Discover Food

Review

An overview: exploring the potential of fruit and vegetable waste and by-products in food biodegradable packaging

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Abstract
Food waste and by-products negatively impact the environment, economy, and society. One solution to this issue is repurposing this waste by creating food packaging materials. Packaging is safe for food, but using non-biodegradable materials, including microplastics, has led to pollution. The food industry generates substantial amounts of waste that creates environmental concerns. Edible and functional food packaging, crafted from food waste and natural materials, presents a sustainable approach by reducing waste and plastic usage. These edible materials are consumed with food, reducing disposal and environmental impact. This manuscript explores the potential uses of biopolymers, packaging, and edible films and coatings As alternatives to traditional food packaging. By-products of fruits are valuable food waste, often discarded despite containing beneficial compounds like polyphenols, vitamins, and minerals. This review focuses on recent research using vegetable and fruit waste to improve packaging systems, antioxidant, physical, and mechanical properties, and antimicrobial features; advancements in synthetic and biobased films enhanced with by-product compounds; and their role in biodegradable food packaging.

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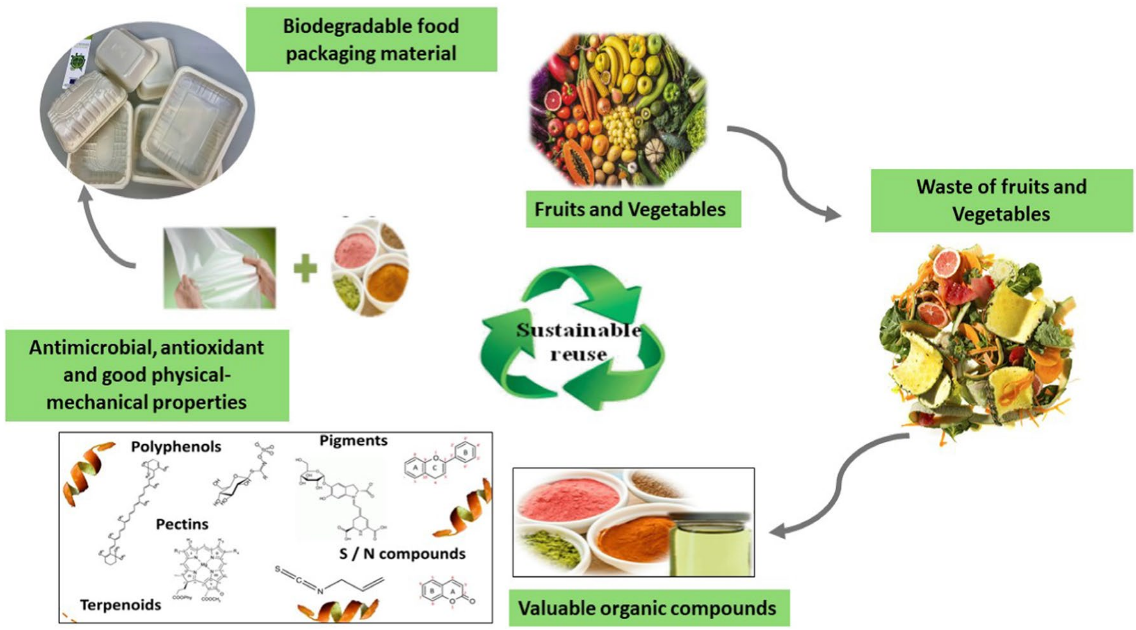
Graphical Abstract



Keywords Biopolymers · Fruit and vegetable by-products · Biodegradable packaging · Edible films and coatings · Food waste

1 Introduction

The worldwide food industries produce significant amounts of waste and by-products, mostly from fruits and vegetables [1]. These waste materials possess the unused potential for utilization in food packaging because of their organic compounds. Food waste and products negatively impact the environment, economy, and society. According to the Food and Agriculture Organization, global food loss and waste are continuously rising, with an estimated $400 billion units of food wasted annually [2].

This wastage costs food and reduces vital capital like water, land, and energy. There is a global consensus on the urgency of addressing this issue. Governments, including the European Union (EU), recognize its seriousness and advocate for strategic measures to combat food waste; waste legislation and addressing food waste offers opportunities to lower production costs and improve food system efficiency [3]. Fruit and vegetable waste have bioactive compounds that create eco-friendly, sustainable packaging with versatile polymers. However, for practical food waste-based packaging, upcoming research should address key aspects like cost, scalability, moisture resistance, mechanical strength, regulations, and consumer approval [4].

Mostly, the food sector prioritizes preventing and reducing food waste because it's a key aspect of achieving a circular economy that involves waste valorization of by-products, where waste materials transfer into valuable goods like fuels, materials, and chemicals. Repurpose of food waste involves generating value-added products that find applications in diverse sectors, including animal feed, biofuels, organic fertilizers, and energy production [5, 6].

In the last decade, extensive research has been done into using food residues to create food ingredients. These food waste products have organic compounds like polyphenols, dietary fiber proteins, vitamins, lipids, and food waste, which can offer health benefits. These compounds can improve food products' nutritional, functional, and technological quality [7, 8].

Recent research has found that incorporating natural materials from waste and by-products into food packaging technologies effectively decreases food waste and related goods. This strategy demonstrates a proactive approach to improving waste utilization regarding environmental sustainability [1, 9]. Food waste refers to the edible portions of food discarded or lost at different supply chain stages, from harvesting to processing, distribution, and consumption. This wastage can occur due to inadequate storage facilities, transportation issues, suboptimal processing methods, and consumer behaviour [10].

Biodegradable packaging material made from food by-products improves packaging film qualities and prolongs the shelf life and quality of food products. These by-products also facilitate the creation of eco-friendly, biodegradable packaging with positive attributes like recyclability and safety [4]. Roots, tubers, and other fruit and vegetable by-products comprise a substantial portion of waste, about 40–50% of discarded materials. Around 10–35% of unprocessed fruits and vegetables, including seeds, pulp, skin, and pomace, are commonly discarded as by-products [11, 12].

Industrial processes mostly produce these byproducts, such as grapes in wine, olive pomace in oil production, and products derived from various fruit varieties used in the juice, jam, and jelly industries. Furthermore, processing vegetables, including potatoes, tomatoes, fennels, artichokes, and carrots, also adds to this by-product [13]. Food by-products have natural bioactive compounds, including sugars, pectin, fibers, polysaccharides, and essential bioactive molecules like tocopherols, flavonoids, carotenoids, vitamins, and aromatic compounds that have good antioxidant value and antiviral properties, making them beneficial for human nutrition [14, 15].

Recently, researchers have increasingly determined to utilize fruit and vegetable by-products as diet components such as food enrichment by incorporating fruit by-products, cereal-based, and dairy foods [16, 17] enhanced with powder attained, commencing these leftover food materials to improve their nutritional values. Represents various uses of vegetable waste enriched to cereal-based [18–20] fish and dairy-based goods [21–24].

This review explores the utilization of by-products in food packaging materials to reduce global microplastic contamination. Adding antioxidant compounds from food waste to packaging materials can make food items safer and more durable, preventing spoilage. The review highlights new research on such functional packaging material and its benefits. It focuses on using industrial food waste to improve and emphasize the impact of by-product extracts on film performance and biodegradable packaging.

