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Natural polyphenols for sustainable active, smart, and intelligent food packaging: a structured narrative review

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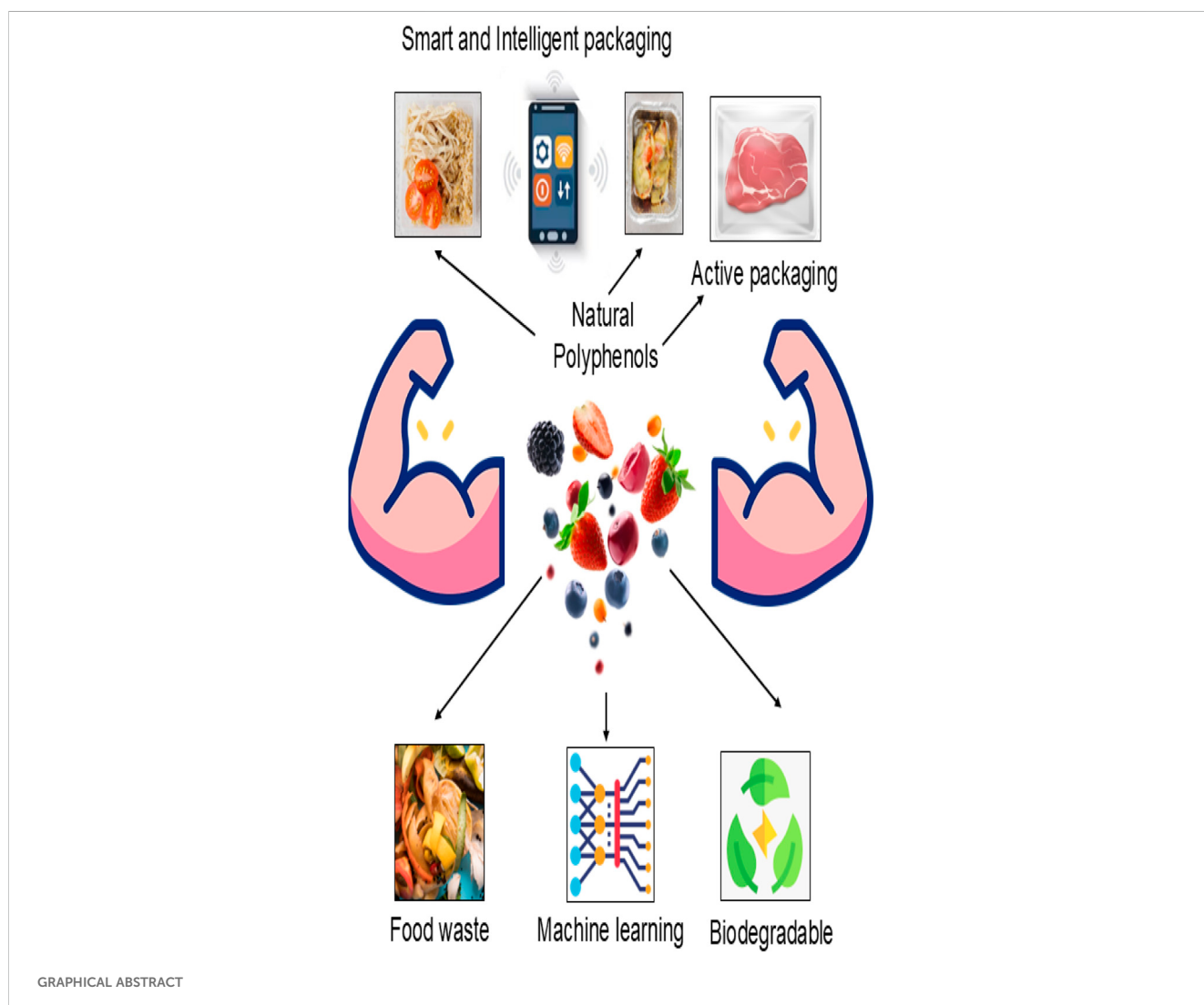
Food packaging offers essential food safety to the consumers. Conventional plastic-based food packaging offers only ordinary physical protection and may sometimes accelerate plastic pollution. Approximately one-third of all packaged foods are known to spoil in the supply chain mainly because of ordinary food packaging. Active, smart, intelligent, and nanocomposite food packaging measures offer many advantages over conventional food packing to retain quality while ensuring extended shelf-life. Natural fruits, vegetables, and tea are abundant source of polyphenols. Notably, recent trends in research demonstrate the utilization of natural polyphenols sourced from food-waste materials for sustainable use in active/smart/intelligent/nanocomposite food packaging. In this narrative review, we explore studies on active, smart, and intelligent food packaging films prepared using natural and food-waste polyphenols. The active packaging films/pads prepared using food-waste polyphenols and fruit polyphenols offer excellent antibacterial, antioxidant, antibrowning, and health-friendly effects. Thus, active, smart, and intelligent packaging materials using natural and food-waste polyphenols help to extend the shelf life of food and ensure minimal wastage of packed food. In addition, some of the active packaging films are edible while some others are biodegradable. In conclusion, the present review is expected to be helpful for promoting more sustainable use of food-waste-polyphenol-based active, smart, and intelligent food packing research.

