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Review of the Extraction, Functionalization and Application of Starch as an Edible Coating for Postharvest Preservation

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ABSTRACT

Starch is one of the most abundant renewable polysaccharides in nature and has been widely studied as a material for edible coatings and films. Its biodegradability, low cost, film-forming capacity and consumer acceptability have positioned it as a sustainable alternative to synthetic plastics in the post-harvest preservation of food. This paper presents a review of starch as an edible coating material, tracing its chemistry, structure, extraction techniques, modification strategies, physicochemical properties, formulation principles, mechanisms of protective action and applications across food commodities. The discussion synthesizes recent studies while highlighting practical considerations for laboratory and industrial deployment. The review underscores starch's potential to extend shelf life, improve food safety, and reduce post-harvest losses, while also addressing its limitations such as moisture sensitivity and brittleness.

Keywords: Amylopectin, amylose, edible coatings, extraction, post-harvest preservation, starch

INTRODUCTION

Food spoilage and post-harvest losses remain major challenges to global food security, particularly in developing countries [1]. The Food and Agriculture Organization estimates that approximately one-third of all food produced globally is lost or wasted along the supply chain, with the highest losses occurring during post-harvest handling and storage [2, 3]. Such losses have profound socio-economic and environmental consequences, increasing production costs, reducing farmer income and contributing to greenhouse gas emissions [4]. Conventional preservation strategies such as refrigeration, waxing and synthetic packaging can slow spoilage but are often energy-intensive, environmentally unsustainable and sometimes associated with consumer safety concerns [5, 6]. These challenges have fueled growing interest in natural, biodegradable and safe preservation alternatives. Among such approaches, edible coatings and films derived from natural polymers such as polysaccharides, proteins and lipids have attracted significant attention. These coatings form thin, consumable layers on food surfaces that regulate gas and moisture transfer, reduce respiration rates, delay ripening and serve as carriers for antimicrobial and antioxidant agents [7, 8].

Among natural polymers, starch has emerged particularly as a promising material due to its abundance, low cost, non-toxicity, biodegradability and excellent film-forming ability [9-11]. Starch-based coatings have been successfully applied to a wide range of fruits, vegetables and even animal-derived products, demonstrating significant reductions in weight loss, microbial spoilage and quality deterioration [7]. This paper presents a review of starch as a material for edible coatings, beginning with its chemistry and extraction, through its modification and formulation, to its functional performance.

METHODOLOGY

This review was compiled using a systematic narrative approach. Literature was retrieved from Scopus, Web of Science, and Google Scholar databases using keywords such as "starch edible coatings," "starch films," "post-harvest preservation," and "starch modification," with emphasis on studies published from 2017 onwards. Foundational older works were also included where necessary. The selection prioritized experimental studies detailing starch extraction, composition, coating formulation, physicochemical characterization and application outcomes. Following the compilation of search results from these three databases, a stringent process of scrutiny and evaluation was undertaken. Each retrieved journal article underwent a critical and systematic review, wherein its relevance, methodological rigor, and scientific contributions were assessed. The objective was to distill a select authoritative journal articles that would form the foundation of this review.

Chemistry and Structure of Starch

Starch is a high-molecular-weight polysaccharide composed of repeating α-D-glucose units linked primarily by α-(1→4) glycosidic bonds, with α-(1→6) branch points occurring approximately every 20–30 glucose units [12, 13]. It is the primary carbohydrate reserve in many plants and is stored as discrete semi-crystalline granules in seeds, tubers and roots. Starch consists of two macromolecular fractions: amylose and amylopectin [9, 14].

Amylose is essentially linear, typically comprising 200–2000 glucose units and can form strong intermolecular hydrogen bonds, which promote dense packing and good film-forming ability [15]. It contributes to higher tensile strength and lower solubility of starch films [15]. Amylopectin is highly branched, containing short chains linked by α-(1→4) bonds and branching at α-(1→6) linkages [16]. This structure gives amylopectin-rich starches greater viscosity and gel-forming capacity but poorer film strength and higher water permeability than amylose-rich starches [15, 16].

