moisture, Suitable for coating applications	Seed separation, washing, grinding, drying, alkaline treatment	Granular structure, Polygonal or irregular shapes

legumes varies within varieties. Legumes provide a valuable source of dietary fiber in addition to starch, contributing to a slower digestion process and helping regulate blood sugar levels [30]. The unripe fruits and vegetables, while not typically considered primary sources of starch, do contain some amount. The starch content in banana, for example, gets converted to sugar during the ripening process. Similarly, green bananas, plantains, and some types of squashes contain starch that can be utilized as a source [31].

Grains like maize (corn) and rice are seeds by themselves, and they contain starch as an energy reserve that can be exploited for the germination process. The seedlings emerging utilize the stored starch for their growth and development. Additionally, pseudo-cereals like quinoa and millets also contain starch with other nutritional compounds, and they add advantages in many culinary applications [32]. Modified starches and starch derivatives fall under the category of processed starches, which undergo various physical and chemical modifications, thus enhancing their thickening, gelling, and stabilizing properties. They find application in a variety of food products such as soups, sauces, snacks, and baked goods [33]. Traditional foods like tapioca pearls made from cassava in Southeast Asia [34], fufu made from yams or cassava in Africa [35], and arepas made from corn flakes in South America [36] are rich in starch.

3 | Physicochemical and Functional Characteristics of Starch

Starch exhibits a complex array of physicochemical and functional characteristics that determine its behavior in various applications, particularly in food systems and packaging materials. Gelatinization, a fundamental property of starch, occurs when starch granules are heated in the presence of water, causing them to swell and absorb water while disrupting their molecular structure (Figure 2). This process, as described by Li and Wei [37], triggers the release of starch components into the surrounding medium, transforming the amorphous structure into a crystalline one. The resulting changes significantly affect texture, viscosity, and other functional properties in starch-containing systems. The mechanism behind gelatinization involves water molecules interacting with starch chains, weakening the intermolecular forces within granules and forming a gel-like consistency as amylose and amylopectin molecules create a continuous network, as elucidated by Zhu [38].

The gelatinization process is influenced by numerous interconnected factors, with temperature being the most significant. The rate and extent of gelatinization increase with rising temperatures until reaching a plateau where the process either stabilizes or begins to degrade [39]. Each type of starch

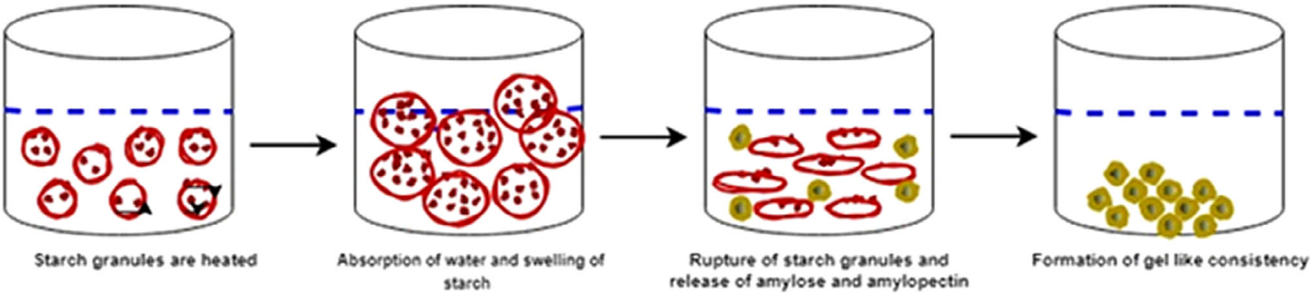

FIGURE 2 | Gelatinization of Starch.

possesses a unique gelatinization temperature range due to variations in molecular structure. Equally important is moisture content, which facilitates the disruption of hydrogen bonds in starch. Achieving optimal moisture balance ensures even heating and complete gelatinization, while insufficient moisture hinders the process and excessive moisture may cause over-gelatinization or undesirable textural changes [40, 41].

The source and type of starch substantially influence gelatinization behavior due to variations in amylose and amylopectin content. Starches with higher amylose content form stronger gels [42], while those with greater amylopectin content produce weaker gels. Additionally, starch concentration affects gelatinization kinetics, higher concentrations typically result in increased viscosity and prolonged gelatinization due to limited water availability for hydration [43]. The pH environment also plays a crucial role, as extreme pH levels can inhibit or slow gelatinization, affecting the final product's texture and properties [44].

Mechanical factors such as stirring and shear help disperse starch particles evenly, ensuring uniform heat distribution and reducing lump formation. However, excessive mechanical force can lead to undesired breakdown of gelatinized starch [45]. Various additives, including salts, sugars, and hydrocolloids, modify water-binding capacity, viscosity, and gel structure during gelatinization. These additives produce different effects depending on their concentration, with salts potentially strengthening gels while sugars and hydrocolloids may either enhance or hinder gel formation [46]. Pressure represents another significant factor, particularly in industrial processes like extrusion cooking, where high pressure enables gelatinization at lower temperatures [47]. Chemical or physical modifications of starch through pre-gelatinization, cross-linking, or hydrolysis significantly alter gelatinization behavior, with modified starches often exhibit improved stability, texture, and gel strength compared to native starches [48]. Heating rate and duration impact gelatinized starch quality. Rapid heating may cause uneven gelatinization, while prolonged heating can degrade starch and reduce gelatinization efficiency [49].

Following gelatinization, starch undergoes retrogradation, a process where starch molecules reassociate upon cooling (Figure 3). This phenomenon, driven by hydrogen bonding between amylose and amylopectin molecules, has attracted significant attention for its ability to influence material properties and extend shelf life. Gelatinized starch molecules realign upon cooling, forming a network through hydrogen bonding that affects texture and firmness in starch-containing products [50]. Amylopectin molecules exhibit Brownian motion due to collisions with surrounding molecules, constantly moving randomly as a manifestation of their kinetic energy [51]. The incorporation of retrograded starch into food packaging materials can enhance mechanical and barrier properties, the tight network formed during retrogradation strengthens the structural integrity of packaging materials [52].

Retrogradation behavior varies significantly based on both intrinsic and extrinsic factors. Different botanical sources of starch exhibit distinct retrogradation patterns. Higher amylose content starches retrograde more readily due to their linear structure, while amylopectin-rich starches show reduced retrogradation [53]. The amylose-to-amylopectin ratio influences retrogradation, with higher amylose content starches forming more stable retrograded structures [54]. Molecular weight also plays a role, as higher molecular weight starches provide more sites for intermolecular interactions, showing enhanced retrogradation tendencies and improved structural integrity [55]. The degree of branching in amylopectin reduces retrogradation tendency due to increased steric hindrance limiting hydrogen bond formation [56], while amylose's quick retrogradation significantly affects starchy food textures [57]. Granule size impacts retrogradation, with smaller granules' increased surface area facilitating more rapid intermolecular interactions [58]. The crystalline regions in starch granules serve as nuclei promoting starch molecule reassociation during cooling [59].

