Review Article

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# Biodegradable Packaging Polymers:- An Overview of Starch-Based Biofilms and Natural Antioxidants in Food Processing and Preservation

**Anaeke, E.J.[1], *[1]Ofoedum, A.F., [1]Uzoukwu, A.E., [1]Ezeji C.C, [1]Odimegwu, E.N., [1]Alagbaoso, S.O., [1]Eluchie, E.N., [1]Umelo, M.C., [1]Odeyemi, T.A. and [1]Ezeh, C.F.**

*[1]Department of Food Science and Technology, School of Engineering and Engineering Technology, Federal University of Technology, Owerri, Imo State, Nigeria.*

***Correspondence Author:**
Ofoedum Arinze, Department of Food Science and Technology, School of Engineering and Engineering Technology, Federal University of Technology, Owerri, Imo State, Nigeria.

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**Abstract**

*This review dives deeper into the principles of edible film production, concentrating on the role of plasticizers in enhancing flexibility and overcoming intrinsic problems with native starch films, such as poor moisture resistance, brittleness, and retrogradation. Plant-derived antioxidants such as avocado (Persea americana), ginger (Zingiber officinale), and garlic (Allium sativum) are particularly mixed into starch matrices to provide active packaging solutions. These plants include bioactive compounds such as tocopherols, carotenoids, gingerols, shogaols, allicin, and flavonoids, which have high antioxidant properties through mechanisms such as metal chelation and free radical scavenging. The increased environmental impact of standard petroleum-based plastics has prompted the development of new environmentally friendly food packaging options.*

*Starch-based edible films have emerged as a feasible biodegradable material due to its renewable nature, biodegradability, availability, low cost, and film-forming abilities. This study critically assesses the potential of starch-based biofilms and natural antioxidants as innovative food preservation and ecologically friendly packaging solutions. The structural and functional features of starch are addressed, including the roles of amylose and amylopectin, granule crystallinity, and the influence of botanical sources on film performance. In connection to film production, the physicochemical, thermal, and rheological characteristics of conventional starch sources such as maize, potatoes, and cassava, as well as underused tropical crops such as plantain and yam, are investigated. These organic extracts may boost antioxidant activity, improve barrier qualities, and extend the shelf life of food products by reducing oxidative destruction. However, difficulties with film homogeneity, lipophilic bioactive compatibility with hydrophilic starch, active chemical stability throughout processing, and potential sensory consequences must all be considered. The study shows how locally available starch sources and natural antioxidants may be used to create practical, eco-friendly packaging materials that meet the circular economy's objectives while simultaneously solving present food preservation difficulties.*

**Keywords:** Biodegradable polymers, Starch, biofilms, Antioxidants, Bioactive compounds, Packaging, Food processing and Preservation

## Introduction

### *Biopolymers for Sustainable Food Packaging: A Global Perspective*

Traditional petroleum-based plastics were invented and widely used in the middle of the twentieth century, revolutionizing the food packaging industry and ushering in an age of unprecedented efficiency, safety, and convenience. Polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) are examples of synthetic polymers that quickly became popular due to a compelling combination of desirable qualities. According to [1], these characteristics include lightweight, mechanical durability, chemical

inertness, and superior barrier capabilities against moisture, oxygen, and other environmental factors that contribute to food degradation. These characteristics have proven crucial in reducing food waste, extending the shelf life of perishable foods, and permitting the complex global supply chains that keep modern society functioning smoothly.

Nonetheless, the very qualities that made these materials so successful—their amazing resistance to deterioration and durability—have become the cause of a significant and ongoing environmental problem on a worldwide scale.

Aside from the obvious harm caused by macroplastics, microplastics pose a considerably more subtle and widespread threat. Microplastics are plastic particles having a diameter of less than 5 millimeters. These particles can enter the environment as primary particles (for example, microbeads in personal care products) or, more critically, as secondary fragments created when larger plastic items degrade over time owing to oxidation, mechanical abrasion, and photodegradation [2].

A significant shift in materials science and industrial strategy has resulted in the development and marketing of biodegradable polymers as a sustainable alternative in response to the rising environmental challenge caused by the persistence of traditional plastics. These materials represent a fundamental shift in product longevity, stressing both a safe and integrated end-of-life pathway and usable performance during usage.

According to [3], a biodegradable polymer is a compound that, given particular conditions and time periods, may be broken down into carbon dioxide, water, methane, and biomass by the enzymatic activity of microorganisms such as bacteria and fungi. The inherent sensitivity to natural biological processes instantly counteracts the recalcitrance of petroleum-based polymers.

Many concerns remain unsolved concerning starch-based films and natural antioxidants, particularly in light of Nigeria's undeveloped agricultural resources. Existing research frequently focuses on specific starches or extracts using different approaches, so meaningful comparisons are limited.

Plantain, yam, and corn starches have not been directly compared in the same conditions. There is also minimal study on combining these easily accessible carbs with natural antioxidants such as avocado, ginger, and garlic. Furthermore, much study concentrates on the final film's qualities rather than completely explaining the core parts. As a result, this study covers these gaps by providing important knowledge to help in the development of bioactive, sustainable packaging solutions, as well as the use of antioxidants in food processing and preservation.

## Biodegradable polymers: The Rise of a Sustainable Alternative

Biodegradable polymers can provide substantial environmental advantages by integrating packaging materials into organic waste management systems, lowering the amount of trash disposed of in landfills. Many of these materials are compostable, which means they may disintegrate under regulated industrial composting conditions that include high humidity, microbial activity, and temperature. This method turns packaging detritus into nutrient-rich humus, which improves soil fertility and structure while fostering the circular economy. Compostable packaging is particularly beneficial for food-contaminated materials that are difficult to recycle using standard techniques.

The majority of newly developed biodegradable polymers are bio-based, meaning they are made from renewable resources like potato starch, maize, and sugarcane rather than fossil fuels.

Bio-based polymers get their carbon from atmospheric carbon dioxide that plants absorb during photosynthesis, in contrast to traditional plastics, whose manufacturing significantly increases greenhouse gas emissions. As a result, these materials may be able to reduce their carbon footprint and help mitigate climate change.

Demand for eco-friendly packaging has grown due to growing consumer awareness of environmental sustainability, which has prompted businesses to use biodegradable substitutes as part of their corporate responsibility programs. The shift to sustainable materials is further aided by government policies such as extended producer responsibility programs, plastic fees, and limitations on single-use plastics.