2 Organic compounds of vegetable and fruit byproducts

Vegetable and Fruit by-products contain beneficial compounds like phenolics and carotenoids that contribute to their antioxidant and antimicrobial properties against foodborne pathogens and spoilage. The residues of fruits and vegetables have phytochemical substances that offer diverse health advantages, such as antibacterial, antidiabetic, cardioprotective, antioxidant, anti-inflammatory, and anti-carcinogenic properties [25].

Pomegranate and grape byproducts, particularly rich in phenolics and antioxidants, are extensively used in various foods. Adding these byproducts to food enhances bioactive compounds and dietary fiber for reducing oxidation and microbial growth. Sensory outcomes depend on quantity, byproduct form, and food composition [26]. Re-integrating these byproducts into the food supply chain addresses environmental and economic concerns. This advantage, coupled with valuable components, likely increases consumer acceptance. However, most studies neglect to evaluate these new products' toxicity, in vivo effects, and bioavailability, which are essential to validate their safety and potential health benefits [27]. The foods that go to waste the most are roots, tubers, and oilseeds, which comprise about 25% of all vegetables and Fruits, with 21% of all food consumption. Cereals and pulses closely follow, contributing 14% to dietary intake [28].

Food production industries produce 40–50% of plant waste and byproducts. These byproducts include peels, skins, shells, roots, branches, stones, and seeds of different vegetables and fruits [29]. Mangoes generate the highest waste among all fruit and vegetable types, accounting for 60%, citrus fruits at 50%, fury fruit at 45%, ananas at 33%, pomegranates at 40%, and legumes at 40%. Furthermore, bananas, apples, grapes, potatoes, and tomatoes contribute to waste production [30, 31]. Fruits like (banana, mango, apple) peel, and grape pomace are notable for their high dietary fiber content, ranging from 51 to 70% [32], and tomato and carrot pomace are also rich in fiber, with levels reaching 50% to 64%, respectively [31].

The phenolic compounds concentration depends on the individual part of the material; in the case of avocado fruit, the peel contains a higher concentration of phenolic compounds than the seed and pulp [33]. The skins and seeds of fruits and vegetables are abundant sources of bioactive compounds. The total phenolic content in mango peel was significantly higher (in peel 92.6 in flesh 27.8 mg GAE/g) both in ripened and undeveloped stages [34].

The detection of phenolic compounds, especially trigonelline, in the skins and seeds of purple passion fruit, as well as their antioxidant properties, suggests that these by-products may be suitable for your health and have been used in biotechnology for different industries and research institutions, with the seeds being the main focus [35]. Date palms have significant yield losses during the harvesting, storage, and conditioning stages, accounting for around 30% of the total output. Given the large quantity of second-grade dates and non-edible components harvested simultaneously, it is profitable for farmers and the food industry to capitalize on this by-product by incorporating its nutritional benefits into high-value goods [36]. Table 1 displays elevated concentrations of bioactive composites attained from a waste of fruits and vegetables.

3 Biodegradable materials from fruit and vegetable residues

To produce environmentally friendly and degradable films and coatings, it's crucial to choose suitable components. Polysaccharides like starch, pectin, chitosan, cellulose, alginates, and biodegradable proteins like gelatin, whey protein, casein, and gluten are ideal options [49]. Additionally, incorporating lipids such as oils and waxes enhances the effectiveness and eco-friendliness of these materials [50, 51].

Biopolymer-based biodegradable packaging materials have grown significant interest as a sustainable alternative to non-degradable packaging materials [52, 53]. Polymers are degraded through enzymatic hydrolysis and reactions catalyzed by enzymes, breaking the polymer into smaller components and other chemical reactions [54]. When conditions are appropriate, microbial activity breaks down biodegradable polymers into innocuous by-products like water, carbon dioxide, and biomass. This sustainability distinguishes them from traditional plastics, which may survive for periods [55].

As shown in Fig. 1, the classification of polymers is determined by their origin from Natural, Synthetic, and Microbial fermentation. These materials display some advantages, such as sustainable development, biodegradability, biocompatibility, environmental friendliness, and reduction of carbon emissions, which are also listed in Fig. 2 [54, 56]

The incorporation of biopolymer packaging film offers numerous benefits within the food industry. This film is suitable for its non-toxic properties and effective control over water vapor, oxygen, and fat passage within food products. Crucial for maintaining food quality and prolonging shelf life, biopolymer packaging films have increased agricultural product markets [57].

Moreover, biodegradable polymers facilitate the conveyance of active functional elements like antimicrobials, antioxidants, and nutrients, representing the foremost advantage of utilizing biopolymers [58]. Conversely, most biodegradable polymers exhibit hydrophilic characteristics, producing low moisture or water vapour resistance. Additionally, their melting point often approaches their combustion point, leading to compact processing competencies and constraining their potential for industrial applications [57].

For the processing of fruits and vegetables, rich reservoirs of valuable and nutritious substances are derived; these byproducts are used as biodegradable biopolymers in multiple applications, enhancing artificial materials by incorporating biologically active compounds and additional nutrients into food products [59]. During postharvest handling and

Table 1 Bioactive compounds in some fruit and vegetable residues

Fruit and vegetable by-products	Bioactive compounds	References
Apple pomace	Hydroxycinnamates, epicatechin, chlorogenic acid, phloretin, quercetin, catechins, procyanidins	[37]
Blueberry pomace	Anthocyanins, cinnamic acid derivatives, and flavonols	[38]
Asparagus peel	Rutin, dietary fiber, phenols and flavonoid compounds, peroxidases and saponins	[39]
Tomato skin and seeds	Caffeic acid, caffeoylquinic acid, lycopene, quercetin, naringenin, chalcone etc	[40]
Citrus peel	Eriocitrin, hesperidin, naringin	[41]
Barberry peel	Anthocyanins From Saffron Petal	[42]
Onion skin	Quercetin	[43]
Potato peel, pomace, seeds, leaves, pulp, during processing chain	Protocatechuic, and caffeic acid, chlorogenic acid, gallic and ferulic	[44]
Grape pomace	Phenolic acids, tannins, and stilbenes, flavonoids, anthocyanins	[45]
Jaboticaba pomace	Phenolics, anthocyanins, and tocopherols (vitamin E)	[46]
Broccoli stalk,	Phenolic acids and flavonoids	[47]
Olive press cake residue	Phenolic acids, tyrosol flavonoids	[48]