Environmental conditions significantly affect retrogradation. Lower temperatures promote extensive retrogradation, demonstrating temperature dependence with increased hydrogen bonding during prolonged storage at reduced temperatures [60]. Repeated freeze-thaw cycles accelerate retrogradation as voids produced during these cycles promote reassociation upon thawing [61], while extrusion cooking with rapid cooling results in less retrogradation compared to slow cooling [62]. Moisture content influences the process, as higher moisture levels may hinder retrogradation by disrupting hydrogen bond formation [63]. Acidic pH conditions enhance hydrogen bonding through protonation of hydroxyl groups, affecting retrogradation behavior [64]. Additives like emulsifiers and hydrocolloids disrupt starch reassociation by interfering with hydrogen bonding, while enzyme modification significantly affects retrogradation potential [65]. Lipids can slow retrogradation by restricting water migration through interactions with starch molecules [66].

The functional characteristics of starch, particularly its solubility and water absorption properties, are integral to its applications. Ghasemlou et al. [67] highlighted starch's hydrophilic nature

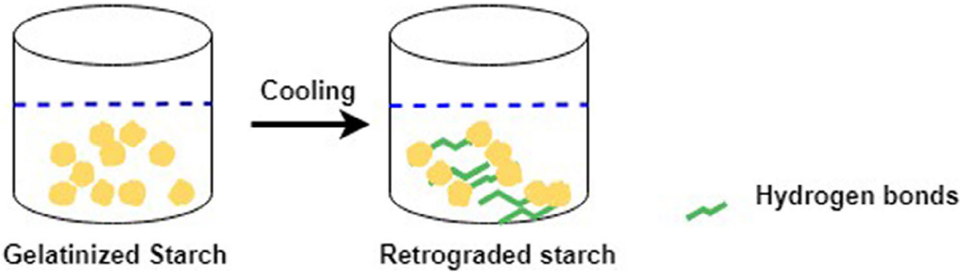

FIGURE 3 | Retrogradation of Starch.

and strong water affinity, which influence its functional characteristics and environmental impact, especially in starch-based packaging materials. The composition of starch, with its linear amylose and branched amylopectin molecules, determines its water-absorbing capacity. Moisture exposure forms hydrogen bonds that weaken starch molecules, leading to their dissociation from polymer matrices and subsequent dissolution [68].

Solubility significantly impacts packaging performance in multiple ways. The water solubility and swelling of starch reduce the permeability of gases like oxygen and carbon dioxide, affecting packaged food shelf-life and quality by altering gas exchange rates. However, starch solubility in packaging materials can reduce mechanical strength, potentially compromising structural integrity during handling and transportation. Starch-based materials with lower solubility degrade more slowly than highly soluble ones, with rapid degradation and decomposition aligning with circular economy principles and environmental sustainability goals [69].

Starch's swelling behavior in aqueous solutions results from the arrangement of glucose units in linear and branched forms. While starch-based packaging materials offer renewability and biodegradability, effective moisture control critically impacts product quality and shelf life [70]. Starch swelling influences permeability pathways by increasing mass transfer rates through materials, with starch gelatinization and retrogradation serving as the primary mechanisms behind swelling [71]. Different starch-based packaging formulations exhibit distinct swelling behaviors, affecting their application suitability.

The pasting behavior of starch represents another crucial functional characteristic. When exposed to heat in water, amylose and amylopectin molecules leach out, forming a paste as the crystalline structure of starch disappears. As starch granules absorb water and heat, they swell and lose their crystalline structure, creating a network that traps water and increases solution viscosity. Marta et al. [72] defined the point where paste viscosity reaches its maximum as peak viscosity, with the corresponding temperature termed pasting temperature. Upon cooling, starch paste experiences further viscosity increases, termed setback viscosity [73]. This phenomenon measures the paste's resistance to flow after cooling, influenced by starch source, granule size, amylose-amylopectin ratio, impurities, pH, and heating rate [74]. This property enables starch processing into various packaging materials, including films, coatings, and containers, with proper pasting control ensuring functionality for intended applications.

The interconnected nature of starch's physicochemical and functional characteristics creates a complex system that can be manipulated for specific applications. The gelatinization process allows starch molecules to form networks that act as barriers against moisture, oxygen, and other gases [75]. Starch-based films offer good printability and label adhesion for branding and product information, with gelatinization ensuring film integrity during common printing processes [76]. These properties, along with starch's biodegradability and renewable nature, make it increasingly valuable in sustainable packaging applications, representing a holistic approach to addressing both functional requirements and environmental concerns in modern material science.

4 | Measuring, Modifying, and Extracting Starch: An Overview

The measurement, modification, and extraction of starch represent interconnected processes essential for understanding and optimizing this versatile biopolymer for various applications. Researchers and industry professionals employ a diverse array of analytical techniques to characterize starch properties, with the selection of appropriate methods depending on the specific attributes under investigation (Table 3). The simple iodine test offers a rapid qualitative assessment by exploiting the characteristic blue-black complex formed when starch molecules bind with iodine, with color intensity providing a rough indication of starch concentration [77]. For more precise quantification, enzymatic assays break down starch into simpler sugars using specific enzymes. Both the amount of enzyme required and the reaction rate can yield valuable information about starch concentration [78]. Chromatographic techniques like High Performance Liquid Chromatography (HPLC) and Gas Chromatography (GC) offer more sophisticated analysis as it can identify starch components based on molecular size using detection methods such as refractive index or UV absorption, while GC can analyze volatile compounds produced during starch hydrolysis to determine the type and quantity of sugars present [79].

Spectroscopic methods provide valuable insights into starch's molecular structure and organization. Fourier Transform Infrared Spectroscopy (FTIR) exploits the absorption of infrared light by different functional groups in starch molecules at specific frequencies, enabling researchers to identify and quantify starch [80]. Nuclear Magnetic Resonance (NMR) examines the behavior of atomic nuclei in a magnetic field, revealing detailed information about the types of starch molecules present and

TABLE 3 | Comprehensive Overview of Analytical Techniques for Starch Characterization.