Widespread adoption is hampered by a number of issues, including as increased manufacturing costs, restrictions on mechanical and barrier qualities, inadequate infrastructure for composting, and worries about using food crops to produce materials.

These issues underscore the necessity of creating second-generation fuel from non-food biomass and agricultural leftovers.

Next-generation edible and biodegradable packaging is based on natural biopolymers such as proteins, lipids, and polysaccharides. The creation of customized packaging solutions for sustainable food systems is made possible by their renewability, safety, and variety of functional qualities.

## Overview of Natural Biopolymers (Polysaccharides, Proteins, Lipids)

The most prevalent, economical, and well-studied class of biopolymers for film production are polysaccharides. They are ideal because of their strong intermolecular hydrogen bonding and outstanding film-forming capabilities. Starch is perhaps the most well-known and commercially viable

carbohydrate for this use. Biodegradable polymers provide substantial environmental advantages by integrating packaging materials into organic waste management systems, lowering the amount of trash disposed of in landfills. Many of these materials are compostable, which means they may disintegrate under regulated industrial composting conditions that include high humidity, microbial activity, and temperature. This method turns packaging detritus into nutrient-rich humus, which improves soil fertility and structure while fostering the circular economy. Compostable packaging is particularly beneficial for food-contaminated materials that are difficult to recycle using standard techniques.

Other important polysaccharides used in food packaging include alginates, carrageenans, and pectins, which are excellent gelling agents capable of forming cohesive and edible film structures; and chitosan, which is derived from the deacetylation of chitin from crustacean shells and is valued for its inherent antimicrobial and antifungal properties.

The second main type of biopolymers that form films is made up of proteins, which come from both plant and animal sources. Protein-based films are often distinguished by their remarkable mechanical qualities, which frequently show higher tensile strength and flexibility than polysaccharide films, as well as their exceptional barrier qualities against non-polar molecules including lipids, carbon dioxide, and oxygen. Soy protein isolate, maize zein, and wheat gluten are examples of plant proteins that provide sustainable and frequently less allergenic substitutes for animal proteins. For instance, wheat gluten may produce viscoelastic films with superior oxygen barrier qualities, whereas maize zein is noticeably hydrophobic and can make glossy, water-resistant coatings [4]. The main problem with the majority of protein-based films and comparable polysaccharides is that they are hydrophilic and moisture-sensitive, which can plasticize the film and impair its barrier performance.

Lipids, the third class of biopolymers, are a broad category of hydrophobic materials that include resins, fatty acids, and waxes (such as carnauba and beeswax). Lipids create less organized matrices than the highly structured polymer networks of proteins and polysaccharides. They are particularly excellent barriers against water vapor transport because of their non-polar nature [5]. This feature is crucial for applications that try to stop fresh produce from losing moisture or stop moisture from moving between ingredients in a composite food product. Lipids, on the other hand, seldom form structurally sound, freestanding films; instead, they are typically fragile, opaque, and, if swallowed, can give the tongue a waxy or greasy sensation.

As a consequence, composite systems are highly advantageous. Lipids are commonly used as a thin, continuous coating over a previously produced hydrophilic film, or as an emulsified dispersion phase with polysaccharide or protein matrices. This composite technique generates a multifunctional material by combining the lipid's excellent moisture-barrier capabilities with the hydrophilic polymer's mechanical and gas-barrier qualities [6]. By carefully choosing, altering, and combining these three classes of natural biopolymers, scientists may create a vast range of environmentally friendly packaging materials that are precisely adapted to the preservation needs of various food systems.

## Starch as a Premier Biopolymer for Edible Films

Starch has become known as a front-runner among the several natural biopolymers found as potential synthetic plastic alternatives, attracting significant attention from academic and industrial researchers. Its dominance stems from a potent combination of economic, environmental, and functional advantages. Starch, one of the world's most numerous and widely spread organic molecules, is a substantial byproduct of photosynthesis in most green plants, ensuring a consistent and stable source of feedstock. This availability, along with existing agricultural and processing infrastructures for starch-rich crops, results in a lower cost than alternative biopolymers, which is crucial for commercial viability in the price-sensitive packaging business.

Starch is an excellent fit for the circular economy concepts since it is completely biocompatible, biodegradable, and fully absorbed back into natural ecosystems [7]. Starch may naturally gelatinize and dry into a continuous, cohesive matrix, resulting in films that are usually tasteless, odorless, and clear—all of which are necessary for food packing. Because it is a major nutritional staple, it is also Generally Recognized as Safe (GRAS) for human consumption, making it an excellent material for producing edible and biodegradable films and coatings. Because of its distinct mix of affordability, versatility, and sustainability, starch is regarded as a critical biopolymer in the ongoing effort to produce the next generation of environmentally friendly food packaging solutions.

Starch is a complex polysaccharide composed of two distinct glucose polymers, amylose and amylopectin, rather than a chemically homogenous substance. The relative numbers, sizes, and structural configurations of these two macromolecules have the greatest influence on the physicochemical features of native starch granules and, as a result, their capacity to create films [8].

## Starch Structure and Composition: Amylose and Amylopectin

Amylose is a linear polymer with little branching, composed of α-D-glucopyranosyl units linked by α-(1→4) glycosidic connections. In aqueous solutions, it forms a helical structure with a molecular weight of $10^1$ to $10^1$ g/mol. Retrogradation is the process by which amylose molecules readily detach from starch granules during gelatinization and then reassociate via hydrogen bonding after the granules cool. This results in the formation of a semi-crystalline network, which produces strong but often brittle films and stiff gels.
As a result, starches with a high amylose concentration often have better oxygen and oil barrier qualities, reduced

solubility, and greater tensile strength, although they are more likely to become brittle and opaque over time.

Amylopectin, on the other hand, has a molecular weight of more than $10^1$ g/mol and is a highly branched polymer. Short α-(1→4)-linked glucose chains joined by α-(1→6) branch points make up this structure. By arranging amylopectin double helices, this intricate structure creates the semi-crystalline areas of starch granules. Amylopectin mainly contributes to granule swelling and paste viscosity during gelatinization because of its enormous size and branching design, which keeps it mostly inside the granule. By preventing excessive amylose reassociation, amylopectin improves flexibility, elasticity, and transparency in film applications.

