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Trends in starch-based edible films and coatings enriched with tropical fruits extracts: a review

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ABSTRACT

Petroleum-based food packaging materials are non-degradable and considerably affect the environment. In this context, edible films and coatings for food preservation represent a feasible alternative that could potentially reduce conventional non-biodegradable materials. It has been shown the suitability of starch as a non-toxic, widely available, low-cost and adequate film-forming biopolymer. In addition, natural compounds contained in tropical fruits are of great interest due to their proven antioxidant and antimicrobial properties, which are beneficial for the health of consumers and for obtaining more stable and safe foods. This review focuses on the new trends and benefits of incorporating tropical fruit extracts into starch-based edible films and coatings formulations as a source of bioactive compounds. The starch and fruit resources, extraction techniques, filmmaking methods, assays for determining functional properties and the potential uses of edible films and coatings in the food industry were stated and described.

1. Introduction

Petroleum-based polymers have dominated the packaging market due to their low price, mechanical properties, and processing adaptability. However, plastics derived from fossil hydrocarbons are accumulated in the environment (soils, water ending and coasts), where they can suffer the transformation to macro, micro, and nanoparticles (commonly known as microplastics), or they can sink affecting the marine environment, involving long periods of time to be degraded (Westlake, Tran, Jiang, Zhang, Burrows, & Xie, 2023; Crisafi, Valentino, Micolucci, & Denaro, 2022; Lebreton et al., 2018). Latin America represents 4% of the world's plastics production, reaching 367 million tons in 2020 (Plastics Europe, 2022) and being 40.5% of the packaging segment (Hernalsteens, 2020; Rhein & Schmid, 2020). During the last decades, the environmental consciousness has created global interest in the use of renewable and biodegradable resources (Jafarzadeh, Jafari, Salehabadi, Nafchi, Uthaya, & Khalil, 2020; Rhein & Schmid, 2020). In this context, different researches have been carried out focusing on degradable packaging (Ordoñez, Atarés, & Chiralt, 2022) in order to develop new materials, reducing plastic packaging by using renewable resources (Chiralt, Menzel, Hernandez-García, Collazo & Gonzalez-Martinez, 2020; Tapia-Blácido, da Silva Ferreira, Aguilar & Lemos Costa, 2020). Biodegradable materials, naturally or synthetically produced, are a promising alternative since they decompose after fulfilling their purpose, being bio-assimilated or mineralized in the environment through a process in which the polymer chains are broken down into monomers or dimers, which leads to decomposition (Zoungranan, Lynda, Dobi-Brice, Tchirioua, Bakary, & Yannick, 2020).

Among different possibilities of biodegradable materials, edible films and coatings can be a proper option for minimizing the use of non-degradable packaging. Edible films and coatings are defined as thin layers used as a primary food packaging (Shahidi, & Hossain, 2022). Basically, films are stand-alone structures pre-formed separately (molded as solid sheets, casted and dried) and then applied on food surface as a wrapping packaging material, between food components, or even sealed into edible pouches, preserving product from mechanical stress (Otoni et al., 2017). On the other hand, edible coatings are formed directly onto the food surface by dipping or spraying followed by

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drying, acting as a protective barrier (Kouhi, Prabhakaran, & Ramakrishna, 2020). To constitute a continuous matrix, natural macromolecules with film-forming properties, such as proteins and polysaccharides, have been used (Amin et al., 2021). On the other hand, they are considered as effective carriers of many functional additives and ingredients such as antimicrobials, antioxidants, colorants, nutraceuticals, minerals, vitamins, pigments and flavorings, which can be added to the film formulation to introduce a new functionality and enhance the quality of food products (Pedreiro, Figueirinha, Silva, & Ramos, 2021; Pająk, Przetaczek-Rożnowska, & Juszczak, 2019). Due to their hydrophilic nature, biopolymers have limited mechanical and barrier properties. In addition, the film properties might not be maintained once applied, depending on the environmental conditions or the characteristic of the food in contact. For these reasons, edible films and coatings are not intended to totally replace traditional packaging materials but would reduce their use by profiting from the own functionalities of edible coverings such as controlling mass transfer or carrying of active components (Azeredo, Otoni, & Mattoso, 2022)

Particularly, starch is widely used due to its filmogenic properties, neutral organoleptic characteristic, relatively low cost and abundance (Oyom, Zhang, Bi, & Tahergorabi, 2022; Sudheesh et al., 2020; Valencia-Sullca, Vargas, Atarés, & Chiralt, 2018). It is interesting to remark that there is a growing market demand for "gluten-free" (GF) products, which represents one-third of the global food intolerance market and has grown very fast in the last ten years. This has been due to the consciousness growth of celiac disease and gluten intolerance (Juhász, Colgrave, & Howitt, 2020; Mancini, Fratini, Tuccinardi, Degl'Innocenti, & Paci, 2020) . Considering this, most biopolymers, including starches, can be used for the development of new packaging materials, suitable for people with gluten intolerance (Mohammed et al., 2023).

Active packaging is an innovative strategy to maintain or extend food products shelf-life, ensuring and/or enhancing their quality, safety, and integrity (Yildirim et al., 2017). As is defined in the European regulation (EC) No 450/2009, active packaging comprises packaging systems that interact with the food in such a way as to "deliberately incorporate components that would release or absorb substances into or from the packaged food or the environment surrounding the food" (European Commission, 2009).

In the last decades, chemical compounds that are generated naturally in plant tissues, have been studied to be incorporated into film and coating formulation (Wang et al., 2023; Daniloski et al., 2021; El-Sayed, El-Sayed, Mabrouk, Nawwar, & Youssef, 2021), avoiding the use of chemical additives of synthetic origin such as antioxidants or preservatives. Thus, these active materials could be useful to prevent oxidative degradation, the growth of pathogenic and spoilage microorganisms on a critical zone like food surfaces, that threatens numerous products like cheeses, baked products, meats, and poultry (Kumar, Daniloski, D'cunha, Naumovski, & Petkoska, 2022; Chiralt et al., 2020; Kouhi et al., 2020; Alkan Tas et al., 2019; Majidi et al., 2019; Vahedikia et al., 2019).

Fruits and vegetables can be considered a reservoir of natural bioactive substances (nutrients, antioxidants and antimicrobials) that are located in different parts of the plant with promising health benefits (Sorrenti, Burò, Consoli, & Vanella, 2023; Chiralt et al., 2020). Nowadays, industry and researchers have recognized the importance and benefits in the addition of fresh fruits and vegetables extracts as well as their by-products due to its high content in bioactive compounds to edible packaging formulation (Bayram, Ozkan, Kostka, Capanoglu, & Esat-Beyoglu, 2021; Kharchoufi et al., 2018; Kumar, Pratibha, & Sharma, 2020; Yadav, Kumar, Upadhyay, Pratibha, & Anurag, 2021). Furthermore, the use of fruit and vegetable by-products not only benefits the consumers, but also helps to minimize the residues generated in the food industry creating a feasible alternative to reduce the production costs of edible films, and to add value to food by-products (Gaspar & Braga, 2023; Pathania et al., 2022). Particularly, tropical fruits represent a good natural alternative that can be added to edible packaging due to its antimicrobial and antioxidant effects (Molnar et al., 2023; Sani et al., 2022, Munekata et al., 2020), being a potentially valuable reservoir of phenolic compounds to promote health properties of the human diet (Magalhães et al., 2023).

Biodegradable active edible packaging technology represents an innovative and promising alternative to face up to the aforementioned environmental issues and contribute to improving food safety and human health quality. In such context, this review aims to summarize the research and current trends in relation to the obtaining and functional properties of active starch-based edible films and coatings enriched with tropical fruit extracts, as a source of natural antioxidant and antimicrobial compounds, and their potential industrial applications. Aspects as the starch and fruit resources, extraction techniques, filmmaking methods, and assays for determining functional properties were also described.

2. Components for edible films and coatings manufacture

Edible films and coatings constituent materials are biopolymers, plasticizers, and other additives. The structural materials are usually classified according to their biopolymer matrix in: a) hydrocolloids based materials that includes proteins (collagen, gelatin, gluten, mung bean protein, corn zein, soy protein and/or casein) (Majeed et al., 2023) and polysaccharides (starch, cellulose and its derivatives, pectin, chitosan, alginate, carrageenan, pullulan and gellan gum) (Muñoz-Tebar et al., 2023, b) lipid-based materials (bee wax, paraffin wax, carnauba wax, polyethylene wax, candelilla wax, rice bran wax, ouricouri wax and jojoba oil) (Milani & Nemati, 2022 and c) blend of hydrocolloids and lipids (Jeya Jeevahan et al., 2020), directly obtained from biomass (Zhong, Godwin, Jin, & Xiao, 2019).

Mostly polysaccharides and proteins based films and coatings exhibit poor moisture barrier properties due to their hydrophilic nature, however, they have good film forming ability along with the good gas (O_2, CO_2) barrier. On the other hand, lipids show better water vapor barrier than polysaccharides and proteins due to their hydrophobic nature, but are not capable of making self-supporting structures, being weak in forming flexible films (Yousuf, Sun, & Wu, 2022). Thus, to obtain edible films with the desired functionality, polysaccharides, proteins and lipids are usually combined to produce mixed films (Chen, Dong, Zhao, Li, & Chen, 2019). The main motivations for developing blended films are the improvement of the gas permeability, the reinforcement of the mechanical properties and the increase of the film functionality. The nature and structural features, chemical functional groups, biopolymers hydrophobicity and the interaction of the lipids with hydrocolloids and other components (Krochta, 2002), influence the efficiency of mixed films and coating. Therefore, the hydrophilic/hydrophobic nature of the structural materials should be considered to avoid incompatibility or phase separation issues (Zhang et al., 2019).

Plasticizers are another necessary additive to be incorporated to film and coating formulation. They are clear and odorless substances, and they are often used to increase the flexibility and the elasticity of films, due to the polymer-plasticizer interactions, avoiding brittle character. Based on the literature, there are many food-grade plasticizers with different effects on film properties, such as, polyols (sorbitol, glycerol and mannitol), glycols (ethylene glycol, propylene glycol and polyethylene glycol), sugars (mannose, glucose and fructose) and lipids (fatty acids and derivatives, lecithin, oils, and waxes) (Dong et al., 2023; Izzi, Gerschenson, Jagus, & Ollé Resa, 2023). In the case of lipids incorporation to film-forming solutions, emulsifier agents should be added to improve the structure of a continuous and dispersed phase, avoiding phase separation and coalescence, due to a reduction of the surface tension between phases (Amin et al., 2021).

2.1. Starch as biopolymer matrix for edible films and coatings

Worldwide starch production is mainly based on four common sources: corn, which represents 75% of world manufactory, cassava, wheat, and potato (Henning, Ito, Mottin Demiate, & Lacerdaet, 2022; Vilpoux, Brito, & Cereda, 2019). However, researchers have studied the potential of non-conventional starch sources searching for novel properties and diversification of agricultural resources such as the reuse of vegetable waste and underused vegetable species (Zhu et al., 2023; Costa, et al 2023).

Starch is a glucose polymer consumed in the human diet from plant sources such as grains, legumes and tubers (Alvarenga, Aldrich, & Shi, 2021; Li, Chen, Bui, Xu, & Dhital, 2021). Some of its most important properties are: biodegradability, abundance, renewability, low cost and easy availability (Apriyanto, Compart & Fettke, 2022) being a suitable base material for films and coatings manufacture. Starch is a polymeric carbohydrate composed of amylose (~25%) and amylopectin (~75%), comprising together 98-99% of the dry mass of starch, and forming semi-crystalline hierarchical structure (Thakur, Pristijono, Scarlett, Bowyer, Singh, & Vuong, 2019). Amylose is a linear molecule formed by around 1000 α-D-glucopyranosyl units linked with α-D-(1-4) linkages, that contributes mainly to the amorphous phase of the starch granule (Tester, Karkalas & Qi, 2004). Amylopectin is the branched counterpart of amylose and is composed by approximately 4000 glucose units with α-D-(1-6) bonds, and contributes predominantly to the peripheral crystalline organization of starch granules (Fuentes-Zaragoza, Riquelme-Navarrete, Sánchez-Zapata & Pérez-Álvarez, 2010). The shape and size of the starch granule, as well as amylose-amylopectin contents and ratios, branch chain lengths and its composition and functionality vary according to the sources and botanical species (Jingyi, Reddy, Fan, & Xu, 2023). Furthermore, even within them, the properties of starch can be altered by different growing conditions (Moorthy, Sajeev, & Anish, 2018).