Technique	Application	Key Parameters Measured	Advantages	Limitations
SEM/TEM	Surface and internal morphology	Granule size, shape, and distribution; Surface topography; Internal structural features	High-resolution imaging of starch microstructure; Direct visualization of structural changes after modification; Can reveal nanoscale features	Sample preparation may alternative structure; Limited to morphological analysis; Requires specialized equipment
DSC	Thermal properties	Gelatinization temperature; Enthalpy of transition; Glass transition temperature; Melting point; Retrogradation behavior	Quantifies energy changes during phase transitions; Small sample size; High sensitivity to thermal events; Provides insights into processing behavior	Interpretation can be complex; Results affected by sample history; Limited structural information
FTIR	Chemical structure	Functional group identification; Chemical bonding patterns; Modification confirmation	Non-destructive analysis of chemical bonds; Rapid analysis; Minimal sample preparation; Can track chemical modifications	Semi-quantitative without calibration; Peak overlapping can occur; Limited spatial resolution
XRD	Crystalline structure	Crystal pattern; Crystallinity degree; Polymorphic forms (A, B, C-type)	Differentiates between crystalline structures; Quantifies degree of crystallinity; Non-destructive; Reveals molecular ordering	Limited to crystalline regions; Complex data interpretation; Cannot directly analyze amorphous regions
RVA	Pasting properties	Peak viscosity; Pasting temperature; Breakdown; Setback; Final viscosity	Mimics processing conditions; Provides insights into functional behavior; Good reproducibility; Industry-standard method	Empirical measurements; Limited correlation to molecular structure; Sample concentration affects results
NMR	Molecular structure	Chemical environment of protons, carbon; Molecular mobility; Water interactions	Provides detailed molecular-level information; Can analyze both solid and solution states; Reveals dynamic properties	Low sensitivity; Expensive instrumentation; Complex data interpretation; Limited throughput
Mechanical testing	Physical properties	Tensile strength; Elongation at break; Young's modulus; Puncture resistance; Tear strength	Evaluates material performance under stress; Direct application to packaging functionality; Standardized methods available	Results affected by environmental conditions; Sample preparation critical; May not reflect actual use conditions
Water vapor permeability	Barrier properties	WVTR; Permeability coefficient; Diffusion coefficient; Solubility	Critical parameter for packaging applications; Directly relates to shelf-life prediction; Standardized methods available	Time-consuming; Affected by environmental conditions; Requires precise control of testing conditions
Oxygen permeability	Gas barrier properties	Oxygen transmission rate; Permeability coefficient; Temperature and humidity effects	Essential for predicting oxidative stability; Relates directly to food preservation capability	Specialized equipment needed; Long equilibration times; Complex relationships with other material properties

(Continues)

TABLE 3 | (Continued)

Technique	Application	Key Parameters Measured	Advantages	Limitations
Enzymatic analysis	Digestibility and modification	Degree of substitution; Resistant starch content; Enzyme susceptibility	Provides insights into biological interactions; Correlates with nutritional properties; Can verify specific modifications	Variable enzyme activity; Methodology standardization issues; Complex sample preparation

their arrangement [81]. Microscopy techniques allow visual examination of starch granules, with size and shape analysis providing insights into starch content and characteristics [80]. X-Ray Diffraction (XRD) reveals the crystalline structure and organization of starch granules through distinctive diffraction patterns [82]. Thermal analysis via Differential Scanning Calorimetry (DSC) measures critical parameters such as gelatinization temperature, glass transition temperature, enthalpy, and film melting temperature by identifying heat flow associated with phase transitions [83]. The Rapid Visco Analyzer (RVA) assesses starch viscosity during heating and subsequent cooling cycles and these measurements provide valuable information about starch characteristics and behavior [84].

When characterizing starch-based packaging materials, researchers employ specialized techniques targeting specific performance attributes. Electron microscopy methods like Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) generate detailed images of surface and internal structures. These techniques reveal morphology, component distribution, and interactions within the material. These microscopic investigations assist in understanding the structural organization of starch-based materials [85]. Thermal analysis through DSC and Thermogravimetric Analysis (TGA) provides critical information on melting points, degradation temperatures, and heat capacity [80]. Mechanical testing evaluates essential performance parameters including tensile strength, elasticity, and toughness through various stress-strain evaluations [86].

Barrier properties represent crucial performance indicators for packaging applications. Popović et al. [87] outlined methods for measuring water vapor and oxygen permeability by creating artificial environments to determine the rate at which these molecules pass through packaging materials, directly indicating their barrier effectiveness and suitability for food protection. Biodegradability and compostability testing follows standardized protocols such as ASTM D6400 or EN 13432. These assessments determine whether packaging materials degrade under specific environmental conditions [88]. Electron Paramagnetic Resonance (EPR) spectroscopy exploits the magnetic spin of electrons to investigate free radical content and stability within packaging materials [89]. Water absorption and swelling tests evaluate how packaging materials interact with moisture, these measurements help assess material stability under varying humidity conditions [90]. Migration testing ensures food safety by verifying that no harmful substances transfer from packaging materials to food products, which serves as critical evaluation for consumer protection. Rheological analysis examines flow and deformation behaviors using rheometers, providing insights into processing and application characteristics [91]. Colour analysis through colorimetry, measures parameters like L*, a*, and b* values to quantify starch colour that attributes influence consumer perception of packaged products [92].

The modification of native starch represents a critical approach for enhancing its functionality in packaging applications, with researchers employing various physical, chemical, and enzymatic methods to tailor starch properties for specific performance requirements. Physical modification techniques alter starch structure without chemical reactions. Mechanical processing methods like milling, grinding, and high-pressure shearing break down starch granules into smaller particles. Increased surface area improves properties like solubility and viscosity [93]. Heat treatment processes such as annealing or gelatinization involve heating starch in water's presence, causing swelling and amorphous structure formation that enhances film-forming capabilities [94]. Extrusion techniques disrupt starch's crystalline structure by forcing it through narrow openings under controlled temperature and pressure conditions. This process modifies properties to increase water resistance and improve film-forming characteristics. Blending starch with other polymers, including proteins or synthetic materials, creates composites with enhanced mechanical strength, flexibility, and barrier properties [95]. Physical cross-linking through freeze-thaw cycles or irradiation creates network structures that improve film mechanical strength and water resistance [13]. These processes replace weaker hydrogen connections between starch chains with stronger covalent bonds [96]. Compression moulding forms starch sheets or films with modified properties through applied heat and pressure [97]. Nanostructuring incorporates materials like nanocellulose or nanoclays into starch matrices to enhance mechanical and barrier performance [98].

Chemical modification methods introduce new functional groups or create bonds between starch molecules to alter their properties. Etherification replaces some hydroxyl groups in starch molecules with ether groups through reactions with alkylating agents and thereby producing modified starches with improved water resistance, film-forming ability, and stability [99]. Esterification, achieved by reacting starch with fatty acids or anhydrides, enhances hydrophobicity and film-forming properties while improving moisture and gas barriers [100]. Acetylation introduces acetyl groups onto starch molecules using acetic anhydride or acetyl chloride, increasing water resistance, improves film-forming characteristics, and reduces retrogradation [101]. Chemical cross-linking forms covalent bonds between starch molecules, enhancing mechanical strength, water resistance, and thermal stability. Oxidation using agents like sodium hypochlorite or hydrogen peroxide introduces carbonyl and carboxyl groups onto starch molecules, increasing water resistance and interaction potential with other polymers [101]. Hydroxypropylation adds hydroxypropyl groups to starch, improving solubility, swelling behavior, and film-forming properties [102]. Graft copolymerization connects starch with other polymers through radical reactions, enhancing mechanical strength, water resistance, and flexibility [103]. Cationization introduces positively charged groups onto starch molecules, improving their interactions with anionic substances like dyes or proteins [104].