KEYWORDS

active packaging, machine learning, tea polyphenols, food-waste polyphenols, food shelf-life

1 Introduction

Food packaging is a necessary measure for ensuring its original quality, easy transportation, and storage, which is also used as a space for advertising the manufacturer brands to some extent. However, maintaining balance between food production and food demands is challenging given the climate change issues mainly because of the effects of unpredictable weather-related changes on agriculture (Kazmi et al., 2023). About one-third of the total food produced globally is wasted in the supply chain (Bellemare et al., 2017). Furthermore, a recent meta-analysis study projected the global food



demands and populations at risk of hunger, which has raised concerns about the future of food security (Van Dijk et al., 2021). Food security issues are linked to climate change and have been assigned high priority (Lal, 2020) as achieving “zero hunger” is the second most important sustainable development goal (SDG) of the United Nations (Chen et al., 2023). Natural polyphenols are a large class of phytochemicals that are known for their many beneficial properties for human health (Wang et al., 2015; Wan Yahaya et al., 2019; Tkaczewska et al., 2023). Fresh fruits, vegetables, and spices are good sources of natural polyphenols (Valdés et al., 2015; Tudose et al., 2021; Tkaczewska et al., 2023). However, food waste materials have recently been reported as excellent sources of polyphenols and are therefore expected to provide sustainable options for sourcing polyphenols (Urbina et al., 2019; Coman et al., 2020; Rangaraj et al., 2021; Thivya et al., 2021; Deshmukh et al., 2022; Tkaczewska et al., 2023). Although food packaging without active films or pads can fulfil the ordinary needs of packaging, active packaging offers many advantages; for example, active food packaging can minimize food spoilage by inhibiting microbial growth, inhibiting oxidative deterioration of the food, extending the shelf life of the food, maintaining the sensory

properties of food, and offering additional antibrowning properties (Urbina et al., 2019; Thivya et al., 2021). Recently, antibacterial biopolymer films prepared using thyme essential oil were demonstrated to help in the preservation of milk cake (Mulla et al., 2024). Moreover, synergistic mixtures of natural extracts can enhance the antimicrobial properties and can be effectively applied to food safety and packaging technologies (Khanoonkon et al., 2022). Pectin extract from pineapple peel has been found to be an active edible coating that improves the antioxidant properties and maintains the quality of dried pineapple products (Meerasri and Sothornvit, 2023). Importantly, acknowledging that the harmful chemicals in food packaging and other materials that come into contact with food can pose considerable health hazards means that polyphenol-based packaging might even offer health promoting advantages in contrast.

The present review provides comprehensive information on active food packaging films prepared using natural polyphenols from diverse sources, including but not limited to tea, fruits, food wastes, spices, vegetables, and vegetable wastes. The main polyphenols in the total phenolic content are summarized based on their availability in literature. Moreover, biochemical tests like

DPPH, ABTS, and FRAP used to evaluate antioxidant properties as well as the antimicrobial tests, tested microorganisms, and methods used are summarized comparatively. Lastly, the types of active films and their compositions, properties, and technologies used for preparation have been summarized. The antioxidant and antibacterial properties, properties useful for extending the shelf life of food, and antibrowning properties are also discussed using graphical illustrations. Overall, this review provides up-to-date information on the applications of natural polyphenols, with special emphasis on the sustainable use of food-waste polyphenols for active packaging. We expect that this review may be of guidance for achieving the SDGs by promoting the use of food-waste polyphenols and by stimulating further research on biodegradable packaging materials.