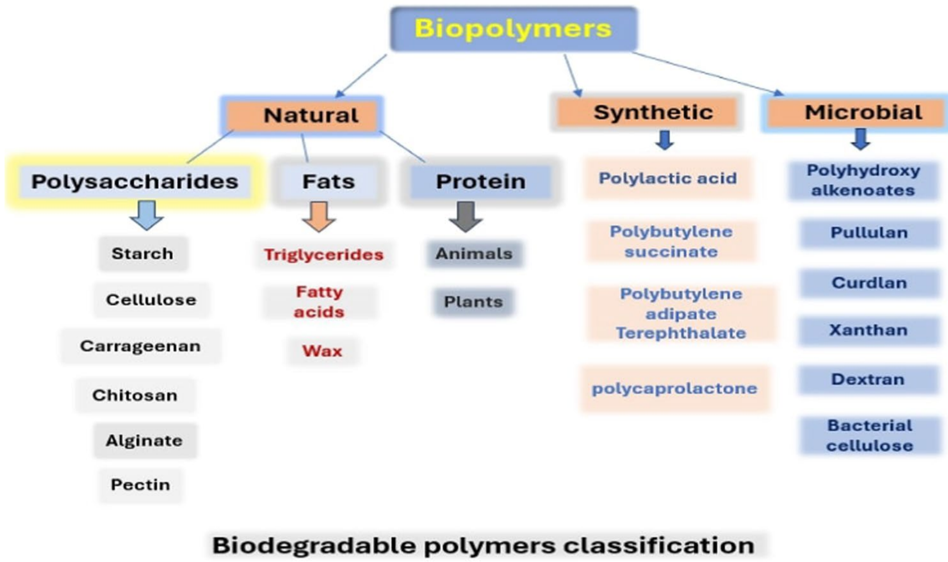


Fig. 1 Shows the classification of biodegradable polymers

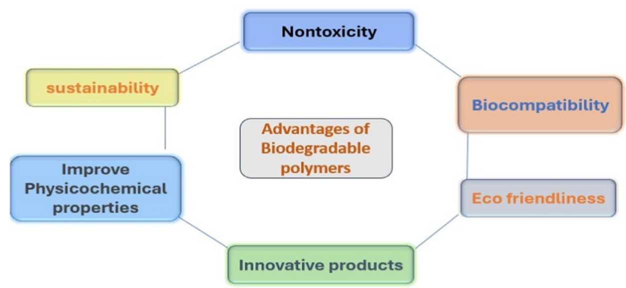


Fig. 2 Shows the advantages of biodegradable polymers

storage, fruits and vegetables generate considerable processing byproducts and junk [29, 60]. These waste materials are predominantly the result of improper storage and treatment procedures, with numerous byproducts being produced during the processing stages. In contrast, processed waste is rich in carbohydrates, fiber, and numerous physiologically active compounds, making them exceptionally valuable as biological resources [61].

3.1 Polysaccharides

Polysaccharides are chains of monosaccharide subunits that are complex molecules derived from carbohydrates. Polysaccharides and proteins are significant in film/coatings because of their biodegradable nature [62]. In addition to cellulose, starch, xanthan, chitosan, inulin, pectin, and sodium alginate, they are essential polysaccharides that provide barriers. Biodegradable polymer films are made from natural polysaccharides because of their excellent homogeneity, biodegradability, biocompatibility and film-forming qualities [63]. Cellulose is a polysaccharide that produces high-fibre plants like cotton, sugarcane, bagasse, fruit peel, oatmeal, and starch in sweet potatoes, beans, peas, and algae [64].

Cellulose is a naturally occurring polymer that is an abundant resource. In addition to inexpensive costs, nanosized crystals recovered from various vegetable wastes exhibit favourable mechanical qualities and environmental benefits [65]. Bioplastics made from chitosan and cellulose nanocrystals, generated from mango waste combined with polyvinyl alcohol, demonstrated their promise as an active film for packaging edible products [66]. Comparable results were observed when chitosan (derived from shrimp waste) and starch from cassava peel were used, with several chitosan compositions (3%, 5%, and 7%) being assessed [67].

The manufacturing of bioplastics from vegetable or fruit waste can be considered sustainable because it is both biodegradable and carbon–neutral. These environmental advantages motivate bioplastics to further their presence in the global market [68]. While certain bioplastics may have adverse effects caused by moisture and sensitivity, future efforts should prioritize operational enhancements. The negative consequences have prompted a global transition towards environmentally friendly materials or biocomposites composed of a blend of food waste. Using different fruit- and vegetable-based substances as potential films for bio-packaging has captured the interest of numerous researchers who aim to create viable materials as a substitute for plastics [69]. Figure 3 depicts the efficient extraction of valuable compounds from waste produced by fruits and vegetables to make environmentally friendly films [70].

The research created an orange peel biodegradable material for preparing packaging film, selected for its abundant cellulose content and easy accessibility. The film with glycerol as a plasticizer has shown consistent and encouraging outcomes. The film exhibits strong durability, flexibility, and disintegration under dirty conditions, characterized by a rough surface, and demonstrates its biodegradable properties [71].

Polysaccharides are completely biodegradable, non-toxic, and derived from renewable sources; their potential is still excellent. Developing blends based on polysaccharides with synthetic/other natural polymers enables the development of usage methods for non-degradable components. One can add antioxidant and antibacterial capabilities using essential oils in polysaccharide-based systems. Pollysacrides-based biodegradable materials help Reduce production costs and enhance mechanical, thermal, water permeability, biodegradability and antimicrobial properties [72].

3.2 Starch

Starch, found abundantly in nature, is a primary energy source for animals and humans [73]. It consists of two key components: amylose, which is composed of D-glucose residues linked in linear alpha-(1–4) formations, and amylopectin, making up approximately 6% and characterized by alpha-(1–6) linkages forming branches in the main structure [74]. Under specific conditions involving plasticizers, elevated temperatures, and mechanical pressure, starch exhibits thermoplastic properties, consisting of water-insoluble units with diverse shapes, morphologies, and crystalline structures [75].

Despite several polysaccharides, starch stands out due to its affordability and versatility. Starchy films, however, have certain limitations, such as thinness, flexibility, transparency, weak mechanical properties, and susceptibility to water vapour permeation, which restricts their use in film production [76].

Starch-based materials used in making biodegradable food packaging can potentially reduce pollution. To enhance the performance of these starch-based products, we can consider adding biopolymers or additives and exploring production techniques. However, research still needs to overcome the challenges associated with large-scale production of performance starch-based biodegradable polymers [77, 78].