Even though native starches have hydrophilic nature, they are poor or not soluble in water at room temperature (Ojogbo, Ogunsona & Mekonnen, 2020). Native starch is considered non-plastic, because it has a molecular structure of strong inter- and intra-molecular hydrogen bonds between the hydroxyl groups, thus disruption of starch granules occurs in a heated aqueous suspension. First, the granule swells because of water absorption in the amorphous zone when the temperature remains under the gelatinization point (T_{gel}). Whereas, if the temperature exceeds that point, the semi crystalline structure starts to collapse irreversibly. Water molecules can easily diffuse into the semi crystalline amylopectin clusters, breaking the hydrogen bonds and making amylose and amylopectin solubilized. Eventually, amylose and amylopectin then entangle one another in a continuous phase to form the so-called starch film (Pelissari et al., 2019). The crystallinity of the granule affects the necessary energy that must be delivered to gelatinize (gelatinization enthalpy ΔH and temperature) and also could affect the viscosity of the initial slurry (Tagliapietra, Felisberto, Sanches, Campelo & Clerici, 2020).

Retrogradation occurs when gelatinized starch, containing dissociated amylose and amylopectin chains, re-associate. The level of retrogradation has consequences on mechanical properties because recrystallization increases stress and stiffness and drastically decreases tensile strain at break (Figueroa-Flórez & Salcedo, 2020). Several variables such as molecular ratio and molecular structures (botanic source of the starch) of amylose and amylopectin, starch concentration, processing conditions and concentration of other ingredients (plasticizers, surfactants, lipids and salts) affects the retrogradation rate (Chang, Zheng, Zhang, & Zeng, 2021).

Edible films based on starch from conventional sources have been extensively studied by several researchers, but they have broadened their knowledge about other promising sources (Tessema, Admassu, & Dereje, 2023; Costa et al., 2023). Non-conventional starch sources are produced in smaller global production than conventional, and generally are native crops or vegetables consumed by local populations (Henning et al., 2022). Moreover, these promote sustainability, since waste and by-products from different sources can be used, availability and technological advantages over the common starches (Makroo, Naqash, Saxena, Savita Sharma, Majid, & Dar, 2021). The extraction of starch from unconventional sources that are suitable for the production of biodegradable packaging, offer an attractive alternative to explore new products with differentiated properties (Kaur, Broadway, Alam, David, & Chattree, 2023). Some examples are: sago, sweet potato, quinoa, lentil, arrowroot, sorghum, chickpea, mung bean, taro, pumpkin, mango seed, among others (Yang, Reddy, Fan, & Xu, 2023). The properties of the films and coatings formed with starches from different sources are quite different due to the differences in particle size, shape, amylopectin/amylose ratio, and crystallinity (Basiak, Lenart, & Debeaufort, 2017). Table 1 shows the characteristics and the differences of non-conventional starches that have been studied for edible packaging applications.

Processing conditions potentially affects film and coating performance such as water vapor permeability (WVP), solubility, and mechanical properties (Thakur et al., 2019; Jiménez, Fabra, Talens & Chiralt, 2012). Flores, Famá, Rojas, Goyanes, & Gerschenson (2007) studied the influence of gelatinization technique and drying method and determined that long periods of gelatinization time and a slow drying rate resulted in a more solid network, a higher crystallinity degree and a smaller WVP. The authors argued that slow drying allows more double helix formation, re-associations and interlinking among chains to form a more elastic film along with rigidity development and structural ordering. Therefore, the most suitable constitution technique to obtain a film with desired properties will be determined by the characteristics of the product to be packed.

The proportion of amylose and amylopectin present in starch-based packaging materials is relevant because the unit chain length distribution pattern in the internal structure of them affects the thermal and mechanical properties and the retrogradation profile of starches (Matignon & Tecante, 2017). Lower amylose content showed a reduction of heterogeneity, lowest maximum tensile strength (TS), and stiffness (Young Modulus, YM) but the highest deformation of films (EAB). On the other hand, starch films obtained from high amylose content have greater mechanical resistance with higher TS and YM and lower the EAB since more hydrogen bonding can be formed between linear chains (amylose) of starch rendering a tighter and stiffer molecular association (Tarique, Zainudin, Sapuan, Ilyas, & Khalina, 2022; Domene-López, Delgado-Marín, Martin-Gullon, García-Quesada, & Montalbán, 2019; Thakur et al., 2019; Basiak et al., 2017). In addition, the crystallinity of the granule affects the necessary energy that must be delivered to gelatinize (gelatinization enthalpy, ΔH, and temperature) and also could affect the viscosity of the initial slurry (Tagliapietra et al., 2020).

The isolated starches from the diverse botanical sources are known as native starches. There are two general methods reported for native starch isolation: wet and dry milling (Möller, van der Padt, & van der Goot, 2021; Wang et al., 2020; Cruz-Tirado, Vejarano, Tapia-Blácido, Barraza-Jáuregui, & Siche, 2019). To make starch suitable for commercial and edible packaging applications, different modification techniques (physical, chemical and enzymatic) have been studied in order to increase their positive characteristics and/or decrease their undesirable ones. It has been reported that the modification of starch produces the decrease in retrogradation, improving the thermal stability, hydrophobicity, freeze-thaw stability, and mechanical strength (Apriyanto et al., 2022; Moreira, Silva, Brandão, Santos, & Ferreira, 2022; Punia, 2020; Ojogbo et al., 2020). The selection of the modifying method will depend on the final use. As aforementioned, different methods lead to various results on the film and coating properties, and also within a specific technique the final outcome may vary with other aspects such as environmental conditions, starch source, plasticizer used, etc. (Christensen et al., 2023; Fashi, Delavar, Zamani, Noshiranzadeh, & Zahraei, 2023; Wang et al., 2023).

Table 1
Characteristics of conventional and non-conventional starches.

Species	Source part	Starch content (%)	Granule Shape	Granule size (μm)	Amylose content (%)	Crystallinity (%)	References
Sorghum (*Sorghum spp.*)	Grain	61.7- 71.1 (db)	Spherical	5-20	24-30	22-28	Rhodes et al. (2017), Mu & Zhang (2019), Pelissari et al. (2019), Ojogbo et al. (2020)
Sweet potato (*Ipomoea batatas*)	Tubers	45.8 - 67.5 (db)	Round, polygonal, oval, bell	2-42	20-25	33-39	Guo, Liu, Xu, Zhang, Bian, & Wei, (2019), Mu & Zhang (2019), Pelissari et al. (2019) Wang et al. (2020)
Cassava (*Manihot esculenta*)	Tubers	83 - 85 (db)	Round, truncated, cylindrical, oval, spherical	4-45	15-27	31-59	Cock & Connor (2021), Mu & Zhang (2019), Pelissari et al. (2019) Wang et al. (2020)
Potato (*Solanum tuberosum*)	Tubers	22 (wb)	Oval, spherical	10–75	20.6-22.6	29.8	Semeijn & Buwalda (2018)
Mung bean (*Vigna radiata*)	Legume	50 (db)	Round, kidney	5-30	40	17.12	Zou et al. (2019)
Corn (*Zea Mays*)	Grain	70-75 (db)	Round, polygonal	5-30	25-32	14-39	Taggar, (2004); Domene-López et al. (2019)
Arrowroot (*Maranta arundinacea L.*)	Rhizome	79.14 (db)	Ellipsoid shape	21.37 28.56	20.34	29.1	De Oliveira Guilherme (2019); Tarique et al., (2022)

db: dry base; wb: wet base.

2.2. Bioactive compounds: tropical fruits extracts

As previously mentioned, some bioactive compounds from natural sources, may be added to develop new properties or to fix film characteristics depending upon the requirements, based on the final needs, such as antimicrobial, antioxidant, flavoring, coloring or some other active compounds (Dinika, Verma, Balia, Utama & Patel, 2020; Jafarzadeh et al., 2020). Particularly, fruit extracts are a rich source of antimicrobial and antioxidant that can introduce important active properties to films and coatings (Rangaraj, Rambabu, Banat, & Mittal, 2021; Santhosh, Nath, & Sarkar, 2021). Tropical fruits have gained popularity due to their appealing taste, exotic appearance, nutritional values and functional properties, hence increasing 3.8% the annual market demand (Alvarez-Rivera, Ballesteros-Vivas, Ibánez, Parada-Alfonso, & Cifuentes, 2020; Altendorf, 2018). These fruits mainly grow in high temperature climatic zones and contribute to 62% of fresh fruit supply in the world occupying a unique niche market in the global agricultural sector (tropical and subtropical areas from Asia, Africa, America and Oceania) (Kusumaningrum, Lee, Lee, Mo & Cho, 2015).

The major tropical fruits world trade informed by FAO (2022) reached 8.5 million tons in 2021, showing percentages of production of 37% pineapple, 29% avocado, 29% mango, mangosteen and guava and 5% papaya, aside bananas, which represent the largest world production (117 Mt) according to FAOSTAT (2020). Contrary, there is also a small production of minor tropical fruits such as lychee, longan durian, passion fruit, rambutan, jackfruit, kiwifruit, among others. Those are less popular outside the areas where they are cultivated and some of them are considered as novelty for international market point of view. Guava and mangosteen are reported together with the more important mango, but available information suggests that guava and mangosteen accounted for shares of only 5 and 3% of the total production, respectively. Moreover, guava is the largest minor tropical fruit in terms of production with an estimated volume of 6.8 million tonnes in 2017 (Altendorf, 2018).

An emerging trend in food science that proved to be a suitable alternative to use food industrial processing wastes and discarded fruit is the recovery of bioactive compounds, being a potentially valuable component with promoting health properties of the human diet (Teshome et al., 2023). It has been reported that such natural compounds can prevent many diseases (cardiovascular, neurodegenerative and chronic) due to their effect as antioxidant, antiproliferative, anti-inflammatory, neuroprotective, antihypertensive, lipid-lowering, hypoglycemic, and antiaging (Rangaraj et al., 2021; Martín Ortega & Segura Campos, 2019).

One of the greatest producers of by-products is the fruit and vegetable processing industry, which generates approximately 50% by-products waste in form of peels, kernels, pomace, unripe, and/or damaged, recognized by the Food and Agriculture Organization of the United Nations (FAO) and the scientific community (Gómez & Martínez, 2017; Padayachee, Day, Howella, & Gidley, 2017). Particularly, tropical fruits by-products can comprise a substantial amount of peel (10%–66%), and seed (1%–22%), depending on species (Cheok et al., 2018). Tropical fruits pulps and their by-products can be potentially use by isolating specific phytochemicals (phenolic compounds, dietary fibers and others) to be incorporated in nutraceutical supplements, dietary additives, new food and pharmaceutical products, promoting the recovery of agro-industrial process waste, with major industrial, economic and environmental impact (Ding et al., 2023). Thus, the extraction of biocompounds from wastes of fruits industrially processed can provide a reasonable yield of phenolic components to be further used in active packaging production. Particularly, mango (*Mangifera indica* L.), papaya (*Carica papaya* L.) are the most produced tropical fruits around the world, which generate high volumes of waste with high content of polyphenol compounds (Vasco et al., 2008). According to Cheok et al. (2018) the yields of phenolic compounds from fruit wastes ranged 1-40 % (d.b.), depending on the raw material and extraction technique used, inferring that high amounts of processed by-products are required to obtain an adequate level of bioactive substances. Such limitations make the extraction technology more recommendable for industrial wastes in contrast to fresh consumption wastes (domestic wastes) which, at the moment, lack an appropriate and standardized collection method.