Enzymatic modification methods offer more targeted approaches to altering starch structure. Amylase treatment hydrolyzes starch using specific enzymes that break it down into smaller molecules like dextrins or oligosaccharides. This reduces starch solution viscosity, facilitating processing into films or coatings [105]. Pullulanase treatment selectively removes branching points from amylopectin in starch molecules and the resulting modified starch with fewer branches exhibits improved film-forming properties and reduced retrogradation [106]. Transglucosidase enzymes transfer glucose molecules between starch molecules to create new linkages, producing modified starches with altered properties including improved water resistance and viscosity [107]. Amyloglucosidase breaks down both amylose and amylopectin into glucose units, enhancing solubility and reducing viscosity to create materials suitable for various applications including coatings [107]. Oxidative enzymes like peroxidases catalyze oxidative reactions on starch molecules altering the functional groups and improving interactions with other materials [108]. Esterification using enzymes such as lipases introduces fatty acid chains onto starch molecules, enhancing hydrophobicity and film-forming properties [109].

The extraction of starch from agricultural waste, such as potato peels, represents a sustainable approach to resource utilization. Potato peels, which are byproducts of potato processing industries, have about 15–20% starch on a dry weight basis [110]. The process of extraction usually includes washing, size reduction, alkaline treatment, filtration, and purification steps.

Some of the recent developments in this field are the optimization of extraction protocols for waste potato peels. One efficient method of extraction is treating washed and milled potato peels with sodium metabisulfite (0.1%) to inhibit browning, followed by alkaline extraction (pH 10.5-11.0) at moderate temperatures (40-45°C), which separates starch from cellular material [111]. The starch extracted may further be altered by cross-linking with dicarboxylic acids like citric acid, adipic acid, or succinic acid to enhance its functional characteristics for packaging uses.

Cross-linking of waste potato peel starch with dicarboxylic acids occurs through esterification reactions between the carboxyl groups of the acids and the hydroxyl groups of starch molecules [112]. This research demonstrated that treating isolated potato peel starch with citric acid (3-5% w/w) at 130°C for 2–3 hours resulted in significant property enhancements. The cross-linked starch exhibited a 42% reduction in swelling power, a 16°C increase in gelatinization temperature (from 63°C to 79°C), and a 35% improvement in tensile strength when formed into films compared to native potato peel starch.

The cross-linked starch showed remarkable thermal stability, with thermogravimetric analysis revealing that the onset degradation temperature increased from 268°C for native potato peel starch to 312°C for the cross-linked product. Water absorption capacity decreased by 61%, from 2.8 g/g to 1.1 g/g, demonstrating significantly improved water resistance. Scanning electron microscopy confirmed structural modifications, showing more compact and less porous granules with smoother surfaces, indicating successful cross-linking between starch molecules.

Biocompatibility tests further demonstrated that these cross-linked starch derivatives showed no cytotoxicity against human fibroblast cells at concentrations below 250 μg/mL, making them suitable for food packaging applications [112]. The enhanced mechanical properties, improved moisture resistance, and demonstrated biocompatibility make cross-linked potato peel starch a promising material for sustainable packaging solutions.

Waste potato peel starch is cross-linked by dicarboxylic acids through esterification reactions involving the acid's carboxyl groups and the hydroxyl groups of the starch molecules. This treatment of starch enormously increases its thermal stability, resistance to water, and mechanical property and thus proves fit for utilization in sustainable packaging applications [113]. The cross-linked starch shows lowered swelling power, enhanced gelatinization temperature, and better film-forming behavior in comparison with the native starch.

The extraction of starch from plant materials employs various methods depending on the source material and desired purity level. The water washing method represents a traditional approach where plant material, typically grains or tubers, is ground into a paste and mixed with water, allowing starch granules to separate from fiber and protein through sedimentation as water is decanted off. Starch purification is achieved by repeating this process several times [114]. The wet milling method offers a more industrial approach for extracting starch from grains like corn, steeped in water and sulfur dioxide to soften it before mechanical grinding separates components, followed by centrifugation, washing, and drying [115]. Centrifugation leverages the higher density of starch particles to separate them from other components during high-speed spinning, however, sedimentation often yields finer starch quality while centrifugation results in higher protein content and lower starch yield [116]. Centrifugal sieves separate starch based on particle size by passing starch-water mixtures through a series of specialized sieves as described by Correia et al. [117].

The dry milling method applies to crops like cassava, involving peeling, cleaning, and grating tubers to create a pulp that is mechanically pressed to remove liquid, leaving a starch cake for drying and grinding into powder [118]. Enzymatic methods use specific enzymes to break down cell walls and proteins in plant materials, facilitating starch separation. Combining enzymatic approaches with other techniques enhances extraction efficiency [119]. Acid or alkali treatments break down cellular structures and proteins to improve starch extraction, though these methods require additional processing steps to

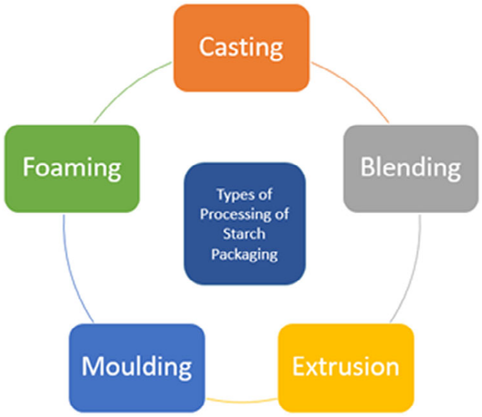

FIGURE 4 | Types of Processing of Starch Packaging Material.

neutralize pH [120]. Physical separation techniques including sieving, filtration, and sedimentation exploit differences in particle size and density to isolate starch granules from other components [121, 122].

The interrelated processes of measuring, modifying, and extracting starch demonstrate how this versatile biopolymer can be characterized, tailored, and obtained for specific applications, particularly in sustainable packaging. The diverse analytical techniques available for starch characterization provide comprehensive insights into its structure, properties, and performance characteristics. Modification methods enable researchers and manufacturers to enhance native starch properties to meet specific application requirements, while extraction techniques facilitate obtaining starch from various plant sources with desired purity levels. Together, these approaches support the growing utilization of starch in sustainable packaging solutions that address both functional requirements and environmental concerns, offering potential alternatives to conventional petroleum-based packaging materials. The ongoing development of more sophisticated analytical methods, innovative modification techniques, and efficient extraction processes continues to expand starch's potential in various industrial applications while supporting the transition toward more sustainable material solutions.

5 | Processing of Starch as a Packaging material

The starch based compounds can be processed by varied methods according to the need of the final product (Figure 4).

5.1 | Casting

A process where starch derived from renewable sources like corn, potato, or tapioca is mixed with water to form a slurry which including additives like plasticizers, fillers and reinforcing agents is poured or spread over a smooth casting surface, which could be a conveyor belt, glass plate, or drum and transformed into solid sheets or films through controlled casting, drying, and curing steps [123]. To ensure uniform properties in the final product, the starch slurry is carefully prepared with consistent viscosity and homogeneity and is spread evenly across the casting surface to achieve a uniform thickness of the film or sheet. The moisture content of cast slurry begins to decrease after entering the drying chamber. The solidification of slurry occurs where temperature and humidity are controlled to prevent cracking, deformation, or uneven drying. In some cases, a curing step follows initial drying to ensure complete removal of water and to improve the material's mechanical properties [124]. Crosslinking agents can be added to improve the material's water resistance and durability which is purely dependent on the type of starch [125]. After complete drying, the material is cut into desired shapes and sizes, such as sheets or rolls. The films made through casting have less opacity [126].