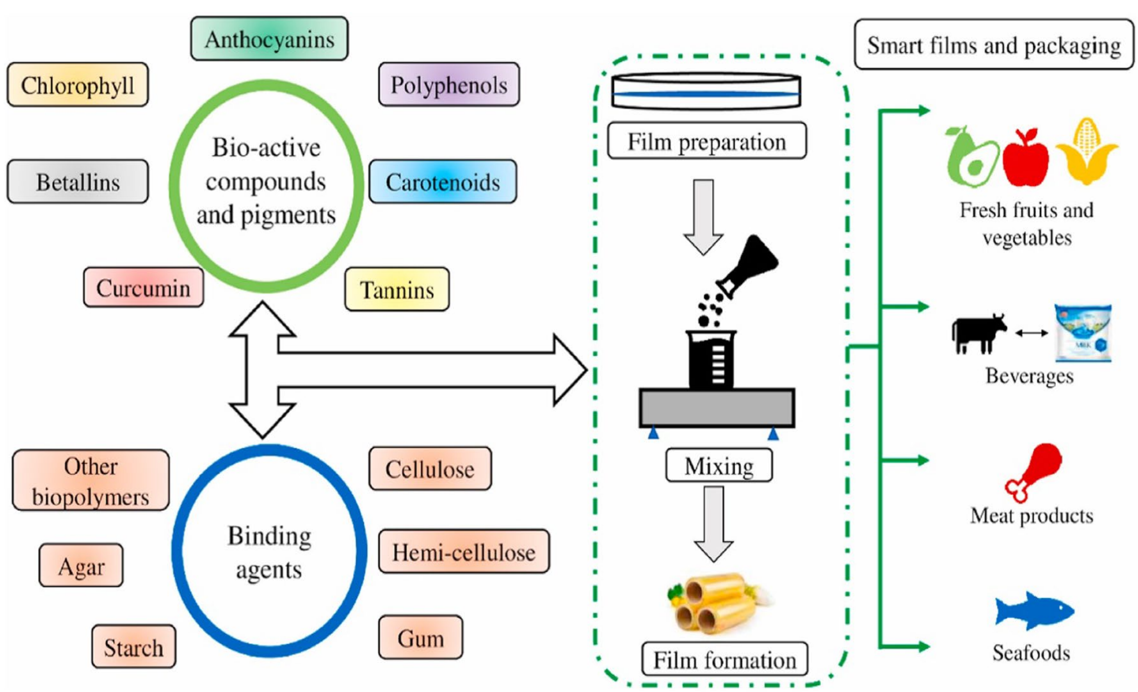


Fig. 3 Using beneficial fruit and vegetable waste substances to create sustainable films [70]

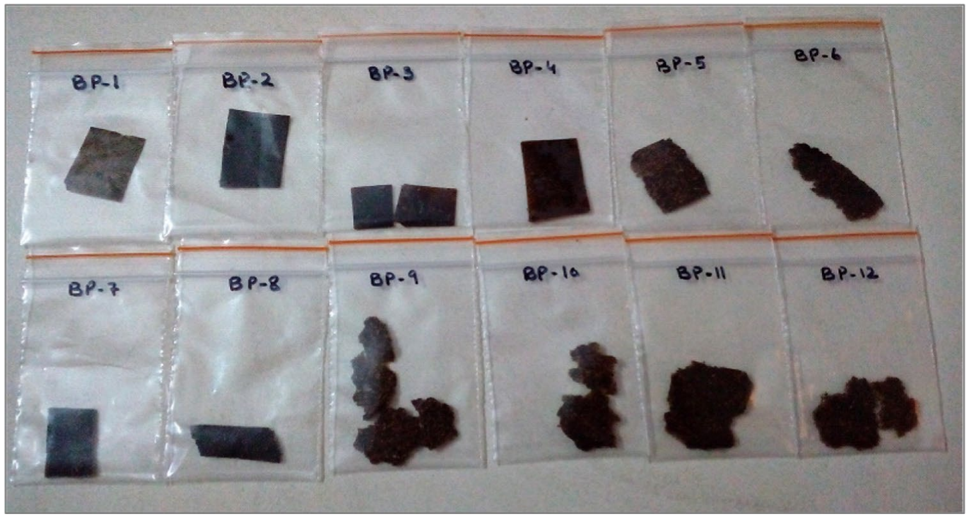


Fig. 4 Showing different banana peel starch biodegradable material samples [79]

Figure 4 illustrates the synthesis of bioplastic samples from banana peel starch (BPP) using various fillers, namely potato peel powder and wood dust powder, using a combination of plasticizer glycerol. The increase in absorption of water capacity and the lowest values for tensile strength were achieved by making 12 samples of bioplastics with different amounts and combinations of fillers and plasticizers [79].

Starch is hydrophilic; therefore, adding more powdered potato peel filler to BPP bioplastic samples will enhance water absorption capability [80]. The improved water absorption ability of BPP bioplastic samples may result from including powdered potato peel filler because The dry weight of potato peel consists of 52.14% starch [81].

Using sorbitol (variant in 20, 25 and 30%) as a plasticizer, the manufacture of starch-based bioplastics materials from cassava peel reinforced with microcrystalline cellulose MCC (Avicel PH101 fillers with a range of 0 to 6%) was explored. The strong hydrogen bonding between MCC and starch improved the tensile strength by increasing MCC concentration to 9 to 12 megapascals. The density, water absorption, and elongation at the break all decreased with adding MCC. Bioplastic has 20% sorbitol and 6% MCC content and has the greatest tensile strength value [82].

3.3 Pectin

Pectin, a derived compound from waste materials, is the polymeric framework for active packaging, providing additional benefits [83]. It is a substance that increases viscosity, provides stability, enhances texture, and creates gel-like structures [84]. It enhances the antioxidant and antibacterial properties of materials added to functional packaging and is compatible with proteins, lipids, and polysaccharides [85]. Plant cell walls contain many colloidal pectin heteropolysaccharides, widely found as waste from food processing and biomass by-products [13]. Biopolymers frequently include pectin because of its eco-friendliness, high storage capacity for volatile chemicals, lack of oxygen permeability, and viscosity [86]. Pectin is used to produce biodegradable packaging for food and edible coatings to extend the shelf life of food products. This is due to its exceptional ability to create thin layers and its low level of toxicity [87, 88].

Fruit juice production byproducts or citrus peels are the sources of commercial pectin [89]. Studies show that pectin sources are citrus peels, apple pulp, beet pulp, watermelon peel, pomegranate peel, and pumpkin [90, 91]. Efficient utilization of food waste has involved various parts such as fruit waste parts, pomace, and vegetable/fruit peels. Pectin was identified in dried peels of citrus, mango, apple, and banana from Indian fruit manufacturing and processing companies [92]. Data on pectin percentage and calcium salt content in various food sector waste products is presented in Table 2.

Citrus fruit peel powder, derived from fruits such as orange, lemon, lime, and pomelo, has been utilized to create food packaging films. Citrus peel powder can serve as a film matrix due to its high levels of pectin and cellulose [98]. Figure 5 shows that other highly viscous polymers like xanthan gum and sodium alginate are included in the films to act as adhesive agents in this situation [99].

A decreased amount of citrus peel powder enhances the tensile strength of the films due to the adhesive interaction between the citrus peel powder and the film matrices. Excessive citrus peel powder might cause the particles to clump together, potentially decreasing the films' tensile strength, water vapour barrier, and oxygen barrier properties [99–104].