2.2.1. Antioxidant effect of bioactive compounds from tropical fruits extracts

Phenolic compounds are a large group of secondary metabolites of plants and some kinds of fungal species, and they represent a huge diversity in their structures, associated with different physiological functions. They are subdivided into three major classes: terpenoids, alkaloids, and phenolics compounds (Savithramma, Rao, & Suhrulatha, 2011).

Phenolic compounds consist of aromatic rings with hydroxyl groups, organic acids, and acetylated sugars. The more structurally complex phenols, i.e. with high-molecular-weight, are often referred as polyphenols (Trigo, Alexandre, Saraiva, & Pintado, 2019). Niaz & Khan (2020) classified polyphenols compounds in different groups: phenolic acids (hydroxybenzoic and hydroxycinnamic), flavonoids (flavones, flavonoles, flavan-3-ols, isoflavones, flavanones, anthocyanidins), other phenolics compounds (stilbenes, lignans, xanthones, lignins, chromones and anthraquinones) and tannins (hydrolysable and non-hydrolysable: condensed and proanthocyanidins).

The amount of these compounds in fruits may vary by the influence of these parameters: maturation state, cultivation conditions and the variety (Maldonado-Celis et al., 2019; Traffano-Schiffo, Castro-Giraldez, Colom, & Fito, 2017). The extraction, separation, and purification of polyphenol compounds are a challenging process due to their chemical complexity, similar structural features, thermal degradability and sensitivity to light and oxygen (Niaz & Khan, 2020). Bioactive compounds can be determined by different qualitative and quantitative methods (Srivastava et al., 2021, Kafkas, 2018). For a global quantification of phenolic compounds, spectrophotometric assays are commonly used. However, more specific analyses can be obtained when they are based on the identification of each of the phenolic compounds. Some of the methods are based on liquid chromatography (HPLC) or gas chromatography (GC) while the identification requires sensitive detectors, such as mass spectrometry (MS) (Srivastava et al., 2021). Moreover, the success of these techniques will depend on the most efficient sample preparation and extraction methods (Swallah et al., 2020).

Tropical fruits can be added to edible packaging in various ways, such as fresh fruit, drying, freezing or lyophilizing fruit powder, or by incorporating polyphenol extracts obtained by different extraction methods (Meena, Rooman Neog, Yashini, & Sunil, 2022; Santos, Lopes da Silva, & Pintado, 2022; Hemeg et al., 2020). Those are influenced by many factors such as fruit matrix, tissue type (cell structure, bound or free form of compounds, moisture content, and particle size), solvent, temperature, pressure, time and the ratio of solvent to the matrix (Alexandre, Moreira, Castro, Pintado, & Saraiva, 2017).

Many techniques have been exploited for the extraction of bioactive compounds, which were classified by Belwal et al. (2018) as conventional and advanced methods. Conventional chemical extraction methods include decoction; maceration; infusion; digestion; percolation, and Soxhlet technique. However, these methods are becoming outdated, since they present some disadvantages, such as long extraction times, large quantities of organic solvents use, many of which can be toxics, volatiles or flammables and low efficiency in extracting bioactive compounds of interest (Alara, Abdurahman, & Ukaegbu, 2021; Srivastava et al., 2021; Alvarez-Rivera et al., 2020; Vinatoru, Mason, & Calinescu, 2017).

On the other hand, advanced or non-conventional extraction techniques include physical, wave energy and biological: Supercritical Fluid Extraction (SFE) (Pimentel-Moral, Cádiz-Gurrea, Rodríguez-Pérez, & Segura-Carretero, 2020), Pressurized Liquid Extraction (PLE) (Pimentel-Moral et al., 2020; Cádiz-Gurrea et al., 2020), Ultrasound Assisted Extraction (UAE) (Traffano-Schiffo, Aguirre Calvo, Avanza, & Santagapita, 2020), Microwave Assisted Extraction (MAE) (Ameer, Shahbaz, & Kwon, 2017), Pulse Electric Fields (PEF) (Chemat, Fabiano-Tixier, Vian, Allaf, & Vorobiev, 2015, Traffano-Schiffo et al., 2016) and Enzyme Assisted Extraction (EAE) (Baiano, 2014). These 'Green Extraction' techniques increased the extraction efficiency and the selectivity of bioactive compounds and they are environmentally friendly compared with the traditional ones (Enríquez-Valencia, Ayala-Zavala, González-Aguilar, & López-Martínez, 2021). They reduced the volume of organic and hazardous solvents used, and they are very simple to perform, achieving higher extraction yields with lower energy consumption (Khoddami, Wilkes & Roberts, 2013). Green solvents as water, carbon dioxide, ethanol, ethyl acetate, ethyl lactate, (+)-limonene and natural deep eutectic solvents (NADES), among others, are being used in alternative technologies to extract bioactive compounds (Xiao et al., 2022; Calvo-Flores, Monteagudo-Arrebola, Dobado, & Isac-Garcia, 2018).

Based on the polyphenol contents, it is possible to classify the fruits from tropical regions into three categories: low (<500 $mg_{GAE}/100\ g_{sample}$ d.b.), medium (500–2500 $mg_{GAE}/100\ g_{sample}$ d.b.) and high (>2500 $mg_{GAE}/100\ g_{sample}$ d.b.) (Vasco, Ruales, & Kamal-Eldin, 2008). Table 2 summarized the bioactive compounds present in each part of tropical fruits, extracted by different techniques and conditions, and that have been used in edible packaging applications.

2.2.2. Antimicrobial effect of bioactive compounds from tropical fruits extracts

Over the last years, the demand for "clean label" products significantly increased as a result of customers demand for food products without synthetic additives or any other substances considered as non-beneficial for human health or for the environment (Nikmaram et al., 2018; Nascimento, Paes, & Augusta, 2018). In such a context, it is relevant to evaluate the antimicrobial action of tropical fruits extracts to propose its use as natural preservatives for food preservation.

Plant extracts represent an important natural source of active compounds, mostly polyphenols, with strong antimicrobial activity and known as consumer friendly (Wu & Zhou, 2021; Olszewska, Gedas & Simões, 2020). Plants contain a large amount of different phytochemical compounds distributed in leaves, bark, roots, fruits and seeds, which confer excellent antimicrobial properties to the plant, being the flavones, phenolic compounds, alkaloids, terpenoids, EOs and peptides the compounds with the main contribution (Jafarzadeh et al., 2020). In their primary structure, these compounds have hydroxyl groups and according to their number and position, they show important inhibitory effects against microorganisms (Lima et al., 2019).

The main mechanism of action against microorganisms are: acidification of the cell membrane; cytoplasmic membrane damage; inhibition of nucleic acid synthesis; inhibition of energy metabolism; permeabilization of the cell membrane; inhibition of extracellular microbial enzyme and deprivation of the substrates required for microbial (Villalobos-Delgado, Nevárez-Moorillon, Caro, Quinto, & Mateo, 2019; Guil-Guerrero et al., 2016).

Many of these compounds with antimicrobial activity are found in fruit by-products or in other parts of the plant, hence being of great interest to incorporate them in films and coatings and to create barriers that prevent the pathogenic microorganism proliferation. The antimicrobial activity of fruit extracts depends on the extraction method and the solvent used, the type of microorganism, the amount of inoculum and the determination method used (Tajkarimi, Ibrahim, & Cliver, 2010).

To evaluate the antimicrobial activity of fruit extracts on their own or when they are already incorporated into edible films and coatings, *in vitro* antimicrobial testing methods are used. Such methods are recommended to carry out a screening of several extracts to evaluate their effectiveness before being incorporated into the filmogenic matrix. To choose the most suitable one, it has to take into account whether an extract, coating solution or film is used (Moradi et al., 2021). The *in vitro* antimicrobial techniques are described below.

Diffusion assays are classified as qualitative methods as they can only determine the presence or absence of antimicrobial activity. Disk and well diffusion assays respond to the same basic principle: the antimicrobial substance is diffused on the inoculated agar and inhibits microbial growth (Abdollahzadeh, Nematollahi & Hosseini, 2021; Aloui & Khwaldia, 2016). The antimicrobial efficiency is determined by the observation of a clear zone of inhibition (mm) around the disk or well (Dafale, Semwal, Rajput, & Singh, 2016). Regarding agar well diffusion assay, the methodology is similar to the disk agar diffusion method unless the fruit extract or the antimicrobial solution is dispensed in a hole made in the agar plate instead of being released from the film matrix. Thus, disk agar diffusion assay (Salam et al., 2023, Mohammadi, Kamkar & Misaghi, 2018; Balouiri, Sadiki, & Ibnsouda, 2016; Campos, Gerschenson, & Flores, 2011) can be adequate for antimicrobial film, while the well diffusion method is usually used for extracts and coating solutions (Moradi et al., 2021).

On the other hand, the broth dilution is a quantitative method where microorganisms are tested at a standard concentration against different concentrations of the antimicrobial agent in a liquid medium (Aloui & Khwaldia, 2016). The minimum inhibitory concentration (MIC) of an antimicrobial agent is that inhibits microorganism growth in

Table 2
Extraction method, total phenolic content, main phenolic compounds and antioxidant activity from tropical fruits.