The most significant element affecting starch functioning is the ratio of amylose to amylopectin. While waxy starches are nearly completely amylopectin, high-amylose starches may include more than 50% amylose. The majority of starches have 20–30% amylose and 70–80% amylopectin. High-amylose starches provide strong but brittle films with superior barrier qualities, while waxy starches generate transparent, flexible films with low mechanical strength.

## Starch Granule and Crystallinity Classification (A-, B-, and C-Types)

Starch granules have a semi-crystalline structure that fluctuates between crystalline and amorphous regions. X-ray diffraction patterns are used to classify starches as A-, B-, and C-type polymorphs. A-type starches, which have densely packed structures, good heat stability, and controlled swelling, are commonly found in cereals. B-type starches, which have more open structures, higher hydration, better swelling capacity, and a larger propensity for retrogradation, are frequently found in tubers. C-type starches, which combine traits of A- and B-types to offer a desirable balance between swelling behavior and heat stability for film formation, are found in legumes, roots, and some fruits.

## Sources of Starch for Film Production

The amylose-amylopectin ratio, crystallinity, granule size, form, and the presence of small non-starch components like lipids and proteins are all determined by the botanical origin of starch, which is a major factor in determining its potential for film production. These sources fall into two general categories: conventional and non-conventional.

## Traditional Sources (such as corn, potatoes, and cassava).

For many years, conventional starches have been produced commercially on a massive industrial scale and are well-characterized. They are commonly employed as benchmarks in research and development.

The most commonly used starch in the world is corn starch, which is made from maize (Zea mays). It is made up of tiny (5–25 μm), A-type crystalline polygonal granules. It is an industrial workhorse due to its reliable quality, affordability, and strong film-forming capabilities. For assessing new starch sources, films manufactured from regular maize starch are a great reference since they are clear and have good mechanical strength [9].

## Non-Conventional and Underutilized Sources (Plantain, Yam)

Unconventional or underutilized starches are derived from crops that are significant regionally and have unique functional properties, but are not yet commonly exploited in large-scale industrial starch production. These resources are particularly valuable for manufacturing high-value commodities from regional agricultural resources. Plantain starch is derived from unripe plantains or fried bananas (Musa paradisiaca).

Unripe plantains, a staple cuisine in Latin America, the Caribbean, and West and Central Africa, have a high carbohydrate content. Its granules have an irregular or oval form, are somewhat big, and have a C-type crystallinity pattern. This unique combination is a highly promising choice for producing strong yet flexible biodegradable films since it commonly produces required functional qualities such as high paste viscosity, good gel strength, and moderate retrogradation resistance [10]. Another key underutilized resource in many tropical countries is yam starch, which originates from a number of Dioscorea species (including D. rotundata in this study). Large yam starch granules feature B-type crystallinity. They usually have a high amylose content, which can aid in the development of strong, self-supporting films but also causes brittleness and rapid retrogradation [11].

In order to broaden the basis of raw materials for bioplastics and to support the economic growth of areas where these crops are plentiful, research into these non-conventional starches is essential.

## Extraction Techniques for Native Starch and their Impact on Purity

Starch extraction aims to isolate native starch granules in their purest form from the plant matrix while producing no structural or chemical modifications. The most critical non-starch components to properly remove from the process are lipids, proteins, fibers, and soluble sugars, since their presence can considerably affect the quality and functionality of the final film. Wet milling, which is based on starch granules' physical properties—namely, their high density and insolubility in cold water—is the most frequent and simple procedure, especially at the laboratory size.

The conventional wet milling technique includes a few important phases. To make a slurry, the source material must first be physically disrupted (usually by grinding or mixed with water). As a result, the starch granules were released as the plant cells broke. Second, the slurry is filtered through a succession of sieves or fine cloths to eliminate any coarse, fibrous particles.

Third, the resulting suspension is either centrifuged or allowed to sit for a few hours (sedimentation). Because starch granules are denser than water and most of the soluble pollutants, they settle to the bottom and create a compact cake. The supernatant is carefully decanted after the sugars, proteins, and minerals have been dissolved.

This cycle of washing and sedimentation is sometimes repeated many times with fresh water to get optimal cleanliness [12].

The purified starch cake is next dried at a low temperature (often 40–50°C) to reduce the moisture content without causing gelatinization, which would irreversibly destroy the original granular structure.

Leftover proteins can produce poor color (browning) and opacity in films in addition to impeding the formation of a homogenous polymer network. Lipids included in cereal starches can mix with amylose helices to form inclusion complexes. This can sometimes be helpful by postponing retrogradation, but it can also keep the granules from completely hydrating and expanding, which can affect the gelatinization process and the ultimate properties of the film [13].

Therefore, the efficiency of the extraction process in removing these components is essential.

## Key Functional and Structural Properties of Starch

Starch's use as a biopolymer for the manufacturing of biodegradable films is hampered by its basic structural and functional characteristics, rather than an inherent quality. Although the basic structure of starch is determined by its molecular composition (the ratio of amylose to amylopectin) and supramolecular structure, the macroscopic manifestation of these features influences its performance. These manifestations, which can be quantified as physicochemical, thermal, and rheological properties, control starch behavior throughout the film-forming process, from initial dispersion to final drying, determining the usefulness, stability, and quality of the resulting film matrix.

As a result, a thorough analysis of these features is necessary for both the practical manufacture of films with customized properties and the reasonable selection of a starch source.

This section covers the primary structural and functional properties of starch, the scientific ideas that underpin them, and their critical importance for the production of edible, biodegradable films. The physicochemical, thermal, and structural properties of starch have a major impact on its utility, processability, and usability for industrial applications, especially in the production of edible films and biodegradable packaging materials. These features provide important information regarding the starch's final performance, storage stability, and processing behavior. They also display the molecular composition, botanical origin, and extraction efficiency of the starch.

The behavior of natural, ungelatinized starch granules in aqueous environments is described by their physicochemical characteristics. Moisture content, pH, swelling power, and solubility are important factors. When taken as a whole, these traits function as the main markers of starch quality and aid in the explanation of its rheological and thermal reactions throughout processing.

### Moisture content

One of the most crucial aspects of starch granules' quality is their moisture content. It describes the amount of chemically bonded and physically adsorbed water that remains in the starch after drying; it is often represented as a percentage of the total weight. The usual moisture content of commercial native starches is from 10% to 14%. Because moisture content has a direct impact on processing efficiency, microbiological safety, and storage stability, it must be kept within this range.