Table 2 Extraction of Pectin from Fruit waste produced by different conditions

Source	Pectin %	Extraction conditions	References
Apple pomace	9.183	At a pH of 1.8, an SLR (Liquid to solid ratio) of 1:10 g/mL, and a duration of 30 min, the most effective conditions for extraction were as follows: 100% amplitude	[93]
Mango peel	21.70	The pH 2.0 extraction was done at 100 °C for 60 min. Adding 95% ethanol	[94]
Banana peel	2.8	During the extraction process, the temperature is 40 °C, 0.05 M HCL, 5 min, 24 h, 95% ethanol	[92]
Apple pomace	12.5	Temperature is 80 °C, Nitric acid (0.05 M) and 90 min, 95% ethanol	[95]
Sugarbeet pulp	34.5	48 h, 70% ethanol, 40 °C Ultrasonic pretreatment/ enzymatic treatment	[96]
Passion fruit rind	14	During extraction, Electric field strength is (1 kV/cm), and Temrarture is 100 °C for 3 min	[97]

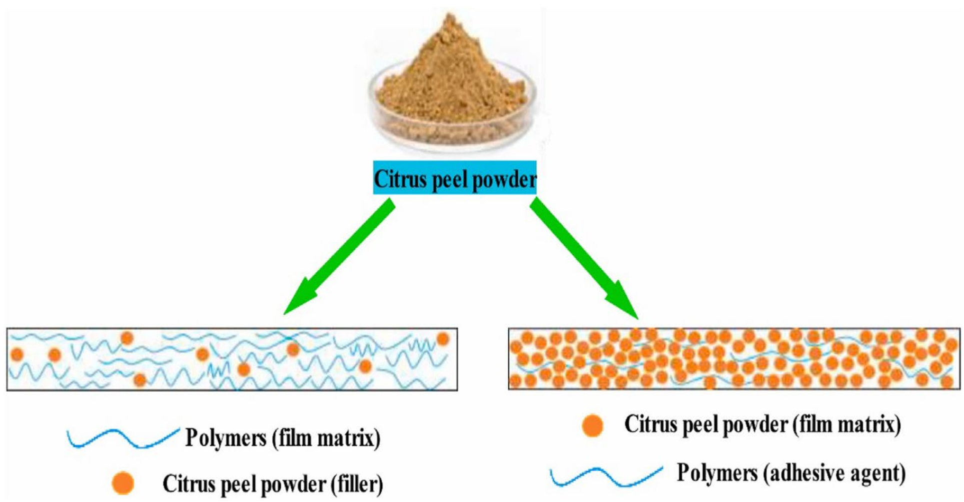


Fig. 5 Citrus peel powder in packaging films as the film matrix [99]

However, a high concentration of citrus peel powder improves the light barrier and thermal stability, as well as the antioxidant and antibacterial properties of the films [100–104].

Another study used a casting technique to create edible composite films from egg albumin, casein, and pectin from red pomelo peel. Different ratios of casein, egg albumin, and red pomelo peel pectin formed the composite films. The absence of cracks and crashes in the structure of pectin-incorporated composite films suggested appropriate homogeneity with no phase separation and a reduction in the degree of disorder in composite films. Film thermal characteristics showed that adding pectin to films improved thermal stability [105].

4 Physical, mechanical, and functional properties of packaging materials

Utilizing fruit and vegetable waste as a substrate for packaging or as a reinforcement for other films is a viable alternative (Table 3). Biopolymers derived from fruit and vegetable by-products can be employed in the production of packaging films. Nevertheless, these films often exhibit optimal mechanical and physical properties. To address these limitations, incorporating various bioactive components sourced from food waste and different food ingredients may enhance and improve the inferior properties [28].

Biopolymers are influenced by applied forces and pressure, encompassing factors such as polymer type, molecular mass, crystalline structure, chemical content, and shape [106]. Introducing different polymers to the film through blending alters its essential and physico-mechanical characteristics. Composite films are improved by combining polysaccharides (like chitosan, alginate, and cellulose) with proteins, such as milk protein, collagen, gelatin, and glute [107]. Starch-based hydrophobic films are crafted utilizing blueberry waste. Including blueberry waste leads to reduced water solubility and growth indicators in the starchy films. The fragrant compounds present within blueberry waste contribute to the ability of starch sheets to provide UV radiation protection [108].

Table 3 Use of Fruit by-products in packaging system and impacts on their properties

By-products	Film making materials	Properties of packaging film	References
Apricot kernel oil	Chitosan film with Apricot kernel essential oil extraction(1:0, 1:0.125, 1:0.25, 1:0.5)	Essential oil improved Tensile strength, Water Vapour barrier, and film solubility was reduced from 18.42% to 4.76%	[117]
Blueberry waste	Cassava starch film with Blueberry waste powder (4, 8, and 12 wt%)	Blueberry waste reduced the Swelling index pH 2.5, 7.0, and 10.0 and put up Ultraviolet protection	[108]
Citrus peel and leaves	Kraft paper and peel/skin and leaf extract (2:1, 3:0)	Peel/Skin and leaf extract (2:1) enhanced the Water vapor and oxygen barrier properties	[118]
Grape seed (GSE)	Chitosan and gelatin films with GSE (1% *v/w*) and *Ziziphora clinopodioides* essential oil (ZEO)	1% (GSE + ZEO), The tensile strength, pierce force, puncture deformation, and swelling index all decreased, but the water vapour barrier increased	[119]
Grape seed (GSE) + Pomegranate peel (PPE)	Surimi edible films with GSE + PPE (0%, 2%, 4% and 6%)	6% Grape seed Extract increased the water vapour barrier and reduced light transmission, while 6% Pomegranate peel Extract improved tensile strength	[109]
Mango peel with mango kernel extract (MKE)	Mango peel coating with Mango Kernal Extract (0.078 g/L)	The water vapour barrier and film solubility were decreased using mango kernel extract, which was reduced from 60 to 52%	[120]
Mango peel extract (MPE)	Fish gelatin film containing varying concentrations of mango peel extract (1%, 3%, and 5%)	The mango peel extract increased the tensile strength from 7.65 to 15.78 MPa (megapascal) while decreasing solubility from 40- 20%	[121]
Pomegranate peel extract (PPE)	The film was prepared using PPE at 0, 25, 50, and 75 mg/mL of film-forming solution	An increase in film solubility, from 6.16% to 18.29%, was observed by incorporating pomegranate peel extract, which increased tensile strength and water vapour barrier	[122]

The physical and mechanical characteristics and properties of derived films from silver carp surimi are enhanced by incorporating extracts from pomegranate peel and grape seeds. Bio-based films exhibit diminished solubility, heightened transparency, reduced flexibility, and decreased water absorbency. The active film displays elevated tensile strength, indicating a crosslinking between the phenolic chemicals and the film matrix [109]. A packaging film has been developed using vegetable protein, fruit pectin, CeO_2 nanoparticles, and cardamom extract, exhibiting robust mechanical strength, moisture resistance, and photocatalytic properties for enhanced durability and antimicrobial benefits. The composite film offers a sustainable and versatile solution for packaging applications [110].

Physiological properties in biodegradable films are enhanced by incorporating diverse substances, including emulsifiers or surfactants, plasticizers, and reinforcing agents. These additives improve emulsion stability, increase flexibility, and enhance physical and mechanical characteristics [107]. Plasticizers from non-volatile substances such as fatty acids, polyols, oligosaccharides, and monosaccharides are employed to prevent polymer cracking. They achieve this by reducing intermolecular hydrogen bonding, reinforcing and connecting polymer chains, and fostering plasticity and extension [111, 112]. The study evaluated films made from chitosan and (CMC) carboxymethyl cellulose enriched with fruit skin (blueberry and red grapes). The extracts impart antioxidant and antibacterial properties, enhancing the properties of edible films (physical, mechanical, and barrier). The bio-based films showed remarkable antioxidant properties and effectively regulated oxygen permeability [113].