2 Data collection and analysis

2.1 Inclusion criteria

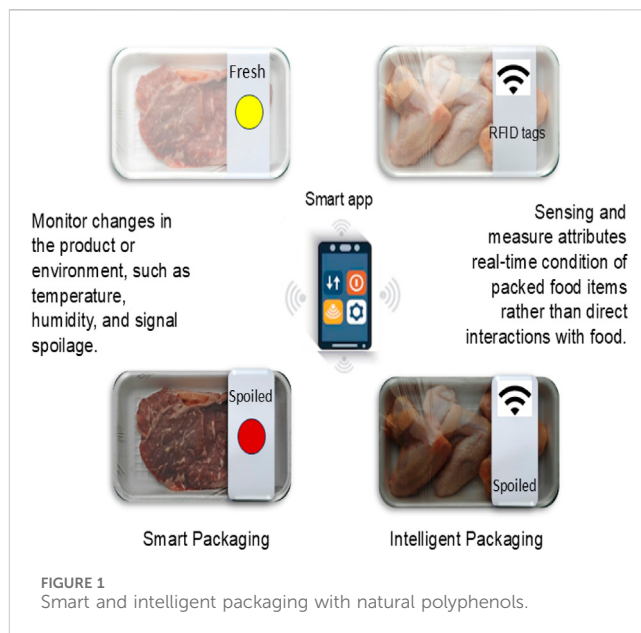
We conducted a literature search on Google scholar using keyword combinations like active packaging fruit polyphenols, fruit waste polyphenols, vegetable polyphenols, and vegetable waste polyphenols. Then, high-quality and highly cited research articles on active food packaging materials using natural polyphenols were selected and used in this review.

2.2 Exclusion criteria

We excluded conference abstracts, review articles, and non-English peer-reviewed publications as well as non-indexed, off-quality, and bad articles from our review.

3 Active food packaging using natural polyphenols

Active packaging materials not only enable performing tasks other than merely containing and physically safeguarding the food products but also ensure the quality of the packed food for a longer period of time (Wyrwa and Barska, 2017). The science and business of the food industry have gained new prospects because of active packaging technologies as these improve food preservation. There are many types of active packaging like antimicrobial, antifungal, and antioxidant films; carbon dioxide emitters/absorbers; ethylene absorbers; ethanol emitters; flavor releasing/absorbing systems; moisture absorbers; oxygen scavengers; and time-temperature indicators (Ozdemir and Floros, 2004). Natural polyphenols are non-toxic, commercially viable, and health-conscious; owing to these brilliant versatile bioactive properties, they are attractive choices for active food packaging applications. In addition, successful applications of natural polyphenols sourced from food-waste materials have been reported recently (Chollakup et al., 2020; Cui et al., 2020; Drago et al., 2022). Notably, a slow-release or controlled-release mechanism of the active polyphenolic compound is an important property of an active packaging film (Arabi et al., 2012).



4 Smart packaging with natural polyphenols

Smart packaging goes a step beyond ordinary packaging by not only preserving food but also providing information about its condition; it includes sensors and indicators that monitor changes in the product or its environment, such as temperature, humidity, or spoilage levels. This technology communicates such information to consumers or supply chain stakeholders, thereby enhancing the traceability and safety of the product (Figure 1). The key functionalities of smart packaging first include real-time monitoring and reporting information about the food and packaging conditions, such as temperature indicators and freshness sensors (Salgado et al., 2021). Second, there is direct interaction with the food that helps to retrieve its real-time condition and packaging data, e.g., color changing indicators that signal spoilage (Yuan et al., 2023). Third, smart packaging utilizes advanced technologies like microelectronics and sensors to gather and communicate data about the packaged product (Nasution et al., 2023). Fourth, smart packaging allows consumer interactions by providing visible indicators or digital information that can be monitored via smart devices to enhance user experience (Vilas et al., 2020). Finally, smart food packaging utilizes the advantages of naturally sourced polyphenols as active ingredients to exploit their antimicrobial, antioxidant, and antibrowning properties while prolonging the shelf life of the food (Rai et al., 2019; Vilas et al., 2020; Ullah et al., 2022; Li et al., 2025).