5.2 | Blending

Blending technology involves the addition of additives like plasticizers, biodegradable polymers, reinforcing agents, and compatibilizers that combining starch with various additives aims to optimize the balance between mechanical strength, flexibility, thermal stability, and biodegradability, has emerged as a promising approach to enhance the mechanical, thermal, and barrier properties of starch-based materials [95]. Plasticizers can improve the flexibility and elongation of starch-based materials, reducing their brittleness [127]. The most commonly used plasticizers that disrupt the crystalline structure of starch are glycerol and sorbitol that leads to increased amorphous regions and improved mechanical properties [128]. Starch blending with other biodegradable polymers such as polylactic acid (PLA) or polyhydroxyalkanoates (PHA) enhances both the mechanical strength and biodegradability of the resulting material by forming bridges between starch and other components [129]. Reinforcing agents such as natural fibers, nanocellulose, and clay nanoparticles can be incorporated to enhance tensile strength, modulus, and thermal stability to improve the material's structural integrity by creating a network within the matrix [130]. To promote interaction and adhesion compatibilizers are included since starch and other additives often have different chemical structures, leading to poor compatibility [131].

5.3 | Extrusion

Extrusion technology is a widely used manufacturing process in the production of starch-based packaging materials. The combination of heat, shear, and additives during extrusion enhances the mechanical strength, flexibility, and barrier properties of starch-based materials, making them suitable for various packaging applications [132]. Extrusion technology can produce a wide range of starch-based packaging products, from thin films to complex three-dimensional shapes like containers and cutlery. Extrusion technology allows for continuous processing, reducing the need for multiple processing steps and minimizing material waste.

5.3.1 | Process Parameters and Material Considerations in Starch Extrusion

Extrusion technology for starch-based packaging materials demands precise control of multiple processing variables that significantly impact final product properties. Starch extrusion typically employs barrel temperature profiles from 80–180°C, with specific zones optimized for different starch sources, potato starch requires lower processing temperatures (90–120°C) than high-amylose corn starch (130–160°C) due to differences in gelatinization temperatures [133], while die temperatures between 120–140°C produce the smoothest surfaces for film applications. Research demonstrated that high-shear screw elements positioned in the compression zone significantly enhance thermoplastic starch (TPS) mechanical properties by improving plasticizer distribution, showing a 30–40% increase in tensile strength compared to standard conveying elements, with screw speeds between 150–300 rpm offering the best balance between residence time and shear-induced degradation [134]. Moisture control is critical, with cereal starches processing optimally at 18–25% moisture content and root starches requiring 22–30% moisture for complete plasticization [135], levels below 15% cause incomplete gelatinization and brittle products, while excess moisture (>35%) leads to unstable processing and poor dimensional stability. Plasticizer concentration and type significantly influence processing parameters. Glycerol, the most widely used plasticizer, is typically added at 15–40% (w/w basis starch), while combining glycerol (20%) with sorbitol (10%) reduces die pressure by 15–20% compared to using glycerol alone, enabling lower processing temperatures and reduced energy consumption [136]. However, starch extrusion faces challenges including thermal sensitivity (requiring residence times of 45–90 seconds), retrogradation (causing tensile strength to decrease by 15–25% during the first week post-processing) [137], and scale-up issues (with plasticizer efficiency dropping by 10–15% in larger extruders due to variations in heat transfer and shear distribution) [76].

5.3.2 | Process Flow in Extrusion Technology

In the starch extrusion process, raw material preparation begins with starch sourced from corn, potatoes, or cassava being combined with various additives including plasticizers, biodegradable polymers, reinforcing agents, and compatibilizers, which are carefully selected to enhance the mechanical, thermal, and barrier properties of the final starch-based material [138]. During the feeding stage, this blended mixture is introduced into the extruder's hopper, with the extruder consisting of a barrel containing a rotating screw [139]. As the mixture progresses through the barrel, the melting and mixing phase occurs where it undergoes mechanical shear and heat generated by the rotating screw, causing the starch and additives to melt and form a viscous, molten mass [139]. The shearing and homogenization stage follows, where the molten material experiences intense shearing forces from the screw's rotation, breaking down agglomerates and ensuring uniform distribution of additives throughout the starch matrix [139]. During the shaping stage, the molten mixture is forced through a die at the extruder's end, which imparts the desired form, whether film, sheet, filament, or other packaging shapes to the material as it exits [139]. The cooling and solidification phase involves rapidly cooling the shaped material using air or water to maintain its form and prevent deformation [139]. During cutting and collection, the cooled and solidified material is cut to the desired lengths or shapes using appropriate cutting mechanisms, with the resulting pieces collected for additional processing or direct use as packaging products [139].

6 | Moulding

Moulding of starch for packaging involves processing and shaping natural starch into various packaging forms using different techniques. Injection moulding adapts traditional plastic production methods for starch-based polymers by heating and injecting the material into a mould cavity under high pressure, allowing for precise formation of complex shapes like cutlery and containers [140]. Thermoforming, a cost-effective method for high-volume production, heats starch-based sheets until pliable, then shapes them using moulds to create items such as cups and food trays [141]. For hollow objects like bottles, blow moulding extrudes a parison of molten starch material and uses air pressure to inflate it within a mould, creating lightweight, durable packaging [142]. Compression moulding applies heat and pressure to starch-based material placed in a mould cavity, causing it to flow and conform to the mould shape, ideal for producing plates and shallow items [143]. Extrusion moulding continuously forces starch-based material through a die to create shapes with consistent cross-sections such as straws and tubular packaging [139]. Though less common for starch materials, rotational moulding creates large hollow items by slowly rotating a mould filled with starch-based material while applying heat, resulting in an even coating along the mould's inner surface [144]. Foam moulding incorporates foaming agents into the starch material before processing, creating lightweight products with improved insulation properties for cushioning packaging and disposable tableware [145, 146]. Hydroforming subjects starch-based material to high pressure from liquid within a mould, particularly useful for creating products with complex geometries and intricate details [147].

7 | Foaming

Foaming of starch-based packaging represents a significant area of research driven by increasing demand for sustainable, biodegradable materials, offering advantages such as reduced material usage, improved mechanical properties, and enhanced insulation capabilities [148]. Physical foaming incorporates gas into the starch matrix to create voids and reduce density, utilizing techniques like melt extrusion and injection molding with physical blowing agents that decompose or dissolve to release gas during processing, resulting in lightweight materials with improved thermal insulation [149]. Chemical foaming relies on reactions between foaming agents and the starch matrix to generate gas and expand the material, commonly using sodium bicarbonate and citric acid to produce carbon dioxide, creating foam structures with controlled expansion and good mechanical properties [150]. Thermo-mechanical extrusion combines heat and mechanical shear applied to starch and foaming agents before extrusion through a die to form foam structures suitable for packaging applications [151]. Supercritical fluid foaming utilizes fluids like carbon dioxide that are dissolved in the polymer and then rapidly depressurized, causing gas nucleation and material expansion to produce foams with fine, uniform cell structures [152]. Microwave foaming employs microwave irradiation to heat moisture within starch, generating steam and forming foam