Starch easily takes in moisture from its surroundings since it is a hygroscopic substance. Overly high moisture content raises water activity, which promotes the growth of bacteria, molds, and yeasts. In addition to decreasing product safety, microbial contamination can cause starch polymers to degrade enzymatically and lose their functionality.

In addition to causing caking, clumping, and poor flowability, high moisture content also changes the physical characteristics of starch granules, making handling, dosing, and mixing tasks more difficult in both industrial and laboratory settings. Additionally, moisture influences thermal parameters like enthalpy and gelatinization temperature by acting as a plasticizer. Thus, it is essential to keep moisture levels low and constant to guarantee the functioning, safety, and quality of starch.

### The pH of starch slurries

Another crucial measure of starch purity and processing appropriateness is the pH of starch slurries. The pH of high-purity starches is usually between 6.0 and 7.0, which is close to neutral. Variations from this range frequently point to the existence of processing chemicals or leftover contaminants. Alkaline conditions may suggest leftovers from chemicals like sodium hydroxide or sodium metabisulfite employed during processing, whereas acidic conditions may be caused by naturally occurring organic acids or microbial fermentation during extraction.

Because starch polymers are vulnerable to hydrolysis in extremely acidic or alkaline environments, particularly when heat is applied, maintaining a proper pH is essential. The glycosidic linkages that bind the glucose units in amylose and amylopectin are broken by hydrolysis, resulting in depolymerization and a decrease in molecular weight.

Starch viscosity, gelling ability, and film-forming capacity are all adversely affected by this deterioration, resulting in weak, brittle films with subpar mechanical qualities. As a result, a neutral pH is crucial for both maintaining the molecular

integrity of starch during heat processing and functioning as a purity indicator.

### Swelling power and solubility

The functional properties of swelling power and solubility, which characterize starch granules' interaction with water during heating, are intimately related. Swelling power is a measure of starch granules' ability to absorb and grow in water, whereas solubility is the amount of starch material, primarily amylose, that leaches into the surrounding medium following heating.

The inherent structure of starch granules determines these characteristics. The balance of water absorption in amorphous areas and structural resistance provided by semicrystalline sections dictates swelling behavior. Granules with disordered crystalline structures develop faster. Amylose concentration has a significant impact on solubility because expanded granules allow amylose molecules to more easily penetrate into the aqueous phase.

For the production of edible films, the optimum swelling power and solubility are essential. High swelling capacity promotes granule dislocation and the formation of viscous casting solutions, whilst enough amylose leaching aids in the production of a continuous polymer network that gives the final film structural strength. However, excessive swelling and granule disintegration can result in weak, sticky pastes that generate films with poor mechanical performance. The ideal starch therefore exhibits a balance between sufficient swelling and controlled solubilization.

### Thermal and rheological characteristics

The changes that starch goes through throughout processing are described by thermal and rheological parameters in addition to physicochemical ones. The creation and durability of starch-based films are determined by these processes, which include gelatinization, pasting, and retrogradation.

### Gelatinization and Pasting Behaviour

When starch granules are heated in the presence of water, they irreversibly change from an ordered, crystalline form to a disordered, amorphous one. This process is known as gelatinization. Water seeps into the granules during this process, breaking up crystalline areas and enabling significant swelling and amylose release. Loss of birefringence, increased viscosity, and greater susceptibility to enzymatic breakdown are all consequences of gelatinization. Each variety of starch has a unique temperature range across which gelatinization takes place, and this range is a crucial indicator of the starch's processing needs.

The viscosity changes that follow prolonged heating and mechanical shear are referred to as pasting. Viscosity rises with the swelling of starch granules until it reaches a maximum value called peak viscosity.

Granule rupture and viscosity decrease are caused by continuous heating and shear; this phenomena is known as breakdown. Increased ultimate viscosity is the consequence of starch polymers reassociating to form a gel network after cooling. The starch's propensity to retrograde is shown by the setback—the difference between the final viscosity and the minimum viscosity following breakdown.

Designing film production procedures requires an understanding of pasting behavior. While information on peak viscosity and breakdown helps improve heating and mixing parameters to minimize excessive degradation, complete gelatinization guarantees a homogenous polymer solution.

### Retrogradation and its Effects on Films and Texture

During chilling and storage, gelatinized starch molecules progressively reassemble into more ordered structures through a process known as retrogradation. There are two stages to this phenomena. Rapid amylose reassociation occurs during the first phase, which results in gel formation and adds to the starch films' initial strength. Amylopectin recrystallization occurs in the second, slower phase, gradually increasing the material's stiffness and crystallinity. Excessive recrystallization has a detrimental effect on long-term film performance, even while retrogradation improves the initial film structure. Starch films lose their mechanical durability with time as they become less flexible, more brittle, and stiffer. Transparent films may become opaque or translucent materials due to retrogradation, which can potentially alter optical characteristics. Starches with high amylose content are especially prone to retrogradation.

Plasticizers like glycerol are added to film compositions to lessen these effects and preserve flexibility by reducing polymer interactions.

Techniques for structural characterisation that disclose morphology and chemical composition are also necessary for a thorough comprehension of starch behavior. Analytical techniques including scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) offer important insights into molecular interactions, functional groups, granule surface properties, and structural organization. By clarifying the connections between starch structure and functioning, these methods enable researchers choose and process starches more effectively for particular uses.

### Edible Films and Coatings: Principles and Applications

A complex and increasingly important field of food science and technology is the creation of edible films and coatings, which directly address the dual problems of improving food quality and safety and decreasing waste from synthetic packaging. Although the terms are frequently used interchangeably, there is a small difference: an edible coating is created directly on the surface of a food product, usually by dipping, spraying, or enveloping it with a film-forming solution, while an edible film is a pre-formed, freestanding thin layer of material that can be placed on or between food components [14]. Both act as a barrier of defense between

the meal and its surroundings.

By using food-grade biopolymers to create a semi-permeable barrier that can regulate mass transfer processes such solute migration, gas penetration, and moisture exchange, these technologies extend the shelf life of food and maintain its quality. Furthermore, more complex formulations transform the packaging from a passive container into an active preservation system by acting as carriers for a range of active compounds, including flavors, nutrients, antioxidants, and antimicrobials [15].

## Concept, History, and Film-Forming Mechanisms

Many societies have used crude coating methods to preserve food for generations. Larding meats, which involves applying a coating of fat to stop moisture loss and oxidative rancidity, is one of the oldest instances. To prevent water loss and maintain freshness during storage and transportation, traders in 12th-century China coated oranges and lemons with wax [16]. However, the scientific and methodical creation of edible films and coatings did not start until the 20th century, driven by the desire to lessen food deterioration and, more recently, to lessen the environmental effect of plastic packaging.