4.1 Intelligent food packaging with natural polyphenols

Intelligent food packaging is a subset of smart packaging that focuses on sensing and measuring attributes related to the real-time conditions of packed food items rather than direct interactions with the food; it does not alter the condition of the food and offers vital

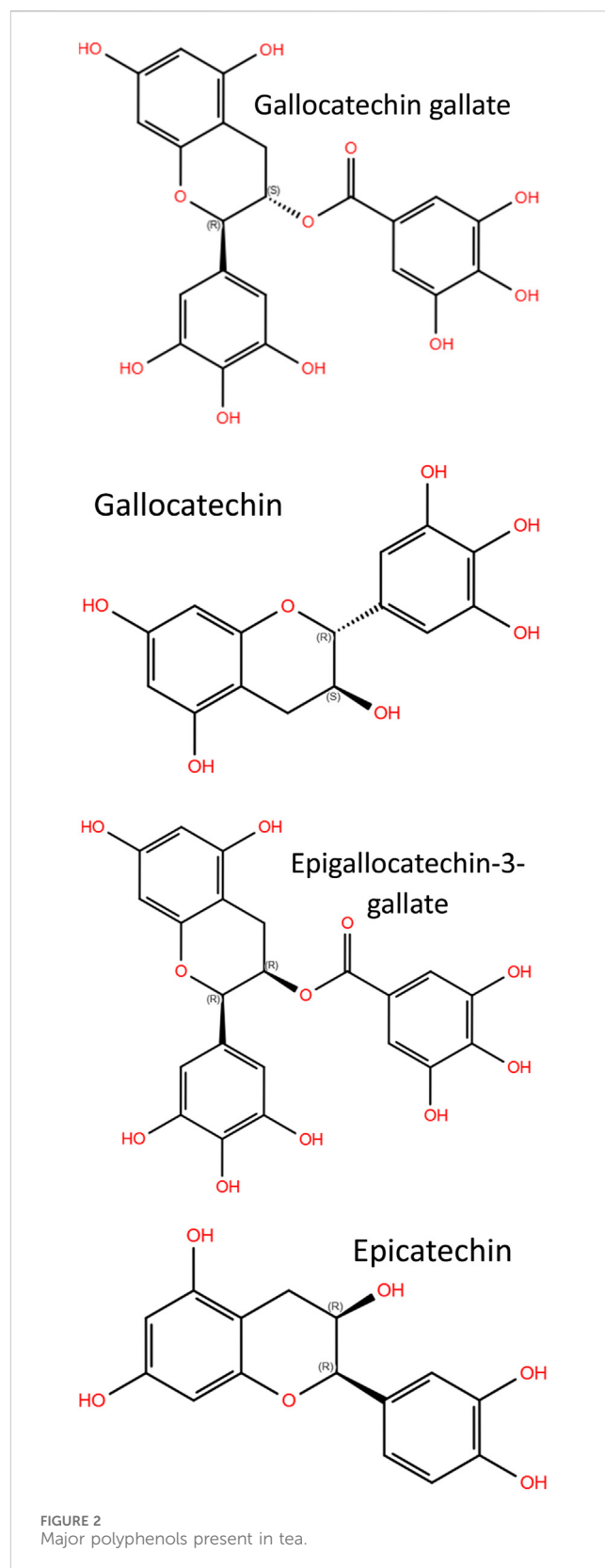
information to both consumers and stakeholders. Intelligent packaging often features time–temperature indicators, freshness sensors, and radio frequency identification (RFID) tags that communicate the product history and quality status (Figure 1). Similar to smart food packaging, intelligent food packaging utilizes the advantages of naturally sourced polyphenols as active ingredients to achieve antimicrobial, antioxidant, and antibrowning properties as well as prolonged shelf life of the food (Kanatt, 2020; Vilas et al., 2020; Sarfraz et al., 2024).