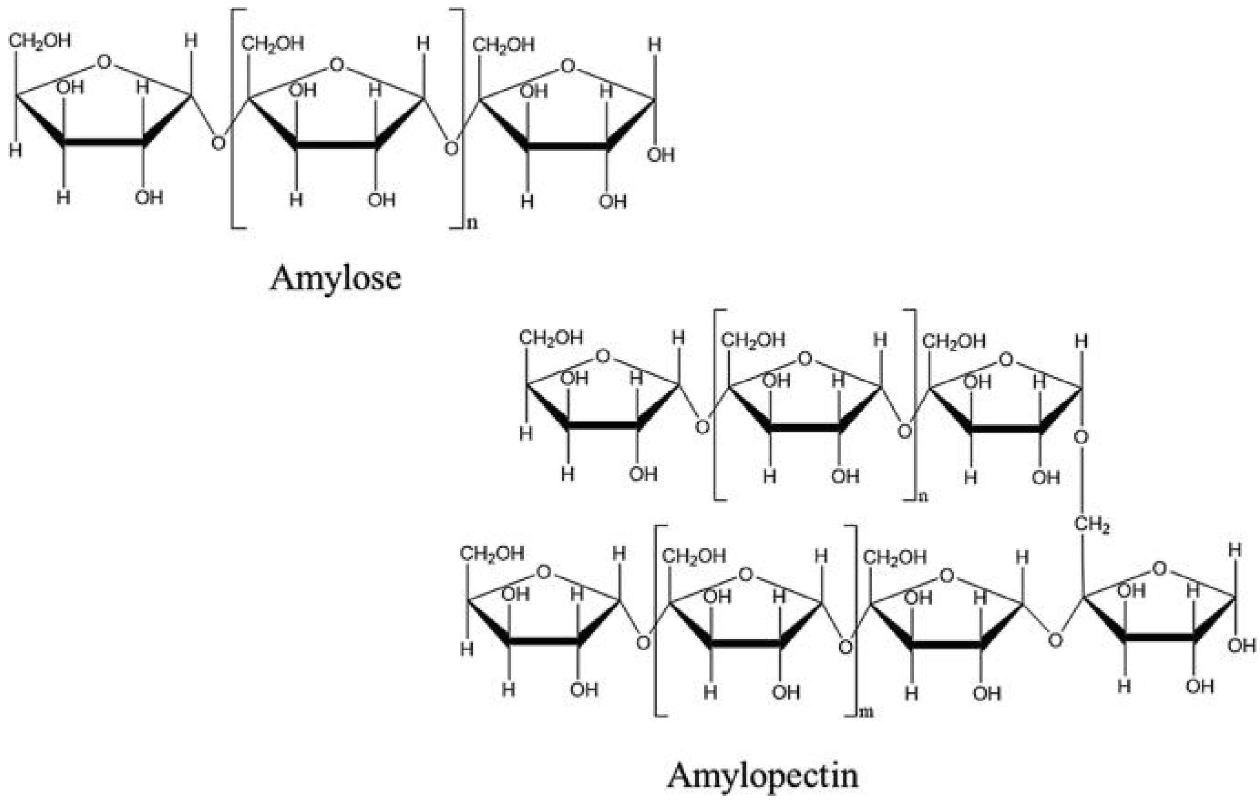

Figure 1. Structure of Starch components: amylose and amylopectin

Granule size varies from 2 to 100 μm depending on the botanical source, being small in rice and large in potato [17]. Starch exhibits alternating amorphous and crystalline lamellae [14, 18]. On heating in excess water, granules swell and lose their crystallinity in a process known as gelatinization, which releases amylose chains to form a viscous paste. Upon cooling, amylose chains can reassociate (retrogradation), affecting film properties [18]. These molecular characteristics especially the amylose/amylopectin ratio strongly influence mechanical strength, water vapor permeability and transparency, which are critical for edible coating performance [19].

Extraction of Starch

Starch is extracted from plant materials by disrupting cells to release starch granules, separating them from fibrous residues and solubles, and then drying them to a stable moisture content.