Wax-based coatings for fresh fruit were among the first commercial uses in the 1930s, and this approach is still used today. However, biopolymer-based systems with carefully designed characteristics are the focus of current study.

A complicated physicochemical process that depends on the polymer's change from a dispersed state to an ordered, solid-state matrix is necessary for the creation of a continuous and cohesive film from a biopolymer like starch. This procedure may be broken down into a number of successive phases for starch. Initially, a suspension is created by dispersing the natural starch granules in a solvent, usually water. Second, this suspension is exposed to mechanical shear (shaking) and heated above the starch's typical gelatinization temperature. In order to cause the granules' irreversible swelling and the leaching of soluble amylose molecules into the aqueous phase, this critical stage, gelatinization, supplies the heat energy required to break the intermolecular hydrogen bonds inside the crystalline portions of the granules. As a result, the opaque suspension becomes the film-forming solution (FFS), a transparent, viscous, and uniform polymer solution [17].

The heated FFS is poured onto an inert, non-stick surface and distributed into a thin, homogeneous coating in the third phase, casting. Drying is the last and most important stage. In this stage, the cast solution's solvent—water—gradually evaporates. The scattered polymer chains are pushed closer together as the water molecules move away.

This enables the hydroxyl groups of nearby starch chains, especially the highly mobile and linear amylose molecules, to establish large new intermolecular hydrogen bonds. The solid film matrix is a continuous, three-dimensional polymer network that is produced by this process of molecule re-association and entanglement [18]. The density, homogeneity, and kind of linkages created inside this network directly affect the final film's strength, flexibility, and barrier qualities. The bigger, branching amylopectin molecules are trapped inside this network, adding to the film's bulk and affecting its flexibility, while the linear structure of amylose serves as the network's principal architect, giving it strength and coherence.

Excessive brittleness and lack of flexibility are common characteristics of native starch films, which are made entirely from the re-association of starch polymer chains. This is a direct result of the polymer chains being drawn into a densely packed, stiff, semi-crystalline structure with very little segmental mobility due to the strong and widespread intermolecular hydrogen bonding that takes place during drying. Such a film is unsuitable for the majority of packing applications since it cannot sustain even small deformations like bending or folding without breaking [19]

## The Critical Role of Plasticizers

A plasticizer is a non-volatile, low-molecular-weight material that greatly improves the flexibility, workability, and elongation at break of a polymer matrix. The internal structure of the polymer is disrupted, which is the basis of the plasticization mechanism. The tiny plasticizer molecules carefully place themselves in between the big polymer chains throughout the film-forming process. By doing this, they replace the strong, direct contacts between polymers (mostly hydrogen bonds in the case of starch) with weaker interactions between polymers and plasticizers [20]. The "free volume," or intermolecular space, inside the polymer matrix is increased by this activity. The energy barrier for segmental motion is lowered by the increased free volume and decreased intermolecular friction, hence improving the polymer chains' mobility.

This is seen macroscopically as a notable decrease in the glass transition temperature (Tg) of the material, which is the temperature at which the polymer changes from a glassy, hard state to a rubbery, more flexible state. At room temperature, a material with a lower Tg is more flexible.

The most popular plasticizers for starch-based edible films are polyols, or sugar alcohols, such sorbitol, xylitol, and glycerol. Their tiny molecular size and many hydroxyl (-OH) groups, which enable them to easily make hydrogen bonds with the hydroxyl groups on the starch polymer chains, are responsible for their effectiveness [21]. The most popular and efficient plasticizer for hydrophilic biopolymers is probably glycerol (propane-1,2,3-triol).

It effectively penetrates the polymer matrix due to its short molecular size, which results in a notable improvement in flexibility and elongation. Its strong hygroscopicity, however, can be a double-edged sword; although it keeps the film flexible, it can also weaken its water vapor barrier qualities and cause tackiness in high humidity situations [22]. Another well-liked option is sorbitol, a bigger six-carbon polyol. It is

typically seen of as a less effective plasticizer than glycerol because of its bigger size, therefore a higher concentration could be required to attain the same degree of flexibility. As a result, choosing the kind and concentration of plasticizer is a crucial optimization stage in the creation of films, necessitating a careful balancing act between obtaining the required mechanical characteristics and preserving sufficient barrier function.

### General Applications of Biofilms in Food Preservation

Edible films and coatings are a versatile platform technology with a wide range of applications designed to preserve the quality and extend the shelf life of diverse food products. Their primary function is to operate as a selectively permeable barrier, carefully controlling how food interacts with its environment. This function may be separated into many major preservation processes.

They act as a gas barrier, regulating the flow of gases including ethylene, carbon dioxide, and oxygen ($O_2$). A well-designed coating can extend the freshness and marketable life of fresh fruits and vegetables by decreasing respiration rates, delaying ripening (by minimizing ethylene exposure), and avoiding enzymatic browning [23].

An efficient oxygen barrier is essential for avoiding lipid peroxidation, which results in the production of rancid off-flavors and aromas, in foods that are vulnerable to oxidative deterioration, such as those high in unsaturated fats (such as nuts and processed meats). At low to moderate relative humidity, starch-based films are naturally effective oxygen barriers because of their highly polar nature and dense molecular packing in the dry state [24].

They also serve as a barrier against moisture. They can minimize weight loss, shrinkage, and wilting by preventing moisture loss from high-moisture foods like fresh produce and meats. They can also prevent moisture intrusion into dry, crispy products like crackers, cereals, and snack foods, maintaining their desired texture.

Third, edible coatings serve as a solute barrier that stops tastes, colors, oils, and lipids from migrating. According to [25] this is especially helpful in composite meals since it stops oil from a pizza topping from seeping into the dough or color migration between layers of a confectionary product.

Fourth, they offer a glossy, attractive look, a thin sacrificial coating that can assist preserve the structural integrity of fragile objects, and lessen surface abrasions and bruises during handling and transportation. Lastly, and probably most significantly for the creation of packaging of the future, edible films are a perfect vehicle for active substances.

The packaging becomes an active system that can release antioxidants to prevent rancidity, antimicrobials to inhibit spoilage microorganisms, or nutraceuticals to increase the food's nutritional value by directly incorporating functional compounds into the film matrix [15].