5 Sources of natural polyphenols

Natural polyphenols constitute the largest class of phytochemicals and have been extensively studied as they have versatile potential from therapeutics to food packaging applications (Afrin et al., 2016; Heenatigala Palliyage et al., 2019; Coman et al., 2020; Xu et al., 2022; Tkaczewska et al., 2023). In China and India, natural polyphenols have been known since ancient times and are popular for their many benefits to human health (Feng et al., 2015). There are more than 10,000 known natural polyphenols that are sourced from diverse plants, fruits, vegetables, and food wastes (Li et al., 2014). Polyphenols are structurally diverse and can be broadly divided into flavonoids and phenolic acids. Fruit peels are excellent sources of flavonoids, although the number of flavonoids found in each species varies depending on light exposure (Abbas et al., 2017). Conversely, phenolic acids are mainly found in cereal grains (Lafay and Gil-Izquierdo, 2008). Polyphenols sourced from tea, fruits, and fruit wastes have been mainly used in active food packaging research (Amjadi et al., 2019; Chollakup et al., 2020; Cui et al., 2020; Drago et al., 2022; Alvarez-Perez et al., 2023). Previous studies on active food packaging using natural and food-waste polyphenols have mostly reported the total phenolic content, while a few studies have characterized the total phenolic content (Supplementary Table S1). Below, we systematically discuss the various attributes of active packaging films prepared using diverse sources of natural and food-waste polyphenols.

5.1 Tea polyphenols

Catechins are the primary polyphenols in tea and comprise galliccatechins, galliccatechin gallate, epigallocatechin-3-gallate (EGCG), epicatechin-3-gallate, and epicatechin (Figure 2). However, EGCG is the most extensively researched catechin of green tea (Khan and Mukhtar, 2018). The active food packaging films prepared using tea polyphenols are mostly sourced commercially as high-purity tea polyphenols (Supplementary Table S1). The active packaging films/pads prepared using tea polyphenols have improved properties, such as UV-barrier property, water-vapor barrier property, tensile strength, surface hydrophobicity, roughness, and gas-barrier property. Nonetheless, some properties of the polyphenol-based active packaging films are diminished, such as the elongation at break, water vapor permeability (WVP), swelling degree, and optical transmittance (Supplementary Table S2). Solution casting is the most widely used method to prepare polyphenol-based active packaging films; however, electrospinning, temperature-assisted electrospinning, and ultrasound-assisted solution casting methods



are also reported for the preparation of tea-polyphenol-based active films (Supplementary Table S3). The antioxidant properties of these polyphenol-based active packaging films have been evaluated using ABTS, DPPH, and FRAP assays, whereas the agar disk diffusion assay

and CFU count of viable microorganisms have been used to assess the antimicrobial properties. Furthermore, food-infection-associated microorganisms have been used for such antimicrobial tests (Supplementary Table S3), such as *Listeria monocytogenes* (NCTC 7973) and *Escherichia coli* (NCTC 9001); *Staphylococcus aureus* (ATCC 29215) and *E. coli* (ATCC 25922); *S. aureus* (ATCC 6538), *E. coli* (PTCC 1330), and *Staphylococcus aureus* (PTCC 1112) (Siripatrawan and Harte, 2010; Ashrafi et al., 2018; Chenwei et al., 2018; Biao et al., 2019; Chen et al., 2019; Wu et al., 2019; Yuan et al., 2020; Yang et al., 2021; Zhang et al., 2021; Miao et al., 2022; Zhou et al., 2022). Lastly, it has been recognized that the catechins from green tea possess antioxidant, anticancer, and cardiovascular disease preventive properties (Mandel et al., 2006; Tsai and Chen, 2016).