Industrial extraction from roots or tubers such as cassava and potato follows several steps: (i) washing and cleaning to remove soil and debris (ii) rasping or milling to rupture cells (iii) sieving to separate fibrous pulp from the starch suspension (iv) removal of solubles by centrifugation or hydrocyclones (v) repeated washing and refining to purify the starch (vi) dewatering using centrifugation or vacuum filtration and (vii) flash drying to about 12–15 % moisture [20].

At laboratory scale, sedimentation can replace centrifugation. After settling, the supernatant is decanted and the starch cake is washed several times before drying at 40–45 °C in a hot-air oven. The dried starch is then pulverized and stored in airtight containers. The yield and quality depend on the botanical source and processing parameters [20]. Figure 2 presents a typical summary of a starch extraction process

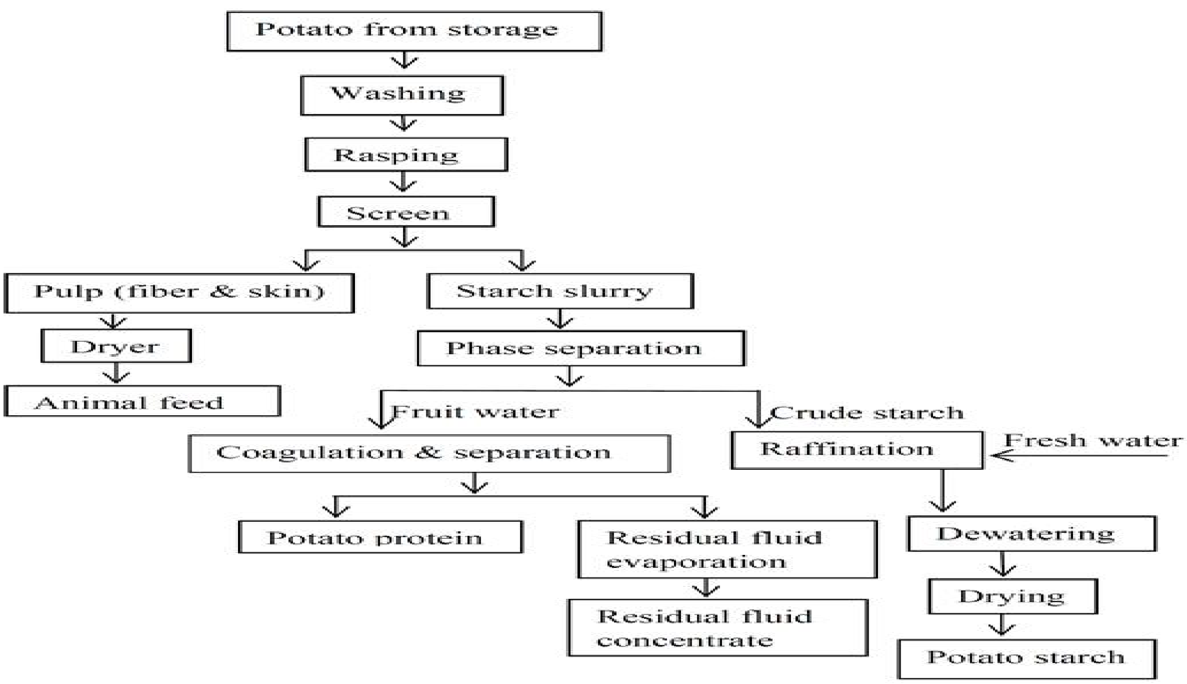

Figure 2. Typical extraction steps of starch using potatoes tuber

Preparation of Starch Edible Coatings

The preparation of starch edible coatings involves a series of critical steps, from selecting the appropriate starch source to formulating the coating solution and applying it to the food product. The production steps are summarized below

Selection of starch source

The first crucial step in preparing starch edible coatings is selecting the appropriate source of starch. Starch can be derived from various plant-based materials, including corn, rice, wheat, potatoes, and cassava. The choice of starch source may influence the coating's properties, so it should align with the specific requirements of the targeted food product [21-23].

Starch extraction

Once the starch source is chosen, the extraction process begins as detailed above.