The nanocomposite film was produced using pectin extracted from apple peel, potato starch, and zinc oxide particles and encapsulated in Zataria multiflora essential oil. The film showed antibacterial and antioxidant properties, extending the shelf life of packaged meats and improving their physical and barrier properties [114]. The extraction, characterization, and utilization of jackfruit seed starch (JSS) and tamarind kernel xyloglucan (XG) were conducted to produce biodegradable packaging materials. Nanocomposite films of JSS/XG were fabricated by incorporating zinc oxide nanoparticles (ZNPs). Mixing JSS with XG decreases the composite films' water-loving properties and enhances the material's mechanical robustness [115].

The study used waste products to produce Date palm pit extract (DPPE) in combination with alginate at different concentrations. The addition of DPPE reduced alginate films' solubility and surface wettability by 37–64%. It also increased vaporization resistance, flexible strength, and extension at break. After three months, the film with 40% DPPE showed the slightest reduction in phenolic content, antioxidant Activity, and FRAP. A scanning electron microscope displayed several pinholes and bulges, which may explain the low mechanical strength and high solubility obtained [116]. Figure 6 shows the properties of Pit extracts in food packaging.

5 Utilization of vegetable and fruit waste products in packaging

Currently, scientists are investigating innovative techniques to increase the durability of food products and improve their sensory attributes [123]. Edible films are employed as coatings and innovative packaging systems by modifying various qualities, including enhancement of mechanical properties, reduction of permeability, augmentation of barrier properties, creation of an actively antibacterial surface, and improvement of heat resistance [42, 52]. The utilization of films and coatings enables customers to incorporate them into food products, hence minimizing the adverse effects on

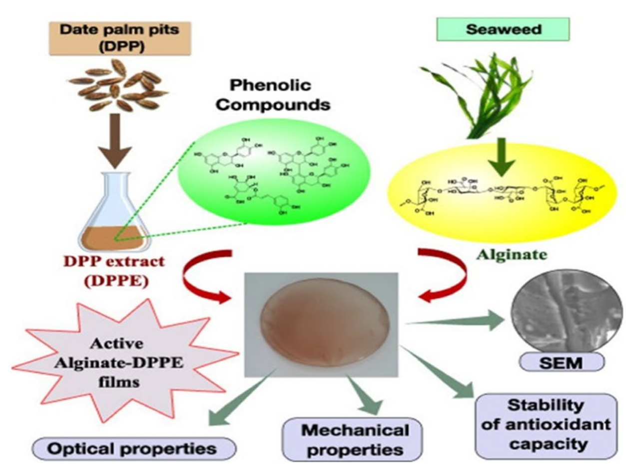


Fig. 6 Properties of date palm (pit extract) by-product film used in food product packaging

the food products' qualities for customers. Utilizing edible materials to fabricate films is preferable for ensuring safety and biocompatibility [124].

Food packaging enhances anticipated product characteristics by suppressing the proliferation of germs, improving resistance to environmental risks and oxidation, and maintaining the taste while concealing offensive odours [125]. A recent development in packaging materials involves integrating active substances to improve quality and extend the product's shelf life [126].

However, a primary method for extending and enhancing the durability of items, the utilization of artificial antioxidants, is prohibited because of their adverse effects on human health and high expense [127, 128]. Consequently, a significant focus is on enhancing the efficacy of natural antioxidants and antibacterial substances as bioactive components in developing packaging and edible coatings [129].

Enhancing biodegradable packaging films is achievable by integrating natural materials often considered waste, like sugarcane bagasse, cereal straw, bran, husks, seeds, stems, leaves, extracts, and pulp. This utilization enhances the overall functionality of biodegradable packaging films, offering a more sustainable and environmentally friendly packaging solution [130] and a good source of value-added compounds and natural polysaccharides [10, 15].

Incorporating fruit waste into packaging offers several benefits, including extending food shelf life, preserving quality, reducing water content, enhancing antioxidant capacity, boosting nutrient levels, less lipid oxidation, preventing browning and weight loss, and preserving food sensory properties [131]. Figure 7 shows the importance of food by-products in packaging.

The study used edible coatings like (Arabic gum, garlic, ginger, and aloe vera gel) to improve the Gola guava fruit's postharvest quality and storage durability. The blend of garlic extract and gum Arabic significantly reduced browning and weight loss, extending the guava's shelf life and increasing total soluble solids [133]. This study explores the creation of an edible antimicrobial film sourced from potato peels, incorporating essential oils to impede the proliferation of Listeria monocytogenes in smoked fish. It indicates that incorporating potato skins and crucial oils as bioactive elements in edible films successfully inhibits the growth of Listeria monocytogenes while improving the functional and structural properties [134].

The findings conclude that a 5% chitosan content is suitable for wrapping packaging of foods like sausages, while bags made from 7% chitosan are appropriate for handling and transportation. Encouraging outcomes were achieved by combining vegetable waste (including parsley, spinach stems, rice, and cocoa husk) with microcrystalline cellulose and ageing the mixture in trifluoroacetic acid (TFA), producing bioplastics [135]. The study used finely ground vegetable waste to create a micronized powder with mechanical properties resembling conventional plastics when exposed to an HCl solution, highlighting the need for precise moisture control and mass reduction [136]. Table 4 shows used fruit and vegetable waste by-products in films and coating, revealing their antioxidant properties, enhanced spoilage and microbial activity resistance, and extended food packaging durability.

Figure 8 illustrates the application of mango by-products (Ataulfo variety), extracted explicitly from the skin and seeds, for developing an edible film. This film is designed to improve gas permeability, ultimately prolonging the shelf life of peaches. The mango peel film showed outstanding barrier properties, reduced gas permeability, extended shelf life, and increased antioxidant and polyphenol content of the processed fruit [120]

The study aimed to create a biodegradable film using different proportions of corn starch and date pit powder. The incorporation of waste Powder resulted in an enlargement of the films' thickness, elasticity, and phenolic and antioxidant

Fig. 7 Utilizing by-products from fruit and vegetables in food packaging [132]

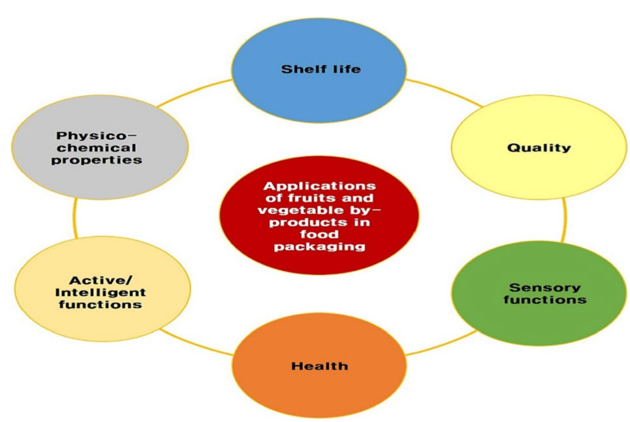


Table 4 Use of fruit by-products as biodegradable polymers for increased properties