### Inherent Limitations of Native Starch-Based Films

Native starch-based films, in their unaltered condition, have a number of fundamental constraints that have traditionally prevented their widespread commercial acceptance, despite their great potential as a sustainable substitute for synthetic plastics. These disadvantages are directly related to the basic molecular structure and chemistry of the starch polymer.

The most important and difficult restriction is starch's extreme hydrophilicity. Hydroxyl (-OH) groups are abundant in the anhydroglucose units that make up the structure of both amylose and amylopectin. These groups are highly attracted to molecules of water with which they readily form hydrogen bonds. This chemical nature makes starch films highly permeable to water vapor, limiting their effectiveness in protecting foods from moisture exchange, especially in high-humidity environments. Furthermore, when a starch film comes into contact with liquid water or a high-moisture food surface, the water molecules are rapidly absorbed into the polymer matrix. This absorbed water acts as a potent plasticizer, disrupting the intermolecular hydrogen bonds between the starch chains, causing the film to swell, lose its mechanical strength, and eventually disintegrate [26, 27].

Their poor mechanical qualities, particularly their innate brittleness, are the second significant disadvantage. As previously mentioned, the film matrix is inflexible and has very little resistance to fracture due to the strong tendency of the linear amylose chains to form a closely packed, strongly hydrogen-bonded, and semi-crystalline network after drying. Native starch films cannot be stretched or flexed considerably without fracturing due to their low elongation at break values. According to [28], this renders them unsuitable for applications in which packaging must endure mechanical stresses during handling and transit or adapt to unanticipated geometries.

The amorphous polymer chains in the film matrix will reconnect and recrystallize over time.

As a result of this aging process, the film becomes brittle and may lose its transparency when light is scattered by newly formed crystalline domains, giving the appearance that it is opaque or hazy [29]. These significant disadvantages—poor moisture resistance, poor mechanical performance, and long-term instability—highlight the need to modify native starch chemically, by blending it with other biopolymers, or, as this study focuses on, by adding functional additives that can improve film properties while also providing active benefits.

### Plant Extracts as Functional Ingredients.

The addition of functional additives to biopolymer matrices is an important strategy for overcoming the disadvantages of native materials and developing "active" packaging solutions that do more than merely retain food.

A particularly interesting type of natural additions is plant-based extracts, which are intricate blends of bioactive substances derived from different plant parts (seeds, leaves, fruits, and roots). Their rich composition of compounds that can impart a wide range of functionalities, most notably antioxidant and antimicrobial properties, and their natural origin, which corresponds with the growing consumer demand for "clean-label" and minimally processed foods, are what make them appealing [30].

## The Role of Natural Antioxidants in Food Preservation

Even at low doses, antioxidants have the ability to considerably slow down or stop this oxidative process. They work by disrupting the oxidation chain reaction, usually by neutralizing free radicals or deactivating molecules that are pro-oxidants. The food industry used synthetic antioxidants including tert-butylhydroquinone (TBHQ), butylated hydroxyanisole (BHA), and butylated hydroxytoluene (BHT) for many years. Despite their great efficacy, regulatory scrutiny and consumer resistance have increased due to worries about their synthetic origin and possible long-term health repercussions [31]. Research and development aimed at finding and using powerful antioxidants from natural sources has increased dramatically as a result.

## Key Bioactive Compounds in Selected Plant Sources

It has been demonstrated that plant extracts from fruits, vegetables, herbs, and spices are remarkably rich in these protective chemicals, providing a safe, efficient, and consumer-friendly substitute for their synthetic equivalents for maintaining food quality and increasing shelf life.

A plant extract's antioxidant capability results from the complex synergistic effect of a wide range of bioactive chemicals rather than from a single molecule. These chemicals' particular profile varies according on the plant species, variety, and extraction technique.

## Avocado (*Persea americana*): Tocopherols, Carotenoids, and Phenolic Compounds

Many lipophilic and hydrophilic antioxidant chemicals may be found in abundance in avocado fruit, especially in its oil. Tocopherols are potent antioxidants that break chains and shield cell membranes from lipid peroxidation. α-tocopherol is the major type found in avocados [32]. Carotenoids, including lutein and β-carotene, are abundant in avocado and are well-known for their capacity to quench singlet oxygen, a highly reactive type of oxygen that can cause oxidative damage. Additionally, the avocado's pulp and peel are rich in phenolic compounds, such as flavonoids and phenolic acids, which are strong metal chelators and free radical scavengers [33].

## Ginger (*Zingiber officinale*): Gingerols, Shogaols, and Zingerone

Ginger's rich spectrum of phenolic chemicals is primarily responsible for the rhizome's well-known strong taste and widespread usage in traditional medicine. The gingerols, of which -gingerol is the most prevalent in fresh ginger, are the main bioactive components responsible for its strong antioxidant activity. Because of the phenolic hydroxyl group in their structure, gingerols are potent free radical scavengers. Gingerols can undergo a dehydration reaction during heat processing or drying to produce shogaols, which have been demonstrated in some test systems to have even greater antioxidant activity [34, 35]. The total antioxidant potential of ginger extracts is additionally enhanced by zingerone, a similar substance that is produced when gingerols break down.

## Garlic (*Allium sativum*): Organosulfur Compounds (Allicin) and Flavonoids

Organosulfur compounds are a special family of bioactive chemicals that give garlic its distinctive strong scent and potent biological effects. The primary sulfur-containing substance in an undamaged garlic clove is alliin, a stable, odorless amino acid. An enzyme called alliinase, which is kept in distinct compartments, is produced when the clove is crushed, chopped, or harmed. Alliinase quickly transforms alliin into allicin, the extremely unstable and reactive substance that gives fresh garlic its strong biological effects and aroma [36]. Strong antioxidants that may scavenge a wide range of free radicals include allicin itself and its transformation products, such as diallylsulfide (DAS), diallyldisulfide (DADS), and ajoene [37].

## Mechanisms of Antioxidant Action in Food Systems

Primary (chain-breaking) and secondary (preventative) processes are the two basic categories into which natural antioxidants may be roughly categorized.

The efficacy of a plant extract often stems from its ability to act via multiple mechanisms simultaneously.

## Free Radical Scavenging

This is the most important primary mechanism of antioxidant action. Lipid peroxidation proceeds via a free radical chain reaction that consists of three stages: initiation, propagation, and termination. The propagation stage is a self-sustaining cycle where a lipid radical reacts with oxygen to form a peroxyl radical which then abstracts a hydrogen atom from another lipid molecule (LH) to form a hydroperoxide (LOOH) and a new lipid radical.