Formulation of edible coating solution

The concentrated starch suspension must be dispersed and dissolved in a solvent such as water, alcohol, mixture of water and alcohol, or a mixture of other solvents to create an edible coating solution. The formulation may include various additives and modifiers to improve film-forming properties, stability and functionality [20]. Common additives include plasticizers (e.g., glycerol), cross-linking agents (e.g., citric acid), antimicrobial agents, antioxidants, vitamins, flavoring agents and colorants. Adjusting the pH and/or heating the solutions may be done for the specific polymer to facilitate dispersion.

Film formation

The edible coating solution is applied to the surface of the food product. There are several methods for applying the coating, including dipping, brushing, spraying, panning and immersion. The choice of application method depends on the food product's characteristics and the desired coating thickness [23].

Drying and film development

After application, the coated food product is subjected to a drying process to remove excess moisture from the coating solution. The drying temperature and duration should be carefully controlled to ensure proper film formation. The result is a thin, protective starch-based film covering the food surface.

Quality control and testing

To ensure the effectiveness of the starch edible coating, various quality control tests are conducted. These tests may include measuring film thickness, adhesion strength, moisture content, and barrier properties such as water vapor permeability [23]. The coating should meet specific quality standards to provide the desired protection to the food product.

Optimization and customization

The preparation process can be further optimized and customized to meet the specific requirements of different food products. This may involve adjusting the formulation, application methods, or drying conditions to achieve the desired coating characteristics [23].

Modification of Starch for Edible Coating Applications

Native starch films are typically brittle and hydrophilic, which limits their direct application as edible coatings. To improve their functionality, starch is often modified physically, chemically, or enzymatically.

Physical modifications such as heat–moisture treatment (HMT), annealing, and extrusion alter the crystalline structure without adding new chemical groups. HMT improves thermal stability and reduces solubility, while annealing enhances crystalline perfection and pasting stability. Extrusion under heat and shear produces thermoplastic starch suitable for casting or extrusion-based coatings [24].

Chemical modifications are widely used to tailor film properties. Acetylation and succinylation introduce hydrophobic groups, reducing water sensitivity and improving flexibility. Cross-linking with agents such as sodium trimetaphosphate (STMP) or phosphorus oxychloride ($POCl_3$) creates covalent bridges that enhance tensile strength and reduce solubility. Oxidation introduces carbonyl and carboxyl groups that improve clarity and reduce retrogradation. Such chemical treatments markedly lower water vapor permeability (WVP) and increase mechanical strength [25, 26].

Enzymatic modifications employ amylases or pullulanase to hydrolyze amylopectin branches, thereby increasing the amylose content and improving film-forming ability. Although precise and environmentally benign, enzymatic treatments are less common industrially due to higher costs [25].

Physicochemical Properties Relevant to Coating Performance

Effective starch-based coatings must exhibit balanced barrier, mechanical, optical, and thermal properties. Barrier properties are crucial for reducing water loss and respiration in coated produce. Amylose-rich starches generally produce films with lower WVP than amylopectin-rich starches, although they may be more brittle [27]. Mechanical properties such as tensile strength and elongation at break determine the coating's ability to withstand handling. Plasticizers like glycerol or sorbitol improve flexibility but can weaken films and increase WVP at high concentrations [28].

Starch coatings are typically transparent and maintain the natural appearance of produce, which is important for consumer acceptance. They must also adhere strongly to the food surface to form continuous coverage, although adhesion can be challenging on waxy fruit skins [28]. Starch films begin to degrade above 200 °C, normal storage temperatures, indicating good thermal stability [16].

Application of Starch-Based Edible Coatings

Starch plays a pivotal role as a prominent polysaccharide in the realm of edible coatings, owing to its natural abundance, cost-effectiveness, and film-forming capabilities. Starch-based coatings exhibit colorlessness, non-toxicity, a lack of taste and odor, rendering them highly suitable for edible applications [29]. They offer control over the respiratory exchange ratio of coated fruits and vegetables, thereby retarding their natural senescence and extending their shelf life. Notably, potato, corn, sweet potato, and tapioca starch are the predominant choices for edible coatings [30].