Fruit part	Extract Type	Total phenolic content (mg_{GAE}/g_{sample} d.b.)	Main phenolic compounds (mg/g_{sample} d.b.)	Antioxidant activity	Reference(s)
			Mango (*Mangifera indica* L.)		
Peel	Acetone/water (70:30 v/v)	29.31 ± 1.75 cv Tommy Atkins-Guayas, 66.24 ± 1.93 cv Haden, 51.49 ± 1.54 cv Kent, 41.46 ± 0.72 cv Tommy Atkins-Imbabura, 39.20± 0.327 cv Tommy Atkins-By-products	Gallic acid: 0.32 ± 0.01 cv Tommy Atkins-Guayas, 0.43 ± 0.00 cv Haden, ND cv Kent, 0.32 ± 0.02 cv Tommy Atkins-Imbabura, 0.28 ± 0.02 cv Tommy Atkins-By-products. Mangiferin: 0.89 ± 0.01 cv Tommy Atkins-Guayas, 0.05 ± 0.00 cv Haden, ND cv Kent, 3.14 ± 0.09 cv Tommy Atkins-Imbabura, 1.94 ± 0.10 cv Tommy Atkins-By-products (UPLC-PDA).	0.23 ± 0.02 cv Tommy Atkins-Guayas, 0.53 ± 0.04 cv Haden, 0.49 ± 0.01 cv Kent, 0.34 ± 0.00 cv Tommy Atkins-Imbabura, 0.34 ± 0.00 cv Tommy Atkins-By-products. ABTS mM Trolox/ g sample db	Marcillo-Parra, Anaguano, Molina, Tupuna-Yerovi, & Ruales (2021)
	UAE 76% amplitude 80% ethanol; volume of solvent/solid 50 mL/g db	112.9 ± 3.70 cv Haden	N.R.	1.15 ± 0.06 ABTS mM Trolox Equivalent/g sample db	Castañeda-Valbuena, Ayora-Talavera, Luján-Hidalgo, Álvarez-Gutiérrez, Martínez-Galero, & Meza-Gordillo, (2021)
	Methanol/water (80:20 v/v) + ultrasonic bath 15 min (*) Green; (**) Ripe; (***) Overripe	103.82 ± 1.79 (*); 78.45 ± 1.78(**); 58.63 ± 9.38 (***) cv Keitt 59.23 ± 2.18 (*); 54.24 ± 2.57(**); 51.78 ± 2.08 (***) cv Kent 39.63 ± 3.80 (*); 46.56 ± 4.59(**); 49.40 ± 0.63 (***) cv Osteen	Galloyl glucose and Hexagalloyl glucose: 1.09 ± 0.01 and 0.66 ± 0.01 (*); 1.09 ± 0.02 and 0.73 ± 0.01 (**); 0.83 ± 0.00 and 0.71 ± 0.00 (***) (cv Keitt) 0.67 ± 0.02 and 0.50 ± 0.02 (*); 0.64 ± 0.02 and 0.41 ± 0.01 (**); 0.53 ± 0.02 and 0.40 ± 0.02 (***) (cv Kent) 1.02 ± 0.08 and 0.54 ± 0.00 (*); 1.00 ± 0.02 and 0.57 ± 0.01 (**); 0.88 ± 0.00 and 0.70 ± 0.00 (***) (cv Osteen) (HPLC-DAD-Q- TOF-MS).	N.R.	Alañón, Pimentel-Corollaries-Román, & Segura-Carretero, (2021)
	70% ethanol	27.51 ± 0.63 cv Kensington Pride	Gallic acid: 14.5 ± 0.4 Quercetin: 11.9 ± 0.4 (HPLC-PDA)	9.32 ± 0.24 ABTS mg ascorbic acid equivalents/g	Suleria, Barrow, & Dunshea, (2020)
	Ethanol-acetone (50:50) Ethanol-acetone (50:50) +UAE	2.69 ± 0.16 14.83 ± 0.56	N.R.	18.99 ± 0.22 20.57 ± 0.08 ABTS mg Trolox/100 g sample db	Martínez-Ramos, Benedito-Fort, Watson, Ruiz-López, Che-Galicia, & Corona-Jiménez, (2020)
	Methanol/H_2SO_4 9:1 (v/v) hydrolysis at 85°C	6.50 ± 0.23 cv Ataulfo	N.R.	10.10 ± 0.54 ABTS mg equivalent Trolox/g sample db	Patiño-Rodríguez, Bello-Pérez, Agama-Acevedo, & Pacheco-Vargas, (2020)
Pulp (flesh)	Methanol/water (80:20 v/v) + ultrasonic bath 15 min (*) Green; (**) Ripe; (***) Overripe	5.27 ± 0.42 (*); 4.82 ± 0.62 (**); 3.31 ± 0.62 (***) cv Keitt 3.05 ± 0.04 (*); 3.35 ± 0.03(**); 2.54 ± 0.23 (***) cv Kent 2.25 ± 0.09 (*); 2.56 ± 0.13(**); 1.81 ± 0.01 (***) cv Osteen	N.R.	N.R.	Alañón et al. (2021)
	Methanol/H_2SO_4 9:1 (v/v) hydrolysis at 85°C	58.26 ± 1.80 cv Ataulfo	N.R.	107.16 ± 9.35 ABTS mg equivalent Trolox/g sample db	Patiño-Rodríguez et al. (2020)
	Methanol/water (80:20, v/v) + ultrasonic bath	N.R.	Hydrolysable tannin: Galloylglucose: 0.58 ± 0.01 cv Keitt; 0.48 ± 0.00 cv Osteen; 0.81 ± 0.00 cv Sensación. Galloylglucose isomer VI: 0.29 ± 0.01 cv Keitt; 0.17 ± 0.00 cv Osteen; 0.38 ± 0.00 cv Sensación. (HPLC-DAD-QTOF-MS)	61.4±6.4 cv Keitt; 59.2±2.9 cv Osteen; 102.3±9.0 cv Sensación ABTS μM eq Trolox /mg sample db	López-Cobo, Verardo, Diaz-de-Cerio, Segura-Carretero, Fernández-Gutiérrez, & Gómez-Caravaca, (2017)
	a. Ethanol 50% (v/v) in water solution and b.1.5 N HCl in 85% ethanol 70% (v/v) acetone in water	a. 6.52 ± 0.22	b. Anthocyanins: 0.07 ± 0.00 Coumarin 0.57 ± 0.06 (HPLC UV-Vis)	N.R.	Silva et al. (2014)

(*continued on next page*)

Table 2 (*continued*)

Fruit part	Extract Type	Total phenolic content (mg_{GAE}/g_{sample} d.b.)	Main phenolic compounds (mg/g_{sample} d.b.)	Antioxidant activity	Reference(s)
			Mango (*Mangifera indica* L.)		
Seed	UAE 50% ethanol; volume of solvent/solid 50 mL/g db	94.58 ± 2.13 cv Haden	N.R.	1356.92 ± 76.11 ABTS μM Trolox Equivalent/g sample db	Castañeda-Valbuena et al. (2021)
	Methanol/water (80:20 v/v) US	78.0 – 80.5 cv Kent, Keitt, Osteen	Phenolic acids: Hydroxybenzoic acids Gallic acid 0.21 ± 0.00 cv Keitt; 0.16 ± 0.02 cv Kent; 0.16 ± 0.00 cv Osteen. Flavonol: Flavan-3-ols: 0.29 ± 0.00 cv Keitt; 0.15 ± 0.02 cv Kent; 0.37 ± 0.02 cv Osteen. Xanthone Mangiferin 0.85 ± 0.02 cv Keitt; 0.69 ± 0.06 cv Kent; 0.66 ± 0.00 cv Osteen. (HPLC-DAD-Q-ToF-MS)	N.R.	Alañón et al. (2021)
	UAE 30 min and Solid/liquid 1/20 g/mL	321.5 ± 4.7 and 406.0 ± 4.3 cv Manila	Mangiferin: 17.21 ± 3.46 Chlorogenic acid: 6.88 ± 1.68; Myricetin: 4.92 ± 0.09; Ferulic acid:4.49 ± 1.02; Quercetin:3.87 ± 0.36; Rutin: 2.95 ± 0.16; Caffeic acid: 2.04 ± 0.48 (HPLC-DAD)	2472.40 ± 46.93 μM Trolox equivalents/g sample db	Gómez-Maldonado, Lobato-Calleros, Aguirre-Mandujano, Leyva-Mir, Robles-Yerena, & Vernon-Carter, (2020)
	80% methanol	0.17 ± 3.48 cv Hindi	Cinnamic acid 12.00 ± 0.52 Tannic acid 9.87 ± 0.44 Gallic acid 1.56 ± 0.07 (HPLC)	7.9 ± 0.14 ABTS (IC50) μg GAE/ml	Abdel-Aty, Salama, Hamed, Fahmy, & Mohamed, (2018)
Papaya (Carica papaya)					
Peel	70% ethanol	3.13 ±0.15 cv Sunrise solo	Caftaric acid 5.6 ± 0.1 Quercetin 4.9 ± 0.4	3.30 ± 0.17 ABTS mg ascorbic acid equivalents/g sample db	Suleria et al. (2020)
	Plant material/water mixture of 1%, 20 min, 70°C.	19.87 ± 0.26 cv Ordinary 15.53 ± 5.93 cv Red Lady 23.64 ± 1.29 cv Sunrise	N.R.	27.89 ± 0.75 cv Ordinary 73.44 ± 3.16 cv Red Lady 39.60 ± 1.19 cv Sunrise ABTS mg Trolox equivalents/g sample db	Gaye, Cisse, Ndiaye, Ayessou, Cisse, & Diop (2019)
	Water and ethanol 1:10 (w/v) C. Papaya/ solvent	Water: 32.23 ± 0.64, Ethanol: 43.79 ± 1.20	N.R.	Water 50%, ethanol 55% of DPPH scavenging	Asghar et al. (2016)
	Methanol 80% + US bath 30 min	N.R.	Ferulic acid 2.77* to 1.86** p-coumaric acid 2.29* to 1.35** caffeic acid 1.7* to 1.12** cv Maradol (0-25% yellow area, low ripeness) *; (100% high ripeness) ** HPLC-DAD	N.R	Gayosso-García Sancho, Yahia, & González-Aguilar, (2011)
Pulp(flesh)	50% (v/v) ethanol in water solution and 70% (v/v) acetone in water 1.5 N HCl in 85% ethanol	126.3 ± 12.6	N.R.	N.R	Silva et al. (2014)
	80% aqueous methanol (w/v, 1:25) cv Red fleshed papaya	Ripe:2.72 ± 0.01 Unripe: 3.39 ± 0.09	N.R.	N.R.	Mutalib, (2014)
	a. Ethanol b. water (1:10 fruit: solvent) raw (*) ripe (**)	a. 44.8 ± 1.00 (*); 65.0 ± 2.25(**) b. 37.9 ± 1.28 (*); 75.7 ± 2.43 (**) (Fresh weight)	N.R.	a. 27.0 ± 1.44(*);44.5 ± 1.54(**) b. 42.5 ± 3.56(*); 72.7 ± 2.40 (**) ABTS	Annegowda, Bhat, Yeong, Liong, Karim, & Mansor, (2013)

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Table 2 (*continued*)

Fruit part	Extract Type	Total phenolic content (mg_{GAE}/g_{sample} d.b.)	Main phenolic compounds (mg/g_{sample} d.b.)	Antioxidant activity	Reference(s)
			Mango (*Mangifera indica* L.)		
Seed	a. SWE 10 MPa, 70°C b. Soxhlet with water	a. 34.7 ± 0.4 b. 34.0 ± 1.0	Phenolic acid: Ferulic acid a. 0.1087 ± 0.04 b. 0.3667 ± 0.04 (LC-ESI-MS/MS)	4.1 ± 0.1 (a); 3.74 ± 0.01(b) DPPH EC50 μg/mL	Gonçalves Rodrigues, Mazzutti, Vitali, Micke, & Ferreira, (2019)
Guava (*Psidium guajava L.*)					
Peel	Methanol/water (9/1, v/v) + sonication bath cv friedrichsthalianum Nied.	N.R.	Proanthocyanidins 6.57 ± 0.02 Ellagitannins 2.43 ± 0.01 Flavonols 2.11 ± 0.01 UHPLC-DAD-ESI-MS/MS	N.R.	Rojas-Garbanzo, Winter, Montero, Zimmermann, & Schieber, (2018)
Pulp (flesh)	Methanol/water (9/1, v/v) + sonication bath cv friedrichsthalianum Nied.	N.R.	Proanthocyanidins 3.17 ± 0.02 Ellagitannins 3.06 ± 0.01 Flavonols 1.41 ± 0.01 UHPLC-DAD-ESI-MS/MS	N.R.	Rojas-Garbanzo et al. (2018)
Pulp	3:200 S/L ratio (70% acetone), vortex for 1 min	10.33-17.34 (fb) cv Paluma	185.5-260.6 (fb; mg rutin/ g sample fb)	78 % DPPH scavenging	Del'Arco & Sylos, (2018)
Seed	Soxhlet with hexane 6 h 40°C	124.03 ± 0.13	Tocopherol (ppm) 654 ± 11.00 (HPLC)	58.90 ± 1.31 DPPH (%)	Kapoor, Gandhi, Tyagi, Kaur, & Mahajan, (2020)
Seed	SFE (CO_2) 150 min, 35.7 MPa,52°C	2.63 ± 0.18	γ-Tocopherol 82.6 ± 3.7 mg/100 g oil GC–MS	N.R.	Narváez-Cuenca, Inampues-Charfuelan, Hurtado-Benavides, Parada-Alfonso, & Vincken (2020)
Pineapple (*Ananas comosus*)					
Peel	70% ethanol	7.83 ± 0.35 cv Aussie Rough	Phenolic acids: 10.6 ± 1.9 Flavonoids: 14.8±1.9 (HPLC-PDA)	1.30 ± 0.07 DPPH (mg AAE/g)	Suleria et al. (2020)
	Water, 200°C, 30 min and 1:10 w/v solid- liquid ratio	1.75 g/L (g of pineapple waste dry/mL of distilled water)	Gallic acid: 2.78 g/L Hydroxybenzoic acid: 1.55g/L (g of pineapple waste dry/mL of distilled water)	67.1 ± 2.7 % DPPH scavenging 94.7 ± 2.7 % ABTS scavenging	Sepúlveda, Romaní, Aguilar, & Teixeira, (2018).
	Methanol (1:10 g sample/mL solvent), 4 h stirred	428.13 ± 61.35	Citric acid: 1152.56cd ± 125.31 Malic acid:180.07ghijk ± 20.55 (μg compound/100g fruit part dry weight)	446.69 ± 71.19 DPPH• (IC50) 60.40 ± 14.44 FRAP (μmol FeSO4 /100 g db)	Morais et al. (2015)
Pulp	Methanol (1:10 g sample/mL solvent), 4 h stirred	197.87 ± 45.96	Citric acid: 5281.16b ± 931.92 Malic acid: 648.29cde ± 12.69 (μg compound/100g fruit part dry weight)	666.07 ± 41.07 DPPH• (IC50) 44.77aAB ± 7.99 FRAP (μmol FeSO4 /100 g db)	Morais et al. (2015)
Mangosteen (*Garcinia mangostana* L.)					
Peel	Ethanol 80%- MAE, irradiation time 1.75 min, 25 Solvent-to-solid ratio (mL/g)	309.2	N.R.	75.99 % DPPH 143.6 FRAP (mg_{TE}/g extract)	Mohammad, Zaidel, Muhamad, Hamid, aakob, & Jusoh, (2019)
Banana (Musa *spp.*)					
Peel	Boiled water, 25 min. 2 g peel/ 5 mL solvent.	55.5 ±1.2 cv Musa paradisiaca	Rutin: 973.08 mg/100 g *p*-Coumaric acid: 8.05 mg/g Ferulic acid: 1.63 mg/100 g (HPLC)	66.9±4.8 DPPH %	Devatkal, Kumboj, & Paul, (2011); Behiry et al. (2019)
Peel	70% ethanol	6.13 ± 0.25 cv cavendish	Phenolic acids: 16.3±1.9 Flavonoids: 11.8±2.1 (HPLC-PDA)	1.20±0.12 DPPH (mg AAE/g) 0.81 ± 0.03 FRAP (mg AAE/g)	Suleria et al. (2020)

N.R: not reported; cv:cultivar; db: dry base; fb: fresh base.