## Metal Chelation

This is an important preventive or secondary mechanism. Transition metal ions, especially iron ($Fe^{2+}$) and copper ($Cu^{+}$), have pro-oxidant properties and promote lipid oxidation. These metals can catalyze the Fenton reaction, which transforms pre-existing lipid hydroperoxides (LOOH) to highly reactive alkoxyl (LO•) and peroxyl (LOO•) radicals. According to [38], this creates a new supply of radicals that can start new oxidation chains. Many naturally occurring antioxidant chemicals, such as flavonoids and phenolic acids found in plant extracts, are efficient metal chelators. They have chemical structures that may "chelate" or bind to metal ions, forming stable, inactive complexes such as ortho-dihydroxyphenyl or catechol groups.

## Standard Methods for Evaluating Antioxidant Capacity

### DPPH Radical Scavenging Assay

One of the most popular and simple techniques for figuring out a sample's capacity to scavenge free radicals is the 2,2-diphenyl-1-picrylhydrazyl (DPPH) test. The stable DPPH radical, which has a significant absorbance maximum at around 517 nm and a deep violet hue in solution, forms the basis of the test. The radical is reduced to its non-radical state, DPPH-H (2,2-diphenyl-1-picrylhydrazine), when an antioxidant chemical capable of donating a hydrogen atom is introduced to the DPPH solution. The stoichiometric loss of the violet hue that results from this reduction process is tracked as a drop in absorbance. The antioxidant's capacity to scavenge radicals is directly correlated with the degree of discolouration [39].

The $IC•_0$ value, which is the extract concentration needed to scavenge 50% of the initial DPPH• radicals, is frequently used to represent the results. Higher antioxidant activity is indicated by a lower $IC•_0$ value.

### Ferric Reducing Antioxidant Power (FRAP) Assay

The FRAP test measures a sample's reducing power rather than directly measuring radical scavenging. The idea is based on the fact that antioxidants can use a redox-linked colorimetric process to convert the ferric ion ($Fe^{3+}$) to the ferrous ion ($Fe^{2+}$). The colorless compound of $Fe^{3+}$ and 2,4,6-tripyridyl-s-triazine (TPTZ) is present in the FRAP reagent. To preserve iron solubility, the test is carried out at an acidic pH of 3.6.

The $Fe^{3+}$-TPTZ combination is reduced to the $Fe^{2+}$-TPTZ complex in the presence of an antioxidant that can function as a reducing agent. This complex exhibits a strong blue hue with a maximum absorbance at 593 nm. The overall reducing capacity of the antioxidants in the sample is directly correlated with the decrease in absorbance [40].The findings are usually presented as molar equivalents of the standard per unit of sample and are computed by comparison to a standard curve made using a known antioxidant, such FeSO4 or Trolox.

### ABTS Radical Cation Decolorization Assay

Another widely used technique for determining radical scavenging capability is the 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) test. By reacting ABTS with a strong oxidizing agent, like potassium persulfate, the test creates the ABTS radical cation ($ABTS•^+$). A long-lived radical with a distinctive blue-green hue and a maximum absorbance at around 734 nm is produced by this reaction. When an antioxidant is added to the solution, it neutralizes the $ABTS•^+$ and causes a quick loss of color by giving it either an electron or a hydrogen atom. According to [41], the degree of decolorization is related to the quantity of antioxidants and is evaluated as a drop in absorbance.

The adaptability of the ABTS assay is one of its main advantages. The test can evaluate the antioxidant activity of both hydrophilic and lipophilic substances since the ABTS radical is soluble in both organic and aqueous solvents. Furthermore, compared to the FRAP test, its reactivity is less impacted by pH. Trolox Equivalent Antioxidant Capacity (TEAC), which compares the sample's activity to that of Trolox, a water-soluble analog of vitamin E, is a standard way to present the results.

## Incorporation of Antioxidants into Starch-Based Films: Towards Active Packaging

The development of intelligent and active systems is replacing the conventional paradigm of passive confinement in the field of food packaging research. Active packaging is designed to carry out particular, dynamic functions beyond this inert role, actively improving the quality, safety, and shelf life of the enclosed food product, since the primary job of packaging is to provide a physical barrier. A key component of this shift is the addition of natural antioxidants to starch-based films, which is a calculated move to turn a straightforward biodegradable matrix into a useful, value-added preservation solution.

Conventional or "passive" food packaging is made to be as inert as possible, acting just as a physical barrier to shield food from outside pollutants while keeping the product contained for convenience of handling and transportation. Active packaging, on the other hand, is purposefully made to interact with food or headspace inside the container in order to enhance product condition and prolong shelf life [42]. This is accomplished by adding active ingredients to the packaging material itself, which may either scavenge unwanted compounds from the package environment or release good molecules into the food.

Systems for active packaging can be divided into groups according on how they work. Oxygen scavengers, carbon dioxide scavengers or emitters, ethylene scavengers, and moisture absorbers are examples of scavenging systems that eliminate undesirable molecules from the package [43]. On the other hand, releasing systems release active substances either directly onto the food surface or into the packaging headspace. This area comprises the release of tastes or scents, antioxidants to stop oxidative degradation, and antimicrobials.

According to [44], an antioxidant-active packaging system prevents lipid, vitamin, and pigment degradation by allowing antioxidant compounds integrated into the polymer matrix to migrate to the food surface or package headspace in a controlled manner, intercepting and neutralizing free radicals. This method outperforms adding antioxidants to food because it provides ongoing protection at the food-package interface. This may allow for lower additive doses while increasing efficacy over the product's shelf life.

When plant-based extracts are added to the starch film matrix, the physicochemical, mechanical, barrier, and sensory characteristics of the resulting composite material change significantly. The interactions between the hydrophilic starch polymer, extract, plasticizer, and water shape the enriched

film's ultimate characteristics.

Antioxidant extracts include phenolic chemicals with hydroxyl groups that can create hydrogen bonds with starch polymer chains. This can have a reinforcing effect, making the polymer network more cohesive and stiff, which frequently leads to higher tensile strength but lower flexibility [45]. On the other hand, a variety of extracts, especially essential oils or substances with tiny, movable molecules, can function as plasticizers by sandwiching themselves between starch chains and rupturing hydrogen bonds between polymers. Increased polymer mobility results in more flexible films with higher elongation at break and lower tensile strength [46, 47].