Starch-based edible coatings deliver exceptional gas barrier properties, effectively mitigating senescence and prolonging shelf life. Their robust gas permeability ratios enable precise control over respiratory exchange ratios, which proves advantageous [28]. In the context of meat and meat products, starch-based coatings have demonstrated significant benefits. They curtail browning reactions, dehydration, and oxidation, thereby preserving meat quality [29]. Plant-based starch coatings on beef have exhibited the preservation of color, pH, and enhanced antimicrobial properties [31].

The application of rice and cassava starch coatings to minimally processed pummelo has yielded reduced weight loss and a low water vapor transmission rate, significantly extending product shelf life [30]. Starch-based edible coatings, when combined with antimicrobial agents, enhance both sensory and functional attributes. These antimicrobial coatings offer distinct advantages over synthetic packaging in controlling microbial activity [21]. For minimally processed strawberries, a cassava starch edible coating has notably reduced the respiration rate, increased water vapor resistance, and enhanced sensory acceptance [21]. Incorporating lemongrass essential oil into cassava starch edible coatings for papaya MJ9 has effectively inhibited microbial growth and weight loss in papaya fruits [21, 23].

Furthermore, the application of edible coatings to tomatoes using mango kernel starch, has demonstrated the ability to delay fruit ripening and reduce tomato decay [22]. A blend of rice starch and sucrose esters as an edible coating for Cavendish bananas has shown promising results by delaying chlorophyll degradation and ethylene synthesis, extending the shelf life for up to 12 days at 20 ± 2 °C [23].

Table 1. Effect of starch-based coatings on selected food matrix

Coatings	Active agent	Food matrix	Effect	Ref
Plant-based starch	Antimicrobial	Beef	-Maintained the color and pH of meat with increased anti-microbial property.	[32]
Rice starch	Antimicrobial	Minimally processed Pummel	-Less weight loss -Low water vapor transmission rate -Extension in products shelf life	[33]
Cassava starch		Fruits and vegetables (e.g. strawberry)	-Enhanced the sensory and functional properties of coated materials -Water vapor resistance increased -Sensory acceptance increased.	[34]

Cassava starch	Anti-microbial agent (lemon-grass essential oil)	Papaya fruits	-Inhibition of microbial growth and weight loss	[35]
Mango kernel starch		`Tomatoes	-Delay in fruit ripening -Reduction in tomatoes decay.	[36]
Cassava	Fe and ascorbic acid	Pumpkin (*Cucurbita moschata)*	Higher bio-accessibility at invitro simulated lumen conditions. -Carriers of Fe (mineral) and ascorbic acid (vitamin)	[37]
Rice starch	Sucrose esters	Cavendish banana	-Delay in the degradation of chlorophyll and ethylene synthesis -Extension of shelf life up to 12 days at the 20 ± 2 ^{o}C.	[38]
Chitosan-cassava starch	Essential oils from *Lippia gracilis* mixtures	Guavas (*Psidium guajava* L.)	-Improvement in sensory impact. -Extension of shelf life	[39]
Native and acetylated corn starch	Glycerol, potassium sorbate and citric acid	Cheese samples	-Inhibition of *Candida* spp., *Penicillum* spp., *S. aureus* and *Salmonella* spp. growth. -Extension of product shelf life	[40]

			at 21% (from 14 to 17 days) regardless of pH	
Rice-flour edible starch	Poly (butylene adipate-co-terephthalate), glycerol and potassium sorbate	Fresh lasagna pasta	-Increased microbiological safety of fresh lasagna pasta. -Minimal consumption of excessive food activities.	[41]

Mechanisms of Action on Food Surfaces

Starch-based coatings act primarily as semi-permeable barriers, reducing oxygen ingress and carbon dioxide loss to slow respiration and ripening [42]. They also serve as moisture barriers that reduce transpiration and weight loss, though their hydrophilic nature means they are less effective than lipids. Additionally, they act as carriers of bioactive agents. Antimicrobials, antioxidants, and nutraceuticals incorporated into starch coatings can be slowly released to inhibit spoilage microorganisms and enzymatic browning [43]. Coatings also modify surface morphology by filling microcracks and smoothing pores, reducing the entry of pathogens. These mechanisms collectively help maintain firmness, color, flavor, and sensory quality, significantly extending the shelf life of perishable commodities.