5.2 Fruit and food-waste polyphenols

Natural polyphenols are excellent alternatives to synthetic food additives and also help in minimizing the adverse environmental impacts of industrial byproducts by recovering useful bioactive polyphenols from agricultural and food wastes (Mourtzinou and Goula, 2019). Active packaging films prepared using fruit polyphenols are often sourced from black currants, murta fruit, calanda peach, young apples, Chilean berries, goji berries, mastic leaves, olive fruits, citrus fruits, lychees, mulberries, wolf berries, myrtle berries, red raspberries, pomegranates, Chinese hawthorn, and κ -carrageenan mulberries. However, fruit-waste polyphenols are often sourced from apple peels, pecan nut shells, shallot wastes, pomegranate peels, apple pomace, mango peels, rambutan peels, litchi pericarps, grape pomace, pomelo and lime peels, and coconut water, among others (Supplementary Table S4). However, most of these studies have reported the advantages of the total phenolic contents of fruit polyphenols (Supplementary Table S1). A few reports have analyzed the total phenolic content using different sophisticated analytical techniques, including high-performance liquid chromatography with and without diode array detection, gas chromatography mass spectrometry, and tandem mass spectrometry. Furthermore, the different polyphenols obtained from vegetables, leaves, and spices used in active food packaging are sourced from cinnamon leaves, cinnamon oil, drumstick, papaya, Malaysian herbs, natural phenolic compounds, natural antioxidants, curcumin, soybean husk, and spent coffee ground extracts, among others (Supplementary Table S5). Positive antioxidant, antimicrobial, and antibrowning properties have been linked with extended shelf lives of packed food products. Notably, active packaging films prepared using polyphenols from fruits, fruit wastes, vegetables, and leaves have demonstrated positive antioxidant, antimicrobial, and antibrowning properties, thereby contributing to extended shelf lives of packed foods (Section 6.4).

6 Attractive properties of natural polyphenols

6.1 Antioxidant properties

Oxidative damage is one of the leading causes of quality degradation of packaged foods, mainly because the ambient

oxygen oxidizes the lipids within the food. Even at low concentrations, lipid oxidation produces various non-volatile and volatile chemicals that are sufficient for reducing or removing the organoleptic properties of food (Velasco et al., 2010). There are many ways in which the lipid content in foods can be oxidized, such as autooxidation, hydroperoxide formation, hydroperoxide decomposition, enzymatic oxidation, and photo-oxidation (Figure 3). In addition, the main factors influencing lipid oxidation are oxygen content or availability, storage temperature, light permeability, fatty acid composition, metals, physical structure of the food, and antioxidants (Velasco et al., 2010). Antioxidant active packaging offers excellent protective properties against oxidative damage of the food (Siripatrawan and Harte, 2010; Kan et al., 2019; Zhang et al., 2021); in addition, slow release of the antioxidant compounds from the active packaging films/pads can help extend the shelf lives of packed foods (Section 6.4). Notably, the majority of the active packaging studies concerning polyphenols have reported the antioxidant properties of active packaging films or pads (Supplementary Tables S2–S5); sensitive biochemical assays like DPPH, ABTS, and FRAP have been performed to assess the antioxidant properties of these active packaging films/pads to confirm reliability. Light permeability, O₂ barrier property, and the shape of the packaged food are also some of the major factors influencing oxidative deterioration of food (Velasco et al., 2010); notably, these properties of active packaging films were also reported to positively improve in favor of reducing the oxidative damage of foods such as fresh-cut apples and vegetables (Supplementary Tables S2–S5).

6.2 Antimicrobial properties

The antimicrobial properties of natural polyphenols are well-known (Chollakup et al., 2020), and tea polyphenols are very popular for their antimicrobial properties (Chenwei et al., 2018; Riaz et al., 2018; Wu et al., 2019; Yang et al., 2021; Sharma et al., 2022; Vieira et al., 2022; Zhou et al., 2022). Resistance to microbial growth is also an important property of natural-polyphenol-based active packaging films as it is positively correlated with extended shelf life of the packaged food (Section 6.4). Natural polyphenols, including the polyphenols from tea, fruits, and vegetables, noted herein have been reported to demonstrate antimicrobial properties (Supplementary Tables S2–S5). As noted before, most of the studies on active food packaging have reported mainly the total polyphenolic content (Supplementary Tables S2–S5), while very few studies have reported the active components in the total phenolic content, such as EGCG, catechins, caffeine, tannic acid, gallic acid, bromelain, and ferulic acid (Supplementary Table S1). In general, there are five modes of action for antimicrobial compounds (Figure 4), namely by interfering with cell wall synthesis, plasma membrane integrity, nucleic acids, ribosomes, and folate biosynthesis (Neu and Gootz, 1996). The exact molecular mechanisms of the polyphenolic compounds have not been explored or discussed in extant studies on active food packaging using natural and food-waste polyphenols. However, the antimicrobial action modes of fruit polyphenols have been discussed extensively in an excellent review article by Kumar et al. (2021).