By-products	Film/coating material	Results	References
Mulberry leaf extract	Pectin	The mechanical properties of bell pepper films enhanced their effectiveness as barriers, exhibiting vigorous antibacterial and antioxidant activity and extending their storage life	[137]
Red pomelo peel pectin,	Casein and egg albumin	The reduction of water vapour permeability and the increase in strength tension have enhanced film thermal stability	[105]
Skin and seeds of pumpkin	Protein and pectin	The films exhibited mechanical and barrier properties that were within acceptable ranges	[91]
Fruit pectin *Rubus chingii* Hu	Pectin/Tara gum	By adding gum, both the thickness and the water resistance increased. There was an increase in the mechanical properties	[138]
Orange peel pectin	Fish gelatin	A film using orange peel pectin was more resistant. Orange peel pectin films better preserve cheese	[139]
Pumpkin seed starch	Pea starch	Enhance the resistance to gas permeation and the ability to stretch before breaking while reducing the strength under tension and the capacity to absorb moisture. Adding pumpkin seed starch enhanced the water-repellent properties and reduced the expansion of the film	[140]
Extract of Berry leaf	Sodium Alginate	Improvement in physicochemical properties. Increased yield strength with the decreased length. Higher total phenolic content	[141]
Bagasse extract	Gelatin	The active films extended frozen beef's shelf life. Functional films had sufficient physical and barrier qualities—beef lipid and protein oxidation inhibition	[142]
Kiwifruit peel extract	Rind pectin	The film with watermelon peel pectin had superior tensile and yang modulus. Increasing kiwi peel extract and concentration increased film turbidity, elongation, and water vapour permeability	[143]
Pineapple peel	Alginate	Antioxidant and antibacterial activity is increased. The colour of the cow's red meat was well preserved using pineapple peel	[124]
Grape seed extract	Pectin/pullulan	Increase shelf life, mechanical, antimicrobial, and antioxidant properties, and delay sourness	[144]
Sesame pulp extract	starch	The levels of thiobarbituric acid, total nitrogen, and live bacteria exhibited a reduction. Enhance the shelf-life of beef by subjecting it to extremely low temperatures	[145]
Date palm pits	Alginate	Adding date palm pit extract enhanced tensile strength and water vapour barrier properties. Alginate films' surface wettability and solubility values were reduced by 37–64% and 72–111%, respectively	[116]
Date palm pits	Corn starch	Low-cost biodegradable films made and improved mechanical, antioxidant, and insulating capabilities	[146]

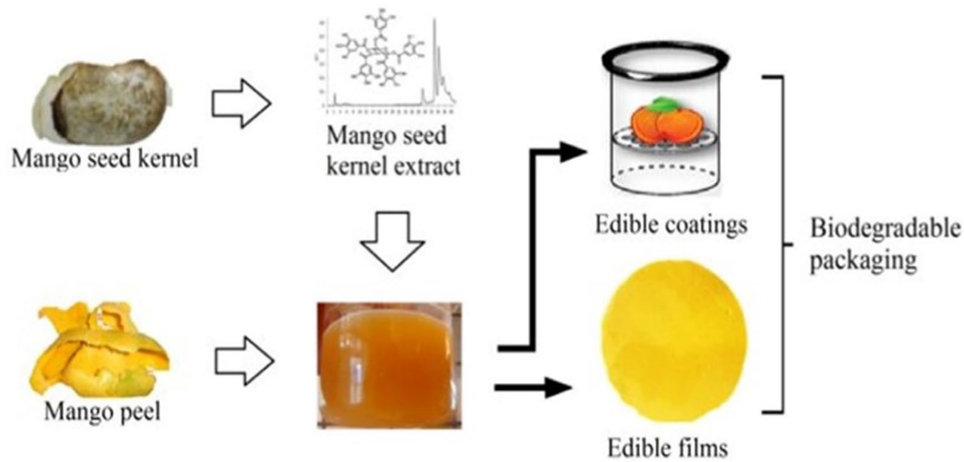


Fig. 8 Application of mango waste in edible coating for biodegradable packaging [120]

properties while also decreasing their water solubility and vapour permeability. SEM showed that up to 30% DPP enhanced the films' morphological characteristics, making them all environmentally degradable. The study suggests DPP's potential for creating composite biodegradable films [146].

Figure 9 shows that The research focused on creating antioxidant-rich edible films using papaya for food preservation. Optimal drying conditions were identified, and Moringa leaf extract and ascorbic acid were integrated. The films underwent characterization for antioxidant activity, physicochemical properties, mechanical properties, bromatology, and sensory acceptance. The dehydrator was selected for film formation due to its efficient drying time and preservation of natural properties. Including both bioactive compounds impacted the shelf-life stability of minimally processed pears, with ascorbic acid influencing sensory acceptance [147]

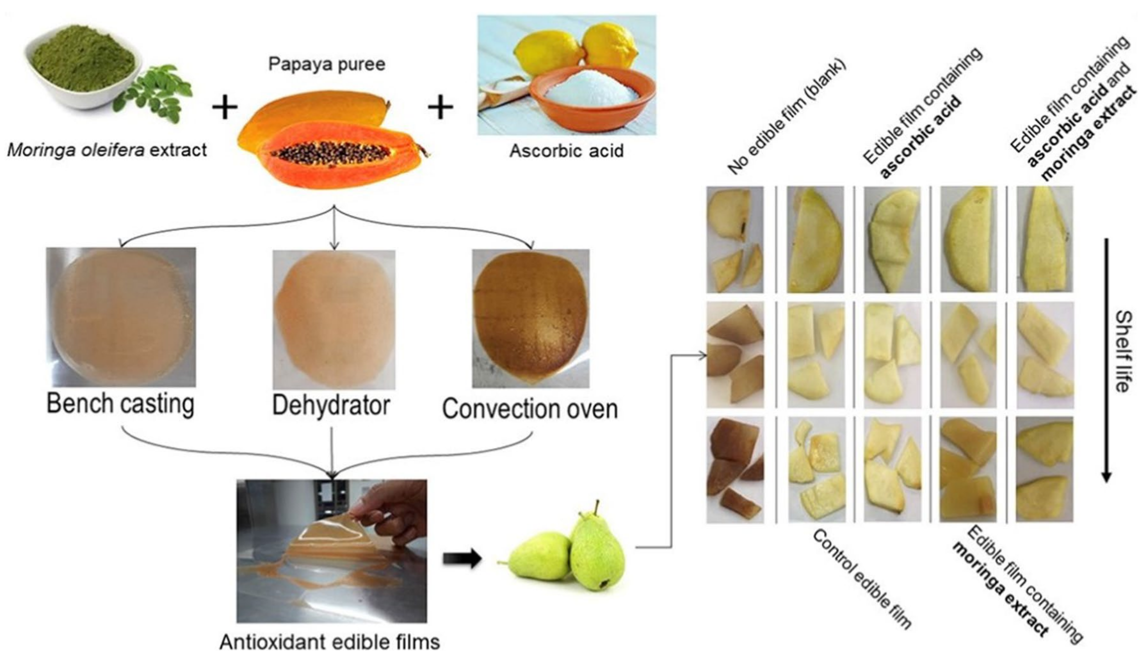


Fig. 9 Different Fruit by-products edible films in food packaging [147]