Another important factor to take into account is how extracts affect barrier characteristics. By decreasing film hydrophilicity and producing a more convoluted channel for water diffusion, lipophilic extracts—like avocado oil or essential oils—can enhance moisture resistance by lowering water vapor permeability [48]. Nevertheless, phase separation brought on by inadequate dispersion or high extract concentrations might result in structural flaws that raise permeability [49]. It affects oxygen permeability in a more sophisticated way. The addition of additives can disturb the tight hydrogen-bonded structure of starch films, increasing free volume and opening up channels for gas passage, putting oxygen barrier properties at risk [50].

The usage of plant extracts also has an influence on optical and sensory properties. Many extracts contain pigments such chlorophylls, carotenoids, and anthocyanins, which give films color while reducing transparency [6].

Antioxidant-rich plants contain strong odors and scents that can transfer from packaging film to food, causing unpleasant off-flavors and restricting commercial usefulness [51].

Formulations must establish a balance between sensory appeal and antioxidant efficacy.

To generate stable and efficient antioxidant-enriched starch films, a variety of scientific and technological difficulties must be addressed.

The first step is to ensure that lipophilic antioxidant compounds and the hydrophilic starch matrix are compatible and homogeneous. Direct mixing often leads in phase separation and heterogeneous film forms with poor mechanical and barrier properties [52].

Maintaining the stability of bioactive substances when making films presents a second difficulty. Numerous natural antioxidants can break down during the drying and gelatinization of starch because they are susceptible to heat, air, and light [53]. Therefore, it is necessary to adjust processing conditions or use protective techniques like microencapsulation.

## Previous Studies on Starch-Based Edible Films

With a large body of literature devoted to defining starches from various sources and improving their characteristics by the addition of various additives, the topic of starch-based edible films is an established and extremely active area of study. The main conclusions from earlier research are summarized in this section, with an initial emphasis on studies pertaining to the particular starch sources being studied (plantain, yam, and maize), followed by studies that have investigated the incorporation of natural antioxidant extracts.

## Studies on Films from Plantain, Yam, and Corn Starch

Because of its commercial significance and well-established qualities, corn starch has long been used as the standard material in starch film research. When the right plasticizer is employed, it may generate clear, homogeneous films with outstanding mechanical strength and excellent oxygen barrier qualities, according to several studies. For instance, glycerol-plasticized maize starch films were comprehensively studied in a research by [54] who reported tensile strength values in the range of 3–6 MPa and demonstrated their efficacy as a gas barrier. In order to produce nanocomposite films with better barrier and mechanical performance, a large portion of current research on maize starch has concentrated on overcoming its hydrophilicity by mixing it with other polymers or adding nanoparticles [55].

Driven by the aim to add value to local agricultural goods, research on films from underused tropical sources, such as yam and plantain, has acquired substantial impetus. Research on plantain starch films has repeatedly shown how promising they may be. In contrast to films generated from cassava starch, another important tropical source, [56] successfully created films from plantain starch and discovered that these films had reduced water vapor permeability and higher tensile strength. The qualities of plantain starch films plasticized with glycerol were further investigated by [57], who noted their strong film-forming ability and mechanical integrity, proving their usefulness as a biopolymer foundation.

Extensive research has also been done on yam starch films. Studies have frequently observed that yam starch films have great tensile strength but suffer from severe brittleness and a strong tendency to regress because to the starch's generally high amylose concentration. [58] characterized films from several yam species and found that although they were sturdy, they needed to be plasticized and frequently exhibited symptoms of becoming opaque and brittle over time. Therefore, a large portion of the research in this field has been on methods to lessen these disadvantages, such as combining yam starch with more flexible polymers or employing various plasticizers to prevent retrogradation and enhance long-term stability [59]. Together, these investigations demonstrate that although all three starches are effective film-formers, their structural variations result in different property profiles, supporting the direct

comparison analysis suggested in this study.

## Studies on Starch Films Incorporated with Natural Antioxidant Extracts

Numerous studies have shown the viability and advantages of incorporating antioxidant extracts into starch films, making this a thriving and quickly growing field of study. Numerous extracts have been studied. For instance, [47] added catechin-rich green tea extract to corn starch films. They discovered that the extract greatly improved the film's UV light-barrier qualities and antioxidant activity as determined by the DPPH experiment. It's interesting to note that the extract increased the film's tensile strength by acting as a reinforcing agent.

Research using the particular extracts suggested for this study has also shown encouraging findings. For example, [60] showed that adding garlic extract to polyvinyl alcohol films—a synthetic substitute for starch in some studies—produced films with potent antimicrobial and antioxidant properties that significantly increased the shelf life of packaged chicken meat. A comparable outcome has been shown in studies with ginger extract. [61] discovered that adding ginger essential oil to starch-based films dramatically boosted antioxidant capacity while decreasing water vapor permeability due to the oil's hydrophobic properties.

Avocado oil's high tocopherol content and lipophilic nature indicate a strong potential for it to confer antioxidant activity while also improving the film's moisture barrier properties, an area ripe for further research, despite the fact that less research has been conducted on its specific antioxidant properties in films. These findings create a strong precedent, confirming the intended study's capacity to yield significant new data in this field and establishing that employing such extracts is a viable technique for designing functional, active packaging materials.

## Conclusion

This study shows that starch-based edible films derived from agricultural resources are a potential and ecologically friendly replacement due to their biodegradability, renewability, edibility, and universal availability. Starch films' functional performance is heavily impacted by their chemical composition, botanical origin, and structural qualities, notably their crystalline properties and amylose-to-amylopectin ratios.

Starch-based edible films are tempting sustainable alternatives to traditional petroleum-based polymers because of their biodegradability, renewability, edibility, and better film-forming capabilities. However, native starch films are restricted by low moisture resistance, brittleness, and retrogradation susceptibility, necessitating formulation modifications.

Plasticizers and naturally occurring antioxidant-rich plant extracts such as avocado, ginger, and garlic are utilized to improve the mechanical, barrier, and functional qualities of starch films, as well as provide active packaging advantages. By scavenging free radicals and chelating metals, these bioactive chemicals help to improve food shelf life and prevent oxidation. Despite hurdles like as stability, compatibility, and sensory impact, more research and technological advancements can help commercialize starch-based active packaging, therefore supporting circular economy aims, decreasing plastic waste, and boosting sustainable food preservation systems.

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