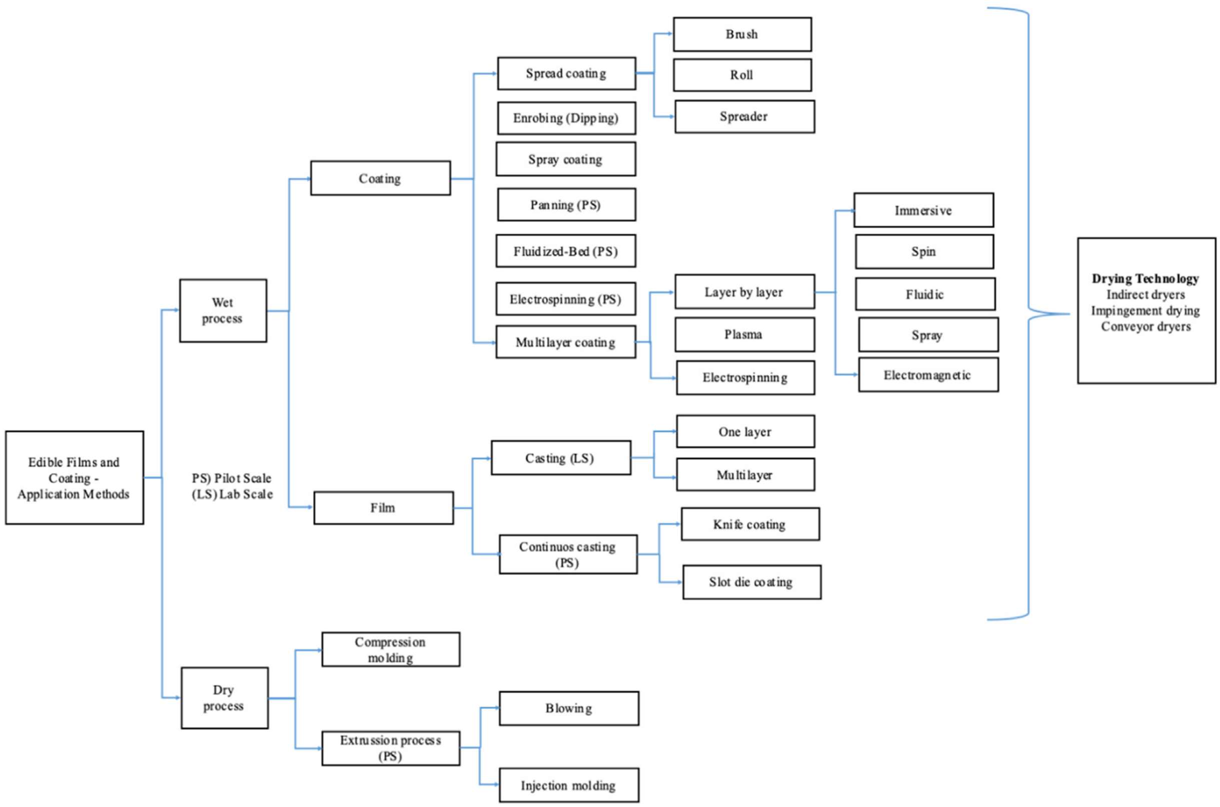

Fig. 1. Application methods for edible films and coatings.

standardized conditions, and usually it is expressed in mg/mL or mg/L (CLSI-M100, 2022). Macrodilution or microdilution techniques can be performed to determine quantitatively the MIC of the antimicrobial compound (Balouiri *et al.*, 2016; Aloui *et al.*, 2016) which must be considered when edible films and coatings are formulated to obtain an effective antimicrobial action once incorporated.

It is also possible to investigate the antimicrobial action of a fruit extract incorporated into the film matrix by placing the film in an inoculated broth media and counting the viable cell after incubation. If an antimicrobial agent can be released from film, a reduction of cell count can be determined against a control broth without film sample (Moradi et al., 2021).

Regarding spectrophotometric techniques for optical density (OD) measurement, they are not recommended to test the antimicrobial activity of all active films, because they can have a high concentration of colorful agents (with high diffusion rate into a liquid medium) and high water solubility (Abdollahzadeh et al., 2021; Radford et al., 2017).

Other methods for evaluating the antimicrobial effectiveness of certain compounds in a film matrix are plate counting method or viable cell count and film surface inoculation test (Zhang, Shu, Su, & Zhu, 2018). The first one consists of counting, at specific time's intervals, the microbial population of inoculated agar plates in contact with the film disk carrying the antimicrobial agent. Samples are taken out at different time intervals with the preparation of serial dilutions and then the viable cells are counted. The results provide information about the film performance in case of entering in contact with a contaminated surface (Hashemi Gahruie, Ziaee, Eskandari, & Hosseini, 2017; Campos et al., 2011). In the second one, the microbial population inoculated on the surface of a film disk in contact with a semisolid media is counted. Also, it is a good test to evaluate surface contamination, and even more, it allows to observe the barrier properties of the film (Alzate, Miramont, Flores & Gerschenson, 2016).

For the selection of an antimicrobial, it must be considered the effectiveness against the target microorganism and the possible interactions among the antimicrobial, the film-forming biopolymer, and other food components present. These interactions can modify the antimicrobial activity and the characteristics of the film (Campos et al., 2011). Table 3 shows the most common methods and antimicrobial agents used for evaluating antimicrobial activity of fruit extracts and edible films and coatings containing fruit extracts.

3. Preparation methods of edible films and coatings

Since the main role of food packaging is to protect the products against chemical, physical or biological damage, it is important to consider how to give it a better quality, safety and product integrity in all food chains, as well as its final destination. Certain films and coatings can be applied to a wide variety of fruits and vegetables, and even meat. Additionally, the developed edible film and coating should be cohesive and free from imperfections (continuous, without cracks, bubbles and holes) (Jeya Jeevahan et al., 2020).

Fig. 1 summarizes the application methods for edible films and coatings. Dipping methods for coating deposition are easy to use and are the preferred methods on a lab scale. Coating is also applied by brushing, fluidized-bed or panning when it is necessary to cover the food surface completely (Suhag, Kumar, Petkoska & Upadhyay, 2020). Spraying method is used when the coating is applied only on one side and is a preferred method for pilot scale. The vacuum-impregnation technique is preferred to be used in products designed with high vitamins and mineral content (Senturk Parreidt, Schott, Schmid, & Müller, 2018). The Layer-by-Layer (LBL) technique has been studied in several coated fresh-cut fruits and has the potential for scalability (Treviño-Garza, García, Heredia, Alanís-Guzmán, & Arévalo-Niño, 2017; Kumar, Pratibha & Sharma 2020). In the LBL technique, several biopolymers are se-

Table 3
Methods used and antimicrobial agents for evaluating antimicrobial activity of fruit extracts and edible films containing fruit extracts.

Test method	Fruit extract	Tested microorganisms /Target microorganism	Antimicrobial effect -Results	Reference
Disk agar diffusion/Broth dilution	Papaya (cv Vasconcellea pubescens) pulp ethanolic convective dried extract TPC: 5.19 ± 0.17	*E. coli, S. aureus, B. cereus*	*E. coli*:9.53 ± 0.40 mm, MIC 31.2 mg/mL *S. aureus*: 9.61 ± 0.10, MIC 31.2 mg/mL *B. cereus*:10.1 ± 0.70 mm; MIC 15.6 mg/mL	Vega-Gálvez et al. (2021)
Broth dilution	Papaya (ripe and raw) fruit extracts TPC: N.R.	*E. coli, S. typhimurium, S. dysentriae, V. cholerae, A. hydrophila,* and *P. shigelloides*	-Acetone extract of ripe fruit (0.39 mg/mL) and the chloroform extract of raw fruit (25.0 mg/mL) showed good activity against the pathogens. -MIC and MBC values ranged between 100-0.39 mg/mL. -Plant extracts exhibited inhibition activity against tested pathogens.	Prabhu et al. (2017)
Disk agar diffusion	Papaya peels, seeds and pulp ethanolic (1:10 w/v fruit: solvent) extracts TPC: Peel: 43.79 ± 1.20; Seed: 43.42 ± 0.06; Pulp: 48.49 ± 0.18	*S. aureus, B. cereus, E. coli* and *P. multocida*	-Ethanolic extracts (peel: 16 to 18 mm; seed: 12 to 14 mm; pulp: 12 to 14 mm) followed by methanolic extracts only presented the best antibacterial activity.	Asghar et al. (2016)
Disk agar diffusion	Papaya (cv Linn) peel and seeds TPC: N.R.	*S. aureus, Escherichia coli* and *P. aeruginosa*	-Aqueous extract of peels and seeds, respectively showed activity against *E. coli* (12.33±1.15, 15.67±1.15), *S. aureus* (8.00±1.73, 11.67±1.15) and *P. aeruginosa* (7.67±1.15, 0.00±0.00). -Ethanol extract against *E. coli* (17.33±1.15), *S. aureus* (15.00±1.73) and *P. aeruginosa* (14.33±1.15) was in each case higher ($p<0.05$) than seeds (14.33±0.58, 0.00±0.00, 9.67±1.15).	Egbuonu, Harry, & Orji (2016)
Disk agar diffusion	Papaya fruit and seed 1:10 (w/v) ratio powder: methanol 80% (15 µL, 20 µL and 25 µL) TPC: N.R.	*E. coli, S. typhi, B. cereus,* and *B. subtilis*	Fruit and seed extracts were more active against gram positives than gram negatives. E. coli (25 µL of extract): Fruit (6.5 mm), seed (7 mm) *S. typhi*: fruit and seed 8.5 mm. *B. cereus:* fruit 8 and seed 9.5 mm. *B. subtilis:* fruit 8.5 and seed 10 mm.	Tumpa, Hossain, & Ishika, (2015)
Broth dilution	Mango cv Ataulfo seed ethanolic (90%) extract with MAE, Fermentation-Assisted Extraction (FAE), SAE (Solvent-Assisted Extraction). TPC: N.R.	*S. aureus*	MIC (*µ*g/mL) MAE 500.0±353.0; FAE 750.0±288.7; SAE 156.3±108.2 -The order of antibacterial activity (against *S. aureus* was SAE > FAE > MAE (although, this could vary depending on the strain).	Torres-León et al. (2021)
Well agar diffusion	Olive leaves (OLE); coriander leaves (CLE) & mango seed kernels (MSKE) extracts 1:10 (w/v) ratio methanol (80%) TPC: OLE: 16.43; CLE: 6.87; MSKE: 29.84.	*B. subtilis, S. faecalis, N. gonorrhoeae, P. aeruginosa, S. aureus* and *E. coli*	*B. subtilis:* OLE: 12 mm; CLE: 9 mm; MSKE:16 mm; *S. faecalis*: OLE: 12 mm; CLE: 10 mm; MSKE:16 mm.; *N. Gonorrhoeae*: OLE: 12 mm; CLE: 10 mm; MSKE:14 mm; *P. aeruginosa*: OLE: 13 mm; CLE: 12 mm; MSKE:15 mm; S. aureus: OLE: 14 mm; CLE: 10 mm; MSKE:15 mm. and *E. coli:* OLE: 13 mm; CLE: 12 mm; MSKE:15 mm.	Badee, Moawad, El Noketi, & Gouda (2020)
Disk agar diffusion	Mango seed ethanolic (10:1 v/w) extracts cv Waterlily	*S. aureus, B. subtillis, E. coli, P. aeruginosa*	21 mm *S. aureus*; 18 mm *B. subtillis;*18 mm *E. coli*; 14 mm *P. aeruginosa*.	Abdullah (2011)
Disk agar diffusion/ Broth dilution	Guajava leave ethanolic 70% extract TPC: N.R.	*S. aureus, E. coli, P. multocida, B. cereus, S. Enteritidis* and *M. gallisepticum*	500 mg/mL extract concentration Inhibitory zone (mm) - *S. aureus* 15.62±1.15 *E. coli*, 10.55±0.15 *P. multocida* 18.02±0.95, *B. cereus* 10.05±0.15, *S. enteritidis* 10.12±0.55 and *M. gallisepticum* 14.62±0.55. MIC (*µ*g/mL) - *E. coli* 625 *P. multocida* 5000, *B. cereus* not detected, *S. enteritidis* 625 and *M. gallisepticum* 1250.	Hemeg et al. (2020
Well agar diffusion/Broth micro-dilution	P. guajava cv Aldabab and Anna peel methanol 80 % extracts TPC: cv Aldabab 8.35; cv Anna 9.87	*E. coli* (EC), *K. pneumoniae* (KP), *P. aeruginosae* (PA) MRSA, *S. aureus* (SAU), *S. agalactiae* (SA) and *E. faecalis* (EF)	cv Aldabab: Inhibition zone (mm)- MRSA: 15±0.9; SAU 10±0.5; SA13±0.8; EF 15±1.6; KP 12±0.2; EC: no detected; PA 15±1.6. MIC (*µ*g/ml) - MRSA: 1974; SAU 835; SA 987; EF 1670; KP 835; EC: no detected; PA 1670. cv Anna: Inhibition zone (mm) - MRSA: 23±1.5; SAU 14±0.8; SA28±1.2; EF 16±1.5; KP 15±0.8; EC: 13±1.7; PA 18±1.3. MIC (*µ*g/ml) - MRSA: 1670; SAU 493.5; SA 418; EF 987; KP 493.5; EC: 1974; PA 987.	Almulaiky, et al. (2018)