Comparative Advantages of Starch

Starch offers several advantages over other biopolymers used in edible coatings, such as pectin, alginate, or chitosan. It is inexpensive, abundant, and widely available from various botanical sources [44]. It forms strong, coherent films, especially when rich in amylose, and is non-toxic, digestible, and recognized as safe by regulatory agencies. Starch's structure is highly amenable to physical, chemical, and enzymatic modification, allowing precise tailoring of its properties [45].

It is fully biodegradable and environmentally benign, making it a sustainable alternative to petroleum-based packaging.

Challenges and Limitations

In spite of its merits, starch-based coatings have several limitations. Their hydrophilic nature results in high water vapor permeability and susceptibility to moisture uptake, which can cause swelling, softening, and loss of mechanical integrity in humid environments [46]. Native starch films are also brittle, requiring plasticizers that can compromise strength if overused [47]. Poor adhesion on waxy fruit surfaces can cause peeling, while variability in starch composition between sources can create inconsistent performance [48, 49]. Chemical modifications improve functionality but may raise regulatory and cost concerns at industrial scale [50].

RECOMMENDATIONS

Edible coating materials must meet stringent criteria, set forth by food safety and hygiene regulatory bodies, owing to their direct contact with food. To be considered for commercialization, these materials must be designated as Generally Recognized as Safe (GRAS) by organizations like the National Agency for Food and Drugs Administration and Control (NAFDAC) and Standards Organization of Nigeria (SON) [4]. Furthermore, natural plant extracts and essential oils, even when approved, may elicit allergic reactions or exhibit toxicity depending on dosage. Regular assessments of the toxicity and allergenicity of these components are imperative.

Initiatives such as the Prime Initiative for Green Development (PIGD) have supported research aimed at developing edible coatings based on starch. These coatings are intended to enhance the shelf life and quality of packaged foods [29]. Materials used for edible coatings must be food-grade, non-toxic, and adhere to proper hygiene processing practices, following Good Manufacturing Practice (GMP) guidelines.

Edible coatings are categorized as food additives, food ingredients, or food packaging materials, as per regulations from bodies like NAFDAC, SON and the US FDA [51]. The acceptability of additives varies by country. For instance, Nigerian regulations include shellac, pectin, lecithin, fatty acids, polysorbates, arabic gums, karaya gums, and beeswax as food ingredients. The US FDA lists castor oil, cocoa butter, polydextrose, and sucrose fatty acids as food additives for edible coatings.

Chemicals used in the food industry are grouped into three categories by NAFDAC, SON, FDA, and EFSA: food coating materials (FCM), food contact articles (FCA), and food contact substances (FCS). Compliance with the Codex Alimentarius is essential for food producers, as well as adherence to regulations like no. 1935/2004 and no. 2023/2006, which govern packaging requirements and GMP for FCM.

Edible coating materials for fresh foods should use acceptable ingredients that adhere to regulations, as they are part of the edible portion of the food and must follow good manufacturing and hygienic practices. Only GRAS or FDA-approved food additives can be used as coating materials for fresh fruits and vegetables. Regulations and rules surrounding food additives and approved edible coating biopolymers may vary by country, necessitating caution when developing new materials. Biopolymers not recognized as GRAS cannot be used for edible coatings due to potential toxicity and allergenicity upon human consumption [29].

CONCLUSION

Starch is a versatile, abundant, and consumer-friendly biopolymer with great potential as an edible coating for post-harvest food preservation. Through appropriate modification and formulation, starch coatings can significantly extend the shelf life of fruits, vegetables, and animal products by reducing respiration, moisture loss, and microbial spoilage while maintaining sensory quality. Although challenges such as moisture sensitivity and brittleness remain, ongoing research in nanocomposites, bioactive coatings, sustainable starch sourcing, and surface engineering promises to overcome these barriers. With its abundance, low cost, and eco-friendly profile, starch stands poised as a cornerstone material for sustainable post-harvest preservation technologies.

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