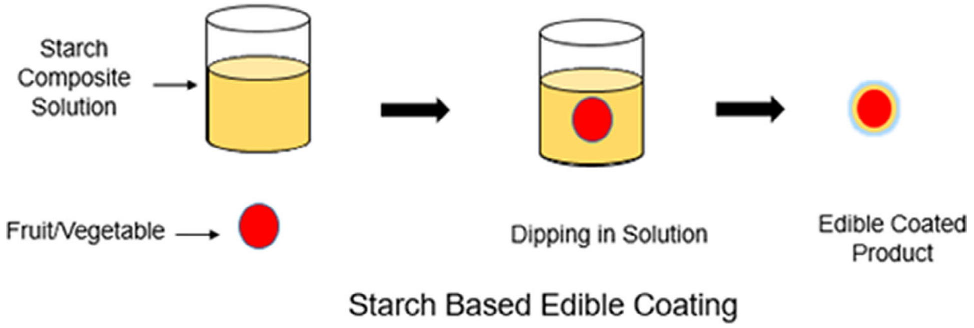

FIGURE 5 | Starch Based Edible Coating.

through a rapid, efficient process with potential for in-situ applications [153]. Physical mixing incorporates gas-producing salts into the starch matrix which, when heated, release gas and expand the material in a relatively simple, cost-effective technique [154]. Blown film extrusion produces thin foamed starch-based films by extruding material through a circular die followed by bubble expansion using air pressure, creating films for packaging and wrapping applications [155]. Compression molding compresses starch and foaming agent mixtures between heated mold plates, causing gas release and resulting in foamed products with good mechanical strength [143]. Freeze drying combines freezing and sublimation processes to create highly porous foam structures by freezing starch suspensions and removing the resulting ice crystals through sublimation [156]. Nanofoaming incorporates nanoparticles into the starch matrix to create smaller, more uniform foam cells, improving mechanical properties and thermal stability of the resulting foam [157].

8 | Starch as Packaging Material

8.1 | Starch Based Films

Starch-based films, also known as starch films or biodegradable starch films, are thin sheets or coatings made primarily from starch, a carbohydrate derived from plants such as corn, potatoes, or cassava [158]. These films are gaining acceptance as a more environmentally friendly alternative to traditional plastic films, which are often non-biodegradable and contribute to plastic pollution (Figure 5). The production of starch-based films is an area of ongoing research and development, driven by the need for sustainable and biodegradable packaging materials [159]. Starch films are used in various food packaging applications, such as wrapping fresh produce, snacks, and baked goods. These can be utilised as an alternative to single-use plastics in applications like disposable cutlery, straws, and bags [160]. While starch is an abundant and renewable resource, achieving cost-effective and scalable production of starch-based films remains a challenge [158].

One of the primary challenges in starch-based film production is achieving a balance between mechanical strength and flexibility. Starch is inherently brittle, which can lead to films that are prone to cracking and breaking. Reinforcement strategies, such as incorporating natural or synthetic polymers, nanomaterials, or fibers, can help improve mechanical properties [161]. They also have insufficient barrier properties against oxygen, water vapor, and other gases. Developing effective moisture barrier coatings or incorporating hydrophobic additives can mitigate this issue [162].

8.2 | Starch Based Nanocomposite Films

Starch-based nano-composites are materials that combine starch, a renewable and biodegradable polymer, with nano-scale particles or fillers to enhance their mechanical, thermal, and barrier properties [163]. They often use nanoparticles like clay, cellulose, or graphene to achieve these enhancements (Figure 6). Clay Nanoparticles, Nano-Calcium Carbonate and Nanocellulose are used to improve barrier properties and mechanical strength. Cellulose Nanocrystals (CNC) which are derived from plant cellulose, CNCs are biodegradable and can enhance mechanical strength and reduce water vapor permeability in starch-based films [164]. Graphene and Graphene Oxide carbon-based nanomaterials can enhance mechanical strength, barrier properties, and thermal stability in starch-based packaging [165].

These nano composites provide benefits like enhanced mechanical properties, improved barrier properties, biodegradability, improved optical Properties and thermal stability. In addition to these, specific functionalities, such as antimicrobial properties, UV protection, or enhanced printability, which can be valuable in various packaging applications. Challenges of starch-based nanocomposites include uniform nanoparticle dispersion, balancing mechanical properties, specialized processing, regulatory approval complexities, cost-effectiveness, potential environmental impact of non-biodegradable nanoparticles, maintaining consistent barrier properties, long-term stability, lack of standardization in testing, and difficulties in scaling up production. [166]. These overall offer favorable solutions for sustainable packaging, with enhanced mechanical strength, barrier properties, and biodegradability. Despite challenges in dispersion, processing, and regulation, ongoing research and collaboration hold the potential to overcome obstacles and realize their significant environmental and functional benefits.

8.3 | Starch Based Thermoplastics

Starch-based thermoplastics are innovative materials transforming packaging. Biodegradable and flexible, they replace conventional plastics with sustainable solutions. Derived from renewable sources, these thermoplastics align with eco-friendly goals,

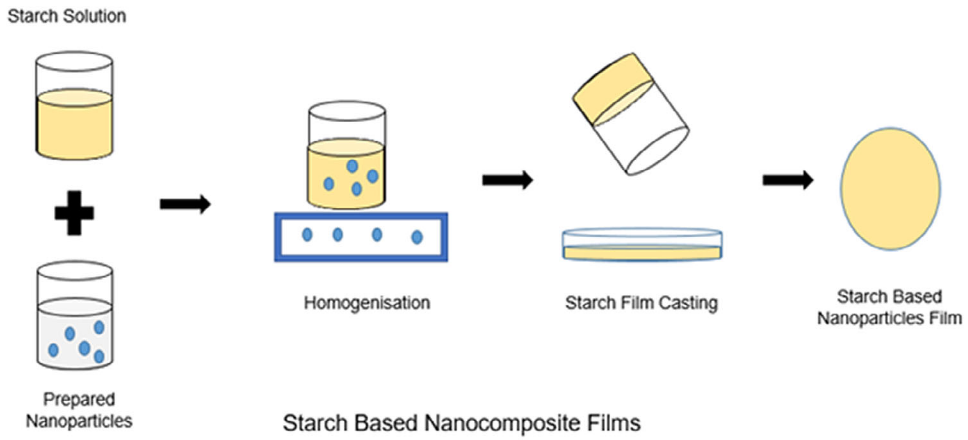

FIGURE 6 | Starch based Nanocomposite Films.

offering a promising path towards reducing plastic pollution and embracing environmentally conscious packaging practices [167]. Starch-based thermoplastics come in various types, such as thermoplastic starch (TPS), starch-based blends, and modified starch polymer TPS is derived directly from starch, while starch-based blends combine starch with other polymers for enhanced properties. Modified starch polymers undergo chemical modifications to improve their characteristics [168]. Each type offers unique advantages, contributing to a wide range of applications in industries seeking sustainable, biodegradable, and versatile packaging solutions. Starch-based thermoplastics present a notable advantage through their eco-friendly nature, offering biodegradability and a reduced carbon footprint. Derived from renewable resources, they contribute to reducing plastic waste and environmental impact [169]. However, these materials can exhibit drawbacks such as lower mechanical strength and increased sensitivity to moisture, potentially affecting shelf life and performance. Balancing these benefits with challenges is essential to harness their potential as sustainable packaging solutions while addressing limitations through ongoing research and innovation [170]. Starch-based thermoplastics hold promise as eco-friendly alternatives, mitigating plastic waste. Despite challenges, their biodegradability and renewable sourcing contribute to sustainable packaging. Recent studies have explored various additives to enhance the properties of thermoplastic starch (TPS) for food packaging applications [171]. Among these, boric acid has shown promising results as a cross-linking agent. When incorporated into TPS formulations, boric acid forms complexes with hydroxyl groups of starch molecules, creating a three-dimensional network structure that significantly improves the material's performance characteristics.