(*continued on next page*)

Table 3 (*continued*)

Test method	Fruit extract	Tested microorganisms /Target microorganism	Antimicrobial effect -Results	Reference
Disk film agar diffusion	Corn starch-gelatin film (CSG) (5–15% w/v) mango (puree and peel) and pineapple pomace Mango puree (MP) and Mango puree with peel (MPP) TPC: MP 15% 16.62 ± 0.002; MPP 15% 23.51 ± 0.006 (μg GAE/g film)	*P. aeruginosa, S. typhi* and *M. smegmatis*	-Antioxidant, antimicrobial activity and TPC were increased with increase in concentration of all active components. - The most effective antimicrobial film formulations were: MP 15%: 26.33 ± 1.25 *P. aeruginosa*; 20.33 ± 1.24 *S. typhi*; 26.33 ± 1.70 *M. smegmatis*; and MPP 15%: 33.66 ± 0.58 *P. aeruginosa*; 22.33 ± 2.51 *S. typhi*; 18.34 ± 1.52 *M. smegmatis*.	Susmitha, Sasikumar, Rajan, Padmakumar, & Nampoothiri (2021).
PDA agar surface in petri dish	Cassava starch (CS)/Chitosan (CH) film/ Pitanga (*Eugenia uniflora* L.) leaf extract (PE)/ Natamycin (NA) TPC: N.R.	*A. flavus, A. parasiticus*	Positive anti-fungal effect of NA containing films. NA (1 g /100 g film): *A. flavus* (10.5 ± 0.7 mm) and *A. parasiticus* (11.0 ± 0.1 mm). PE + NA (2.25 g PE + 1 g NA/100 g film): *A. flavus* 6.5 ± 0.7 mm (antagonistic effect) and *A. parasiticus* 11.0 ± 0.1 mm.	Sirisha Nallan Chakravartula et al. (2020)

TPC: Total phenolic content (mg_{GAE}/ g_{sample} d.b.); N.R: not reported.

quentially deposited, being the assembly and the surface characteristics mainly dependent on the mutual attraction of alternated polyelectrolytes, usually with opposite net charges (Tu et al., 2019). For deposition of a successive layer in a multilayer coating, dipping, spraying and other techniques can be used (Fig. 1).

Edible films can be produced using two main methods, wet (casting) and dry (extrusion, compression molding and injection molding) processes (Fig. 1) (Kumar et al., 2022; Monteiro Fritz, de Matos Fonseca, Trevisol, Fagundes, & Valencia, 2019; Otoni et al., 2017).

Casting is one of the most used methods to obtain edible films (Liu et al., 2020; Oliveira Filho et al., 2020; Nouraddini, Esmaiili, & Mohtarami, 2018) in which initial biopolymer solution contain a significant amount of water or other solvents like ethanol that needs to be evaporated. Thus, casting is regarded as a high energy-consuming process. Other parameters such as drying temperature should be adjusted to determine the mechanical and barrier properties of edible films (Tapia-Blácido, Sobral, & Menegalli, 2013; Wróblewska-Krepsztul et al., 2018).

The solution casting method has very limited industrial applications (Huntrakul & Harnkarnsujarit, 2019), however it is mostly used in laboratory scale (Jeya Jeevahan et al., 2020). This technique consists in three stages: achieving the solubilization of the film components to be dispersed (biopolymer, plasticizers, and additives) in a suitable solvent to obtain the slurry, pouring a determined volume into a flat surface, to have a control of the film thickness (Fakhouri, Martelli, Caon, Velasco, & Mei, 2015), and finally letting it dry completely (by conduction with supports and/or by convection with circulation of hot air and infrared rays) (Suhag et al., 2020). The current laboratory scale for film casting method has some drawbacks such as: inability of making large sized films (>25 cm), long drying times (1-3 days) and inaccurate thickness control (local variations in thickness) (Jeya Jeevahan et al., 2020). To counteract this situation de Moraes, Scheibe, Sereno, & Laurindo (2013) produced a continuous film by using tape casting method. To produce at an industrial scale, further investigation to optimize parameters is required. Although the fabrication processes of edible films differ from synthetic plastic production, the existing machines should be adapted to use for commercial making (Suhag et al., 2020).

On the other hand, drying methods do not require an evaporation step and could save considerable time needed for drying (Jeya Jeevahan et al., 2020). It is the major commercial film production process, used for synthetic polymers and for biopolymers, which are under development. These methods are an excellent alternative for solution casting industrial-scale film production, being difficult to control the film texture (Dang & Yoksan, 2015). Extrusion is a thermomechanical process, without solvent addition. Extrusors have three main zones to be set: feeding zone, kneading zone, and heating zone at the final part from the machine. High temperature causes phase transition, melting the solid. Therefore, extruded films possibly have different properties to those films obtained by solution casting (Huntrakul, Yoksan, Sane, & Harnkarnsujarit, 2020). Due to the extrusion process involving high-shear and high-pressure conditions, thermoplastic starch can be achieved with a low water content, since the shear forces physically can tear apart the granules, allowing faster transfer of water into the interior molecules. Glycerol is one of the plasticizers by excellence in this process and its content may vary from 20 to 45% depending on the type of starch and blowing ability (Lumdubwong, 2019).

Compresión molding and injection molding are also proposed for film formation. Generally, both techniques require a preliminary extrusion step to prepare the film forming material, which will be later subjected to high pressure and temperature in the mold or when injected, until solidification (Kumar et al., 2022).

Independently of filmmaking technique, researchers must regard many properties of the film such as transparency, opacity, gloss, swelling degree, thermal stability, mechanical resistance, flexibility, water solubility, permeability to O_2 and water vapor, functional characteristics such as effective microbial protection and/or antioxidant properties and a reasonable cost (Gheorghita, Gutt, & Amariei, 2020; Khanzadi et al., 2015; Kanatt, Rao, Chawla, & Sharma, 2012). Particularly, mechanical strength is an important parameter because the edible packaging should protect the contained food from external loads, some typical parameters are TS, YM and EAB.

4. Uses and applications of active starch-based edible films and coatings in food technology

Edible films and coatings have been used to extend food shelf-life for centuries, so it is not a new concept, thus different innovative applications have been discovered to take full advantage of their capabilities (Cheng et al., 2021). It is important to remark that the production and application processes must be carried out with high hygienic levels (Pavli, Tassou, Nychas, & Chorianopoulos, 2018).

Films and coatings from biopolymers have created a new alternative for food preservation, increasing food quality, shelf-life and functionality in edible and biodegradable packaging (Umaraw et al., 2020). They protect the food from environmental effects by regulating moisture, oxygen, carbon dioxide, aroma and taste compounds transfer and by controlling respiration. Particularly, starch seems to be one of the most promising biopolymer, among various renewable sources, due to easy availability and processing, higher yield, low cost, biocompatibility, biodegradability, edibility and tailored functional properties. Additionally, starch films are semi-permeable to gases, moisture, lipids and flavor components, which are essential for effective food packaging materials (Majeed et al., 2023; Lumdubwong, 2019; Pérez-Vergara, Cifuentes, Franco, Pérez-Cervera, & Andrade-Pizarro, 2020).

Particularly, starch-based films provide adequate oxygen barrier properties to make them more accurate to be used in fresh fruits and vegetables in order to prevent anaerobic respiration. Moderate barriers with a certain degree of oxygen and carbon dioxide permeability are needed for the respiration of living tissues (Sapper & Chiralt, 2018; Lumdubwong, 2019).

Film and coating properties can be modified during the preparation of film-forming solution by the mechanical treatment (stirring speeds and time) (Brain Wilfer et al., 2021; Santacruz, Rivadeneira, & Castro, 2015), and by selecting a starch concentration, the type of plasticizer and other additives (Majeed et al., 2023; Putri, Adhitasari, Paramita, Yulianto, & Ariyanto, 2023). Particularly cassava starch-based edible films are cheap, taste-less, odorless, colorless. Sweet potato starch shows stable viscosity under severe processing conditions, which indicates its great properties to handling in the film preparation process (dispersion, pasting, casting, and drying) (Zhang, Hou, Liu, Wang, & Dong, 2019; Nwokocha, Aviara, Senan, & Williams, 2014). Sorghum shows a very high productive potential and is a low-cost raw material (Biduski et al., 2017). Its starch could portray good functional properties to be used in formulations of edible films and coatings (Mehboob, Ali, Sheikh, & Hasnain, 2020). In order to display the relevance of the use of conventional and non-conventional starches to develop edible films and coatings to protect food matrices, some recent applications are described in Table 4.

Edible films and coatings also allow to carry antioxidant and antimicrobial materials, inorganic nanoparticles, flavors, enzymes, colors, minerals, vitamins and probiotics (Beikzadeh, Khezerlou, Jafari, Pilevar, & Mortazavian, 2020), constituting an active packaging material. When food is stored in an active packaging system, physical, chemical and biological activities alter its state allowing an increase in shelf-life, without compromising food quality (Pavli et al., 2018).

The use of different active compounds to be incorporated in the films and coating matrix has been the focus in latest investigations. An interesting application is the use of natural antioxidants or antimicrobials as additives to control pathogens and extend the shelf-life of food (Lumdubwong, 2019). Even though these compounds can enhance the functionality of edible films and coatings, they might also alter their original flavor and color (Martín-Belloso et al., 2009).