6 Effect of biodegradable food packaging on shelf life

Incorporating bioactive substances obtained from fruits and vegetables into packaging materials such as films/wraps inhibits the development of microorganisms and extends the shelf life of products [148]. The utilization of by-products in producing edible films/coatings enables the development of a protective barrier on the surfaces of food items. The primary function of this protective barrier is to mitigate the loss of moisture, regulate the flow of gases, and prevent the intrusion of microbiological contaminants [149]. To provide an example, let us consider using pectin-based edible films, derived from the by-product of fruit processing, to encase fruits, thereby extending their duration of storage. The storage trials extended for 16 days and analyzed various fruit attributes, including pH, total soluble solids (TSS), acidity, firmness, weight loss, and vitamin C. It showed that coated guava fruit is fresh and has less weight loss and improved shelf life, but uncoated fruit was weight loss [150]. A study shows that applying almond tree gum for edible coating improves the postharvest quality of tomatoes. Almond gum delays colour changes, decreases weight loss, increases firmness acidity, and decreases soluble solids concentration. The sensory evaluation also indicated a satisfactory level. In conclusion, almond gum shows promise as an innovative edible covering that enhances the post-harvest preservation of tomato fruit [151].

In another study, gelatin, chitosan, pectin and fennel essential oil were included, which increased the films' peak elongation and tensile index. They gained stretchability 14.03 to 31.61% and strength 0.40 to 0.50 N.m/g while retaining their yellowish colour and great transparency. These films have excellent bioactive properties, increasing food shelf life and lowering foodborne illnesses' risk [152]. Ginger Essential Oil, Cellulose Nanofibers, and Citric Acid for food coating exhibit improved flavour, aroma, and texture and extend the shelf life of meat products. Cellulose nanofibers serve not only in coating food effectively but also in preserving it by gradually releasing essential plant compounds. Ready-to-cook barbecue chicken, known for its short shelf life, can benefit significantly from a cellulose nanofiber coating fortified with ginger essential oil and citric acid, allowing for an extended storage period [153].

Figure 10 shows that Antibacterial and antioxidant-rich edible films were made using pomegranate peel extract (PPE) combined with gelatin and carboxymethyl cellulose. Composite films made with PPE outperformed controls. PPE films extended the shelf life of refrigerated beef products by 3 days. The extension was due to reduced viable counts, volatile basic nitrogen, weight loss, and pH changes. Thus, these new antioxidant and antibacterial coatings protect food packaging from mechanical stress, light exposure, microbiological degradation, and oxidative free radicals [154].

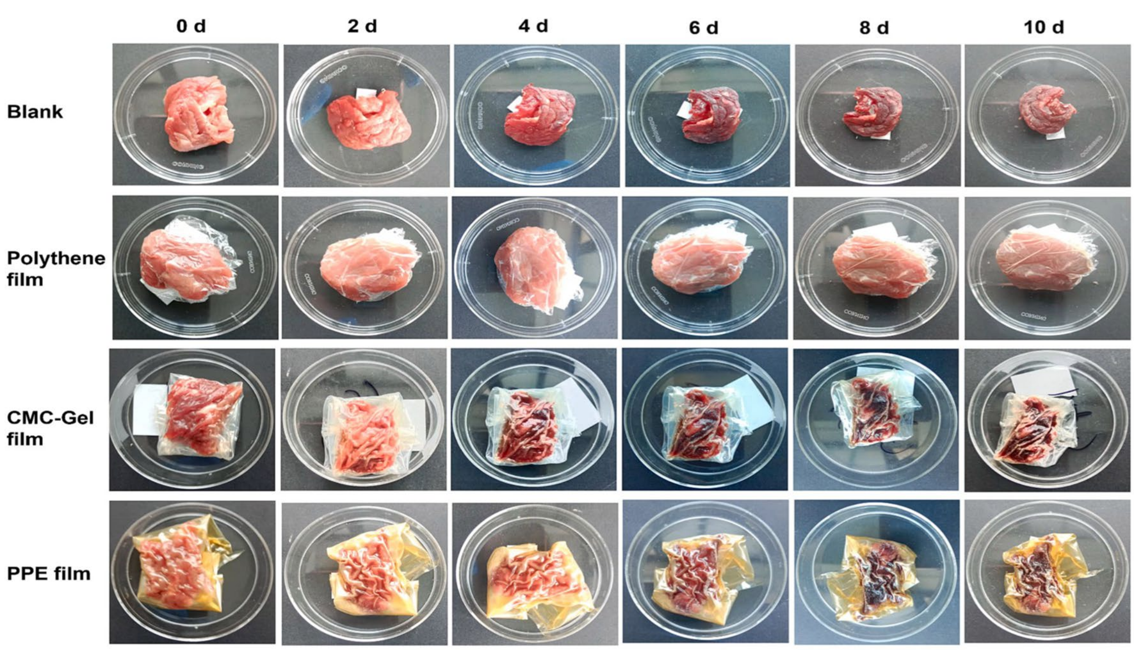


Fig. 10 Shows beef storage (4 ± 1 °C) for 10 days [154]

The antimicrobial potential of nanocomposite films, created from jackfruit seed starch (JSS) and tamarind kernel xyloglucan (XG), was shown in their capability about Staphylococcus aureus and Escherichia coli. These formulations were then utilized on tomato fruits, effectively retarding quality deterioration and extending their shelf life. Consequently, these produced nanocomposites hold the potential as environmentally friendly packaging materials to enhance the long life of food products [115]. More research is needed on other food items like cheese or baked goods; these studies consider the taste and sensory aspects of packaged foods. The natural compounds in essential oils (oregano, cinnamon, thyme, and rosemary) effectively prevent gram-positive, negative, and fungi [155].

7 Conclusion and future perspectives

Edible and biodegradable films and coatings have recently replaced non-biodegradable plastic packaging materials. Biopolymer-based packaging solutions, made from carbohydrates, proteins, and lipids, offer a more sustainable alternative to plastics. Industrial food processing by-products have emerged as valuable resources for creating cost-effective biodegradable packaging materials. Utilizing these by-products reduces waste and minimizes environmental impact while enhancing the properties of the packaging material. Food waste in packaging materials improves their structural and functional attributes and helps to control the microorganism's growth, enhance shelf life, and ensure the food quality of the packed products. The resulting packaging films or coatings exhibit desirable attributes such as biodegradable, recyclable and eco-friendliness. Food waste bioactive components improved the biodegradable film properties.

However, some challenges to overcome; improving mechanical durability, thermal stability, barrier properties, and scalability for large-scale production of these by-product-based materials remains a priority. Researchers have explored incorporating various protective materials, including nanoparticles, nanofibers, and essential oils, to form multi-layered biodegradable films to address these limitations. Additionally, combining these by-products with other polymers or using extrusion methods has been explored for industrial applications. Consumer safety is important, particularly regarding replacing packaging ingredients in food products. Hence, using food waste by-products to produce edible films from natural origins is deemed safe and ecologically sustainable. Future developments in this field should consider improving interactions between food and packaging, utilizing food waste and by-products as valuable resources.

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Data availability Data generated for this study is available from the corresponding author on formal request.

Declarations

Competing interests The authors declare no conflict of interest.

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