Morphological analysis through SEM reveals that boric acid (1-3%) promotes a more homogeneous and compact microstructure with reduced phase separation, resulting in smoother surfaces and fewer micro cracks in TPS films. Yoğurtçu and Gürler (2024), documented an increase in tensile strength by up to 45% and enhancement of the elastic modulus from approximately 350 MPa to 500–600 MPa, depending on plasticizer content [172]. Their stress-strain analyses demonstrated that boric acid-modified TPS exhibits a more balanced combination of strength and flexibility compared to unmodified TPS, which tends to be either too brittle or too weak.

Barrier properties also showed marked improvement with boric acid modification. Water vapour permeability is reduced by 30–40% compared to unmodified TPS, addressing one of the primary limitations of starch-based materials. Oxygen permeability decreases from approximately 40–50 $cm^3 \cdot mm/m^2 \cdot day \cdot atm$ to 15–25 $cm^3 \cdot mm/m^2 \cdot day \cdot atm$ at 50% relative humidity with the addition of 3–5% boric acid. These improved barrier properties extend potential applications to packaging products requiring moderate moisture and oxygen protection.

Optically, boric acid-modified films demonstrate higher transparency (80-90% light transmission compared to 70–75% for unmodified TPS) and reduced yellowness index, making them suitable for applications where product visibility is important. Films containing boric acid maintained their optical clarity for longer periods during storage, suggesting improved aging resistance [172].

Additionally, thermal stability increases with boric acid modification, with degradation temperatures rising by 15–20°C, which expands the processing window for these materials. Differential scanning calorimetry (DSC) analysis revealed that the glass transition temperature increased from 42°C to 58°C with 3% boric acid addition, indicating stronger intermolecular interactions within the TPS matrix.

These improvements collectively enhance the potential of boric acid-modified TPS as a sustainable alternative to conventional petroleum-based packaging materials for food applications. The cross-linking effect of boric acid effectively addresses multiple limitations of unmodified TPS without compromising its biodegradability or requiring expensive equipment or complex processing techniques.

8.3.1 | Formulations and Properties of Selected Edible Starch-Based Films

Recent developments in edible starch-based films have yielded commercially viable formulations with tailored properties for specific food applications:

Cassava Starch Films with Essential Oils Cassava starch-based edible films incorporating cinnamon essential oil (1.5–2.0% w/w) have demonstrated exceptional antimicrobial properties against common food pathogens. These films were optimized using a combination of cassava starch (4% w/v), glycerol (25% w/w starch), and Tween 80 (0.25% w/v) as an emulsifier. These films exhibit tensile strength of 12–15 MPa, elongation at break of 45–50%, and water vapour permeability of 1.5–2.0 × 10ˆ-10ˆ g * m/m^2* s * Pa. When applied to fresh strawberries, these films extended shelf life by 4–6 days at 4°C while maintaining sensory properties [173].

High-Amylose Corn Starch-Gelatin Composite Films Edible films based on high-amylose corn starch (70% amylose) blended with gelatin have shown exceptional performance for products requiring oxygen barriers. A formulation using 3% (w/v) high-amylose starch, 1% (w/v) gelatin, and citric acid (5% w/w starch) as a cross-linking agent displayed oxygen permeability values of 4.8–5.5 × 10ˆ-14ˆ cm^{3}cm/cm^{2}s*Pa, approximately 50% lower than conventional starch films. These films have been successfully applied to extend the shelf life of sliced cheeses, reducing oxidation and moisture loss during refrigerated storage [174].

Rice Starch-Based Edible Films for Fresh-Cut Fruits Rice starch offers unique advantages for edible film applications due to its small granule size and bland flavour profile. Rice starch films (3.5% w/v) incorporating calcium chloride (0.5% w/v) and ascorbic acid (0.2% w/v) effectively prevented browning in fresh-cut apples and pears [160]. These films exhibited water solubility of 45–50%, thickness of 55–65 μm, and light transmission of 85–90%, making them nearly imperceptible when applied to food products. Consumer acceptance studies showed no significant difference in taste or appearance between coated and uncoated fruit pieces during the first 7 days of refrigerated storage.

Potato Starch Films with Nanocellulose Reinforcement The incorporation of cellulose nanocrystals (CNCs) into potato starch films has created edible coatings with enhanced mechanical properties. Liu et al. [175] developed films using potato starch (4% w/v), glycerol (30% w/w starch), and CNCs (0.5–1.0% w/v). These nanocomposite films showed a remarkable 60–70% increase in tensile strength (from approximately 8 MPa to 13–14 MPa) compared to non-reinforced films, while maintaining their edibility and biodegradability. Applications in confectionery products have demonstrated their ability to prevent moisture migration between layers with different water activities.

8.4 | Starch Based Active Packaging

8.4.1 | Mechanisms and Applications of Starch-Based Freshness Indicators

Anthocyanin-Loaded Starch Films pH-responsive freshness indicators based on starch films loaded with anthocyanins extracted from red cabbage, black carrot, or butterfly pea flower respond to volatile amines released during protein degradation. These indicators undergo visible colour transitions: typically from purple/blue (pH 6–7) to pink/red (pH > 7.5) as food spoilage progresses. Chen et al. [176] developed a high-amylose corn starch film (4% w/v) incorporating butterfly pea flower extract (1% w/v) and glycerol (25% w/w starch) that demonstrated a clear colour change from deep blue to purple-pink when exposed to approximately 5–7 mg/L of total volatile basic nitrogen (TVB-N), corresponding to the early stages of fish spoilage. The visual transition enables consumers to assess freshness without opening packaging.

Starch-Based Time-Temperature Indicators (TTIs) Enzymatic TTIs based on amylase-embedded starch films provide cumulative information about temperature history. These indicators consist of α-amylase immobilized in a separate compartment that, upon activation, gradually hydrolyzes a starch-iodine complex from blue-black to colorless. The rate of this reaction is temperature-dependent, accelerating approximately 1.8–2.2 times with every 10°C increase in temperature. For refrigerated products, the indicator is calibrated to complete its colour transition after exposure to temperatures above 7°C for a cumulative period of 2–4 hours, providing clear evidence of cold chain disruption [135].