Several parameters determine the effectiveness of edible films in extending the food shelf-life such as antimicrobial agents incorporated within their structure, their capacity for retention and controlled release of the additives, target microorganisms and their populations, and physicochemical properties of the food product. Regarding antioxidant capacity, the addition of phenolic compounds from fruit extracts can be evaluated by the oxidation level of susceptible components of packed food, such as lipids (Sahraee, Milani, Regenstein & Kafil, 2019). On other hand, it must be taken into account that, extract addition could promote hydrophilic/hydrophobic alterations in matrix films, affecting the mechanical properties, solubility, crystallinity degree, etc., in comparison with films or coatings without active compounds, potentially affecting packaging performance.

The use of fruits and vegetables contributes to mitigate the substantial postharvest loss of fruits and vegetables due to defects or an inadequate ripening stage. Fruits and vegetables (purees, residues, extracts) contain water, pectin, dietary fibers, lipids, phytochemicals, pigments, and phenolic compounds. Fruit puree edible films are composed of pectic and cellulosic substances (primary polysaccharides in fruit). Besides, the variety of sugars in fruit purees has a plasticizing function, depending on fruit cultivar and maturity, as well as agricultural and environmental conditions, so each case and application requires a specific formulation (Hernalsteens, 2020).

Many tropical fruit parts or extracts have been incorporated into active packaging in an effort to demonstrate their suitability to increase food protection and stability. Table 5 shows potential applications of these materials, focusing on the influence of such natural additives on matrix properties and their efficiency as a component of an antimicrobial and/or antioxidant packaging system.

5. Future trends

The main aspects of starch-based edible films and coatings as carriers of active compounds extracted from tropical fruits or their wastes and as packaging material for food applications were summarized. Although profuse literature has been found reporting the properties and the advantages of this kind of material, and many efforts have been done to improve the characteristics of starches materials, a great deal of work is still required to create starch-based films with more suitable functionalities for food preservation, especially if compared to conventional polymers.

There is incipient research focused on overcoming these limitations and improving the efficiency of edible films and coating added with fruit extracts, searching for alternative materials that can offer technologically advanced food packaging, sensing capabilities and improvements. In this context, the advent of nanotechnology, prompted revolutionary perspectives for the advancements in diversified industrial applications. Among different possibilities, the film matrix tightening and the decrease of the WVP can be achieved by formulating nanocomposite materials with the addition of reinforcing nanofillers (Majeed et al., 2023; Ortega et al., 2023; Jafarzadeh et al., 2022; Liao et al., 2023). A nanocomposite that has shown great potential for the development of novel active food packaging films is silver nanoparticle, which exhibited excellent mechanical properties, great inhibition against *E. coli* and lower permeability and water solubility (Yang et al., 2023). On the other hand, micro and nanoencapsulation of bioactive compounds represent a viable and efficient approach to increasing the stability of the active substances (antioxidants, antimicrobials, flavors, etc), protecting them from interactions with the film and food ingredients, controlling their release from film matrix and, because of the subcellular size, increasing their bioactivity (Andishmand et al., 2023). However, the biggest challenge is to take this new technology to a commercial level to extend the shelf-life of fresh foods (Sharma et al., 2023). Among the notable benefits of nanotechnology for food ingredient encapsulation are the increase in surface area that may lead to the improvement in bioavailability of flavors and food ingredients (especially for those that have low solubility and/or low flavor); the improvement in solubility of poorly water soluble ingredients; the optical properties due to

Table 4
Potential applications of starch-based films and coatings in different food matrices.

Type of starch/modification	Active compound	Applied method	Food matrix	Significant Results	Reference
Cassava (ACS)/ Acetylated (25%)	-	Coating	Guayaba	- Increased firmness. - Maintained green skin color. - Reduced ripeness, lasting for 13 days.	Francisco et al. (2020)
Cassava	-	Coating	Guayaba	- Increased the shelf-life in two days - Loss of mass decreased. - Decreased the variations in comparison to non-coated fruits.	Pellá et al. (2019)
Cassava + Chitosan+ whey protein + beeswax	-	Coating	Andean blackberry	- Positive effect in texture, flavor, and aromas. - Color changes due to anthocyanin losses. - After 10 days of storage, (4°C) weight losses were 39.6% lower and firmness was 81.4% higher. - Chitosan reduced the mold and yeast count. - Increase 100% the useful life of the fruit.	Cortés-Rodríguez, Villegas-Yépez, Gil González, Rodríguez, & Ortega-Toro (2020)
Cassava	Propolis (33 and 66 %)	Coating	Strawberry	- 66% of propolis promoted higher Vitamin C content at 8 and 12 days of storage. - For antioxidant activity, fruits treated with CS maintained a higher FRS percentage (free radical scavenging) at all-time evaluations (16 days). - Highest antioxidant capacity (ABTS) observed in CS and CS + P66% treatments. - There was an increased tendency of the phenolic content during storage in all evaluated fruits. - The propolis concentrations used were not sufficient to increase or maintain the antioxidant capacity and phenolic contents of strawberries.	Thomas, Nassur, Boas, & Lima (2016)
Cassava (amylose 19%, amylopectin 81%) Chitosan nanoparticles (CNP)		Film	Cherry tomatoes	- 15 to 20% w/w starch/CNP films exhibited antimicrobial activity - *In vivo* study indicated higher efficacy of 15% w/w starch/CNP film in controlling microbial growth in cherry tomatoes leading to improved shelf-life (10°C, 10 days)	Shapi'I, Othman, Nordin, Basha, & Naim (2020)
cassava starch (native and acetylated) and whey protein (WPI) +	Rambutan peel extract (RPE) and cinnamon oil (CO)	Film	Salami	- WPI-non-active showed no antibacterial activity. - Addition of RPE+ CO enhanced antibacterial activity against *B. cereus, E. coli* and *S. aureus*. - Increased starch content improved the antibacterial activity of active films. - WPI films showed the lowest in vitro antibacterial activity but the highest efficacy to delay microbial growth in salami.	Chollakup et al. (2020)
Cassava (5%)	Grape pomace extracts (Cabernet Franc and Viognier).	Films	Ready-to-eat-chicken	- Inhibitory effect on *S. aureus* ATCC 29213 - Inhibitory effect against *L. monocytogenes*	Xu, Willis, Jordan, & Sismour (2018)

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Table 4 (*continued*)

Type of starch/modification	Active compound	Applied method	Food matrix	Significant Results	Reference
Sweet potato (6% w/v) starch		Films		- Increased plasticizer concentration led to an increase in the percentage of elongation, water solubility (WS), and water vapor permeability (WVP) of sweet potato starch films. - Films plasticized with glycerol have the highest values for percentage elongation and WVP.	Ballesteros-Mártinez, Pérez-Cervera and Andrade-Pizarro (2020)
Sweet potato (3:1) 5 g (w/w)	Waste of lemon (Citrus limon) pectin - TiO_2-nano incorporated at different concentrations (0.5%, 1%, 2%, 3% and 4% wt)	Films		- The increases of TiO_2-NPs concentration significantly decreases in the moisture content, solubility, and moisture uptake of the films. - Mechanical and moisture barrier properties were improved with low concentration nano- TiO_2 NPs. - SEM: good particle dispersion with low content (0.5–2% wt) of nano- TiO_2 NPs. - UV prevention capacity (transmittance decreased with increasing TiO_2) allows biodegradable packaging material to be used as food grade UV screening.	Dash, Ali, Das & Mohanta (2019)
Sweet potato Octenylsuccination	Oregano essential oil (OEO)	Films	-	- Octenylsuccination powerfully retarded the coalescence of oil droplets in film and favored their homogeneity in the dried films. - Comparable inhibitory efficacies were observed against *S. aureus* and *E. coli.* - Octenylsuccination or OEO incorporation decreased film strength, rigidity, water content, water solubility and water vapor permeability while increased film extensibility to a less degree than their combination.	Li, Ye, Lei, & Zhao (2018)
Sweet potato starch	montmorillonite (MMT) nanoclay/ Thyme essential oil (TEO)	Film	Baby spinach leaves	- Efficient inhibition of *E. coli* and *S. Typhimurium.* - Improved microbiological quality of baby spinach during refrigeration. - No adverse effects on the sensory analysis.	Issa, Ibrahim, & Tahergorabi (2017)
Sweet potato	Thyme essential oil- TEO (0, 2, 4 and 6 g/100 g)	Coating	Shrimp	- Coated samples with TEO had lower counts of bacteria and lipid oxidation ($p < 0.05$) toward the end of storage (8 days). - Textural and color properties of coated shrimp were generally more acceptable. - No sensory changes during storage. - TEO (4 g/100 g) extend the shelf-life of shrimp meat during refrigerated storage	Alotaibi & Tahergorabi (2018)
Native Red Sorghum (5%)	-	Films	-	- Films showed a homogeneous surface with no pores, but it was observed some remaining ungelatinized granules that could affect mechanical and barrier performance.	Gómez-Aldapa et al. (2020)
Sorghum starch a. cross-linking b. acetylation c. dual	-	Films o solution casting	Bakery and confectionary items	- More clear and transparent - b, c retained more moisture - a, lower tensile strength, more elastic and flexible than native and a. - c, excellent mechanical properties, lower water permeability compared with native.	Mehboob et al. (2020)
Native Sorghum starch/ Acid Oxidation Dual (acid + oxidation)	-	Films	Rigid packaging (dual modification)	- b and c increased stiffness, higher tensile strength and lower elongation compared with a, and native. - c, increased the water vapor permeability - An increase in sorghum starch concentration in the filmogenic solution increased the thickness, water vapor permeability, and elongation of the films.	Biduski et al. (2017)

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Table 4 (*continued*)

Type of starch/modification	Active compound	Applied method	Food matrix	Significant Results	Reference
Potato starch Cationic	5% Curcumin	Films	N.R.	- Curcumin increased the elongation at break (18%) and hydrogen-bonding interactions and reduced the WVP (21%). - Mechanical properties were slightly improved. - Curcumin improved the UV blocking effect by (53.33%), and reduced the transparency (47.74%). - Good antioxidant activity and the highest scavenging activity of DPPH and ABTS was 86.77% and 98.09%. - Curcumin composite films are potential packaging materials for foods and can alleviate the problem of agricultural waste disposal.	Liu et al. (2022)
Mung bean starch (2 g)	0.75 g Guar gum + 1.5g sunflower seed oil	Coating	Rice Cakes	- Hardness of rice cakes decreased by 29 % and the crystallization rate (k) by 24 % compared with those of uncoated samples. - The moisture loss in uncoated samples was markedly higher than in coated samples. - Crystallinity analysis revealed the retarding effect of the developed coatings in starch retrogradation. - The addition of 0.8 % (w/w) grapefruit seed extract to the original formulation led to a distinct antimicrobial activity.	Lee et al. (2020)
Mung bean protein isolate (MPI)/pullulan (PU)	Marjoram essential oil (MEO)	Films	Minced beef meat	- Significant increment in TS and water-proof properties. The EAB was decreased, while TS and water-proof properties were increased. -Considerable positive effect on DPPH radical scavenging and antibacterial activity against pathogenic bacteria (*S. aureus* and *E. coli*). - Bacterial and chemical analyses of the minced meat samples: enhanced oxidative stability and showed effective antimicrobial activity against all of the tested bacteria.	HaHaghighatpanah et al. (2022)
Corn starch-gelatin (CSG)	Gelatin + (5–15% w/v) mango (puree and peel) and pineapple pomace	Films	N.R.	- Physicochemical properties including moisture content, swelling index, thickness and opacity, were improved. - Biological properties (antioxidant, antimicrobial activity and total phenolic content) were increased with increase in concentration of all the films.-Films showed more than 50% biodegradability after 15 days.	Susmitha et al. (2021)
Arrowroot starch (3.5, 3, 2.5, and 2%)	Iota-carrageenan (IC) (0.5, 1, 1.5, and 2%)	Coating	Cherry tomatoes	- Exhibited higher tensile strength, water solubility, swelling properties, and barrier properties, but completed biodegradation after 30 days.-Successfully inhibited weight loss of cherry tomatoes at room temperature and extended their shelf-life to 10 days.	Abdillah, & Charles (2021)

N.R. Not reported.

Table 5
Potential applications of tropical fruit extracts as antimicrobial/antioxidant active additive in films and coatings in different food matrices.

Tropical fruit extract	Film + coating matrix	Applied method	Food matrix	Significant Results	Reference
Mango peel waste extract (MPE) 5 wt% /AgNO3 1 wt%	Polylactic acid (PLA) 3 wt%	Film	Strawberry	- The film WVTR and OTR of PLA/MPE was improved compared with the pure PLA film. PLA/MPE/AgNPs improved also, and mechanical properties and thermal stability have been maintained. - The addition of MPE conferred excellent anti-oxidation and anti-ultraviolet capabilities. - PLA/MPE/AgNPs film has strong antibacterial properties. - Sensory evaluation: strawberries wrapped in different films for different lengths of period. PLA/MPE/AgNPs film showed excellent freshness-keeping performance as expected, which can potentially significantly prolong strawberries' shelf-life (7 days).	Cheng et al. (2021)
Mango cv Palmer pulp	Pectin 5 wt% (pulp mass basis)	Continuous solution casting films	-	- Continuous casting allowed good retention of the natural mango pulp coloration in the films, while increasing the edible film productivity. - Internal breakdown (IB) level of mangoes (injured mango pulp) affected edible film properties, as the physicochemical parameters of the mango pulps changed with IB progression. - Films with highest WVP, largest ductility and opacity were obtained from mango pulps with the most advanced IB stage. - Mango pulps with IB can be used as raw materials to produce edible films and can be applied to other injured fruits for valorizing fruits wasted due to aesthetical imperfections.	Oldoni et al. (2021)
Mango peel extract (MPE)	Polyethylene (PE) – Fish Gelatin (G)	Film	Margarine	- Thicker coatings produced colored films, which improved light barrier properties and increased DPPH radical scavenging values. - PE/G films (60 μm) had better UV barrier and scavenging activity and were used as an active packaging to evaluate the storage of packed margarine. - Margarine packed in PE/G film and stored at 4 °C significantly ($p \leq 0.05$) improved oxidation stability at the end of 28-day storage period and have potentials to be used as active packaging materials for delaying lipid oxidation. - The color properties of margarine were also affected by the storage conditions regardless of their packaging materials.	Nor Adilah, Noranizan, Jamilah, & Nur Hanani (2020)
Mango and guava puree	Nanofibrillated bacterial cellulose (NFBC)	Film	-	- Films with mango or guava puree exhibited remarkable differences in tensile properties, water vapor barrier and water resistance, compared with films without any fruit purees. - The replacement (partial or total) of pectin (NFBC) - improved physical properties of edible films (with and without fruit purees), stronger, stiffer, more resistant to water, and with enhanced barrier to water vapor films. - Higher NFBC content in film is suitable for applications which require some water resistance and better tensile properties, such as for food wrapping or coating, while films with only pectin as matrix for applications which require water dissolution, such as sachets.	Viana et al. (2018)
Papaya puree	Moringa oleifera leaf extract/ascorbic acid	Film	Minimally processed pear	- Papaya puree: nutritional value and prolong the shelf-life of food susceptible to oxidation, such as pears, due to its high antioxidant capacity. - Moringa: unfavorable impact on sensory acceptance, because of darkening. Important protein contribution. - Ascorbic acid allowed the conservation of the physicochemical properties of the food matrix (pear fruit minimally processed) and high sensory score under refrigeration at 8°C.	Rodriguez, Sibaja, Espitia, & Otoni (2019)
Papaya puree 8% w/w	Starch 2% w/w/gelatin (1, 2 and 3% w/w)/ defatted soy protein DSP (4% w/w)	Film	-	- Gelatin + DSP + papaya puree improved the mechanical, barrier, optical properties along with structural properties. - 3% gelatin, films had shown decrease in EAB. - 3% gelatin or 4% DSP, papaya films had shown an increase in the water contact angle values. - DSP films had low water solubility. - Optical properties: comparable with polymer based packaging materials. - -8% w/w papaya puree +3% w/w gelatin + 4% DSP composite films had highly improved edible film properties.	Tulamandi et al., (2016)

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Table 5 (*continued*)

Tropical fruit extract	Film + coating matrix	Applied method	Food matrix	Significant Results	Reference
Pineapple peel extract (5%, 10%, 15%, and 20%)	Polyvinyl alcohol (PVOH) and corn starch	Film	N.R.	- The results revealed that with the increasing concentration of PPEs, prepared films' thickness and water vapor permeability slightly increased.-Elongation at break of PVOH/ST films was also enhanced with PPEs concentration.	Kumar et al. (2021)
Mangosteen rind (2.5, 5 and 10 wt% on chitosan basis)	Chitosan	Film	N.R.	- Significantly increased the thickness, tensile strength, and UV–visible light barrier, antioxidant and antibacterial properties.Moisture content, water solubility, water vapor barrier ability and elongation at break were reduced by mangosteen rind incorporation. - -Effectively inhibited the increase in the peroxide value and thiobarbituric acid reactive substances of soybean oil during storage.	Zhang et al. (2020)
Banana peel extract (4%, 8% and 12%) (BPE)	Chitosan (CS)	Coating	Apple	- CS-4 %BPE composite film exhibited the most excellent properties.-The decline in moisture contents, water solubility and water vapor permeability of CS-BPE composite film indicated the reduced hydrophilicity.-CS-BPE composite film exhibited excellent antioxidant activity in different food simulants.-CS-BPE coating was more capable of improving the postharvest quality of apple fruit than CS coating.	Zhang et al. (2019)
Pineapple peel extract (PPE) and aloe vera gel (AVG)	Chitosan(C) /gelatin (G)/starch(S)	Film	Strawberry.	- PPE and AVG extract incorporated improved thermal stability of films. - Tensile strength decreased with the addition of extracts; the maximum tensile strength was 8.15 MPa for CGS film. - WVP of the films increased with the increasing PPE and AVG concentration. - Films inhibited the growth of gram-positive (*Staphylococcus aureus*) and gram-negative bacteria (*Escherichia coli*). - Addition of PPE and AVG film enhance antioxidant properties. - -Edible-coated films can be used for active food packaging/coating to extend the shelf-life of fruits.	Gürler (2023)
Mangosteen (MP) peel	HPMC	Film	N.R.	- Films exhibited 30.22 ± 2.14 and 30.60 ± 2.83 mm of growth inhibition zones against *S. aureus* and 26.50 ± 1.60 and 26.93 ± 3.92 mm of growth inhibition zones against *E. coli*.	Chaiwarit et al. (2021)
Mango peels extract (MPE)	Fish Gelatin	Film	N.R.	- Excellent free radical scavenging activity, addition of extract decreases the WVP. - Films incorporated with MPE showed a decrease of water vapor permeability (WVP) and lower film solubility. - High level of MPE films also exhibited more rigid and less flexible film formation. - Higher free radical scavenging activities are also observed for films with higher concentrations of MPE.	Adilah, Jamilah, Noranizan, & Hanani, (2018)
Mango peels extract (MPE)	Poly vinyl alcohol (PVA), cyclodextrin, and gelatin	Film	Chicken meat	- Composite films containing MP had good barrier to UV light. - TS of film containing 70% ethanol MPE was higher than that of control films. - Antioxidant activity and antibacterial activity (against both gram-positive and gram-negative organisms) was observed in films containing MPE. - Minced chicken meat packed in films not containing MPE spoiled within 3 days while that packed in MPE containing films had a shelf-life of more than 12 days during chilled storage.	Kanatt & Chawla (2017)

N.R. Not reported.

nanoemulsions with oil droplet sizes of less than 100 nm are optically transparent, the higher ingredient retention during processing; the homogeneity in system properties and the higher activity levels of encapsulated (Calderón-Oliver & Ponce-Alquicira, 2022). Another perspective is the use of new nanomaterials like nanozymes with enzyme-mimicking properties. Nanozymes potentiate to be a multifunctional active agent to engineer food active packaging, however, the utility of nanozymes in this field still remains largely unknown (Huang et al., 2023). It is important to remark that incorporating nanoparticles or nanocompounds as a constituent of food packaging demands prudent contemplation around peculiar aspects such as costs, legislation, consumer acceptance, cytotoxicity and migration behavior (Ahmad, Qurashi & Sheehan, 2023))

Regarding new improvements in edible films and coatings performance, bacteriophage addition is suitable for the preservation of vegetables, fruits, meat, and cheese by decreasing the growth of pathogenic bacteria. It was identified that the application of bacteriophages into edible films and coatings faces numerous challenges, including bacteriophage stability in the film, bacteriophage release from film to food, as well as the bacteriophage mobility and bacterial availability to promote physical contact (García-Anaya et al., 2023).

On the other hand, progresses in relation to new alternative sources of biopolymers that can be mixed with starch, include the use of *Spirulina* biomass from marine resources and high-value bioproducts (phycocyanin) to develop active and smart biodegradable and edible materials for application as food packaging (Nakamoto et al., 2023). In addition, new physical modification methods such as ultrasound or cold plasma can be useful to obtain starch materials with improved mechanical, solubility and barrier properties by reduction of the molecular weight or by incorporation of new chemical functional groups (Alzate, Gerschenson & Flores, 2020; Otálora González, Flores, Basanta & Gerschenson, 2020).

An important contribution to the understanding of the effect of fruit extract addition to films and coatings properties is the determination and standardization of the composition of extracts. For such proposes, more potent analytical methods are needed to elucidate the main components and their possible interactions of them with the starch matrix that can modulate its performance (Pedreiro, Figueirinha, Silva & Ramos, 2021). In addition, the proper management of the pre-treatment, storage, preservation, collection, controls and transportation of fruit discards and wastes is necessary to assess a continuous, safe and standardized resource of raw material for the extraction process.

In this line, further studies are necessary to rationalize the basic principles involved in the organization and intra and inter-interactions of starch macromolecules with other biopolymers and additives. In addition, the characterization of film and coating constitution processes, as well as, drying parameters and conditions of food covering are also relevant for carrying out preliminary pilot scale assays of filmmaking and food packaging.

Finally, coating techniques are expected to have an easier opportunity of being incorporated into a line industrial process. In contrast, there is still a lack to solve the big challenge of finding a suitable filmmaking technology with the capability to be scalable to an industrial level. Especially, efforts should be addressed to adapt the current equipment, such as extrusion machines, to produce starch-based packaging. All actions are a challenge and required a multidisciplinary approach where food technologists, engineers, chemists, physicians, and environmental specialists from industry and academia can join efforts to develop each time more and better options for active starch-based materials in a framework of the promotion of circular and sustainable processes to be used for reducing environmental pollution and food wastes and for the production of more stable and innocuous foods.

6. Conclusion

Edible films and coating represent a promising alternative to diminishing the use of petroleum-based polymers for food packaging applications. Starch is one of the most studied biopolymers to obtain edible matrices because it is readily available, biodegradable, inexpensive and due to the tailored functional properties of the materials derived from it. Although starch matrices have some mechanical and barrier limitations that should be considered previously to film or coating applications, the formulation and filmmaking methodology can be selected to modulate the performance as packaging material. In addition, the use of conventional and non-conventional starches expands the possibilities of adding value to underused crops, with increased economic benefits for local economies. The addition of extracts obtained from tropical fruits or from its by-products, confers to the edible film an active condition, antioxidant and/or antimicrobial, useful to extend food shelf-life and to promote health benefits, increasing nutritional values and conferring flavor, taste and color to the products. This review discusses and compares the general properties of starch-based edible films and coatings, the bioactive content of tropical fruit extracts and different test methods to prove the antioxidant or antimicrobial capability of matrices. The most recent applications of active packaging based on starch and added with active fruit extracts are summarized in terms of formulation, antioxidant or antimicrobial action and application technique, which are crucial to successfully extend the shelf-life of food products. Further studies regarding practical applications of edible packaging should be carried out to evaluate the environmental impact, the contribution of the ingredients in the film matrix characteristics and its interaction, focusing on film properties and tending to a feasible scaling-up for the food industry.

Ethical statement

The present manuscript is a review. Therefore, studies in humans and animals are not involved.

Declaration of Competing Interest

None.

Data availability

It is a review article, so it summarizes the results of other authors.

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