Humidity-Responsive Starch Nanocomposite Indicators For products sensitive to moisture changes, starch films containing halochromic dyes (e.g., methyl red, bromothymol blue) provide visual indication of humidity fluctuations. These indicators typically transition between colours at specific relative humidity thresholds. Cassava starch films (3% w/v) incorporated with methyl red (0.1% w/v) and montmorillonite clay (0.5% w/v) undergo a colour change from yellow to red when relative humidity increases from 60% to 80%, correlating with conditions that favour microbial growth in dry food products [177].

Gas-Sensing Starch-Based Indicators Specialized starch-based films sensitive to CO_2 or O_2 levels help monitor package integrity and product respiration. Zhang et al. [163] developed a corn starch-based film (3.5% w/v) containing methylene blue (0.08% w/v) and glucose oxidase enzyme (0.5% w/v) that changes from blue to colorless as oxygen is consumed, providing evidence of package leakage when the indicator remains blue. The reaction typically takes 4–6 hours to complete in an intact package containing fresh produce, with the rate of color change proportional to the oxygen infiltration rate in compromised packaging.

9 | Challenges of Starch Based Packaging

Starch-based materials present several significant limitations for packaging applications. They exhibit high moisture sensitivity, which leads to reduced mechanical strength, increased brittleness, and compromised barrier properties, making them unsuitable for packaging highly perishable or moisture-sensitive products [178]. Their poor thermal stability restricts use in applications requiring high-temperature processing or storage, as they may soften, deform, or degrade when exposed to elevated temperatures, limiting their suitability for microwave-safe packaging or hot-fill products [179]. These materials also tend to lack the transparency and clarity of conventional plastics, affecting consumer acceptance and aesthetic appeal of packaged products [180]. A key ethical concern is that starch sourcing from agricultural crops like corn, wheat, or potatoes potentially competes with food production, raising issues about resource allocation and food security [181]. Processing challenges arise from starch's unique properties, requiring careful optimization to avoid uneven distribution, degradation, and difficulties forming complex shapes [169]. While biodegradable, starch-based materials show significant variability in degradation rates depending on environmental conditions, composition, and processing techniques, sometimes degrading more slowly than expected and causing waste management complications [182]. Cost considerations present another barrier, as production can be more expensive than conventional plastics due to raw material costs, processing complexity, and specialized equipment requirements [183]. Compatibility with existing recycling infrastructure remains problematic, as mixing starch-based materials with traditional plastic recycling streams may cause contamination and quality reduction [184]. Performance and shelf life concerns exist due to moisture susceptibility and gas permeability affecting product quality and safety, particularly for goods with longer shelf lives [4]. The industry also suffers from a lack of standardization and regulation, leading to inconsistent quality and performance across different products [26]. Consumer perception and acceptance remain challenges, with preconceived notions about effectiveness and reliability compared to traditional plastics [185].

Starch utilization in food packaging has gained significant attention as the world grapples with the environmental challenges posed by conventional packaging materials. Starch, a natural polymer abundant in plants, holds promise as a sustainable alternative due to its biodegradability and renewability. In recent years, research and development efforts have focused on harnessing starch-based materials to create packaging solutions that balance functionality, performance, and ecological considerations [186]. One of the primary advantages of starch-based packaging lies in its biodegradability. Unlike traditional plastic packaging, which can persist in the environment for centuries, starch-based materials break down naturally into harmless compounds. This feature addresses the growing concern over plastic waste accumulation, offering a potential solution to the pollution crisis that conventional packaging materials have exacerbated [187].

Researchers have made strides in improving the mechanical properties of starch-based packaging. While pure starch films can be brittle and have limited moisture resistance, blending starch with other biopolymers or incorporating additives can enhance its flexibility, strength, and water resistance. These modifications are essential to ensure that packaging effectively protects food products and maintains their freshness, while also meeting consumer expectations for quality and convenience [188]. In addition to its mechanical properties, starch-based packaging has shown potential for controlled release applications. By incorporating active compounds such as antimicrobials, antioxidants, or flavor enhancers into the packaging matrix, researchers aim to extend the shelf life of food products and reduce the need for chemical preservatives. This innovation aligns with the consumer demand for healthier and more natural food preservation methods [189].

Despite these advancements, challenges remain in the widespread adoption of starch-based food packaging. Achieving optimal balance between mechanical strength, water resistance, and biodegradability is a complex task. The variability of starch sources, such as corn, potato, and rice, can lead to variations in material properties. Researchers are working to overcome this challenge by modifying starch at the molecular level and creating standardized processing techniques [190]. Another hurdle is the economic feasibility of large-scale production. Starch-based materials can be costlier to produce compared to conventional plastics due to factors such as raw material availability, processing complexity, and production volumes. However, as demand for sustainable packaging grows and technology advances, economies of scale could make starch-based solutions more competitive [191].

Regulatory frameworks and certifications play a crucial role in the adoption of novel packaging materials. Starch-based packaging must meet food safety and quality standards to ensure that it doesn't compromise the products it contains. Additionally, clear guidelines for disposal and composting are necessary to maximize the environmental benefits of these materials and prevent unintended consequences [192]. Collaboration across industries is vital for the successful integration of starch-based packaging into the mainstream market. Packaging manufacturers, food producers, researchers, policymakers, and consumers must collectively support the development, testing, and implementation of these solutions. Public awareness campaigns can educate consumers about the benefits and proper disposal methods for starch-based packaging, encouraging responsible consumer behavior.

10 | Conclusion

In conclusion, starch-based packaging presents a promising avenue for mitigating the environmental impact of packaging waste, offering biodegradability and renewability as key advantages. However, its path to widespread adoption has been hindered by several significant challenges. These include limitations in moisture resistance, mechanical strength, and barrier properties, which can affect product shelf life and integrity. Additionally, the higher production costs compared to conventional plastics and the need for specialized manufacturing processes have slowed commercial uptake. To overcome these obstacles and unlock the full potential of starch-based packaging, a multi-faceted approach is essential. Technological innovation is crucial for enhancing the material's performance, particularly in areas such as water resistance and tensile strength. Continued research and development efforts should focus on improving formulations, exploring novel additives, and optimizing processing techniques to address current limitations. Collaboration between academic institutions, industry partners, and government bodies can accelerate progress by pooling resources, sharing knowledge, and aligning research priorities with market needs. Such partnerships can also help in scaling up production and reducing costs through economies of scale. Furthermore, consumer education plays a vital role in driving demand for sustainable packaging solutions. Raising awareness about the environmental benefits of starch-based materials and dispelling misconceptions about their performance can foster greater acceptance and willingness to pay potential price premiums. Policy support, such as incentives for sustainable packaging adoption or regulations on single-use plastics, can create a more favourable market environment for starch-based alternatives. As these various elements converge, the potential for starch-based packaging to revolutionize the packaging industry and contribute significantly to global sustainability goals becomes increasingly attainable.

Author Contributions

Conceptualization: Siva Janika. Writing–original draft: Siva Janika and Afrin. Writing–review & editing: Yuvaraj. Visualization: Koteswara and Rahul. Project administration: Yuvaraj. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The datasets generated during the literature review process are available on request from the corresponding author.

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