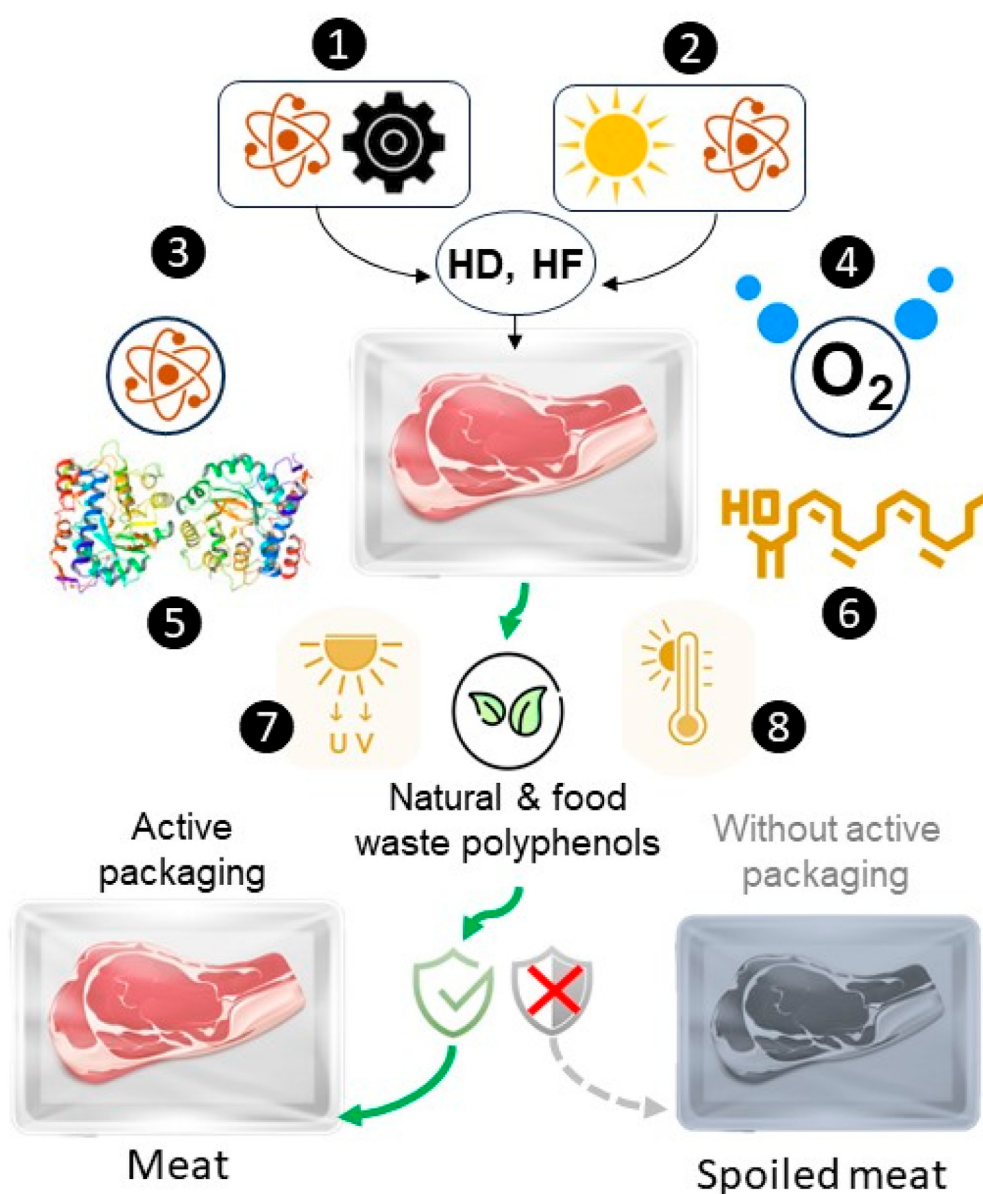
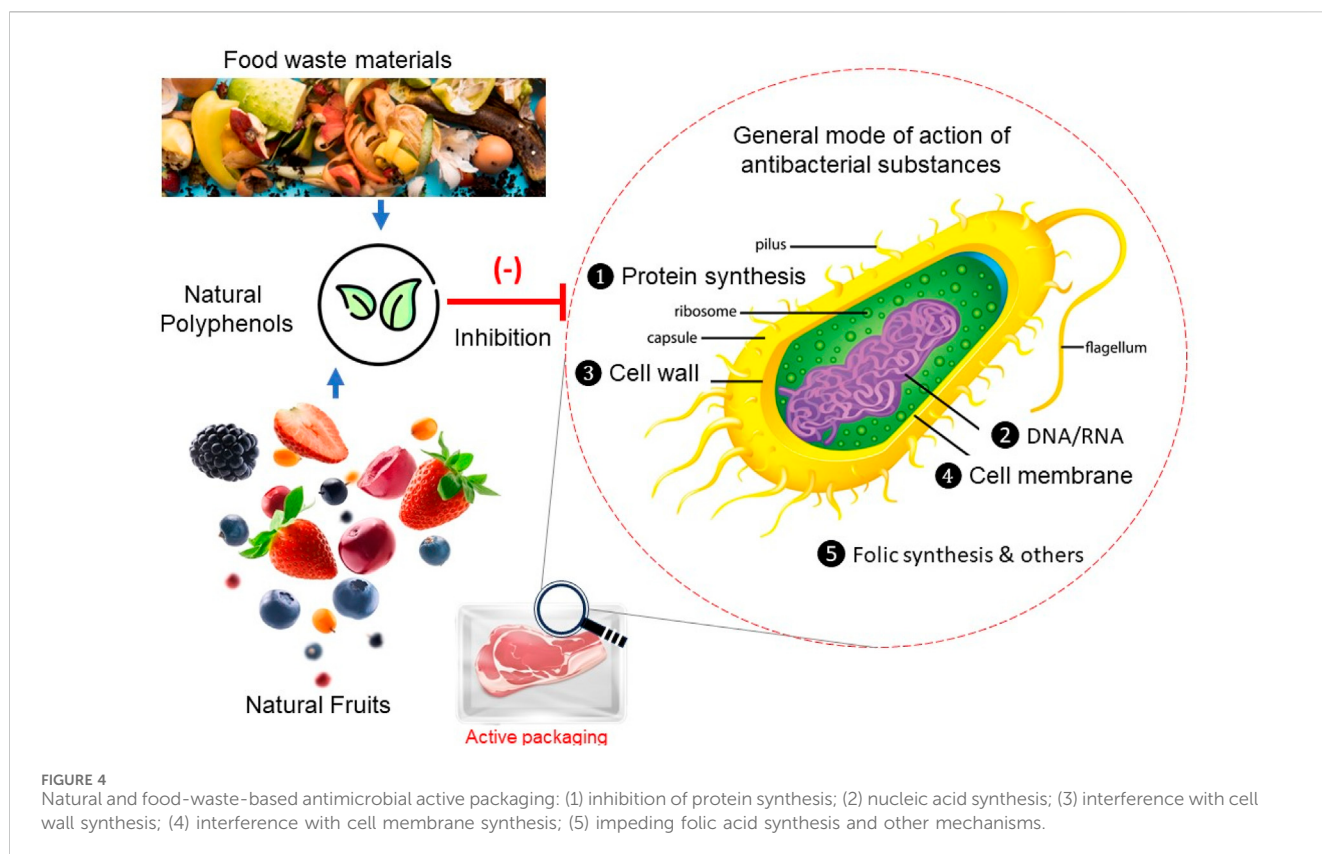


FIGURE 3

Oxidative deterioration of packed foods and the protective roles of polyphenol-based antioxidant packaging: (1) autoxidation; (2) photo-oxidation; (3) antioxidant availability; (4) oxygen availability; (5) enzymatic oxidation (e.g., 5ZBM); (6) fatty acid composition; (7) ultraviolet light barrier property; (8) storage temperature. HD; hydroperoxide decomposition, HF; hydroperoxide formation.

Fruit polyphenols may exert antimicrobial effects by inactivation of lipopolysaccharides (LPSs) (proanthocyanidins), antiadhesion (myricetin and proanthocyanidins), chelation of metal ions (tannic acid), inhibition of amino acid synthesis (gallic acid and caffeic acid), inhibition of binding (proanthocyanidins), disintegration of membrane proteins (bromelain), repression of genes (phloretin), ionic imbalance (p-coumaric acid, ferulic acid), inhibition of enzyme activities (phenolic compounds and catechins), pore formation in the cell membrane (p-coumaric acid and ferulic acid), and cytoplasmic leakage (bromelain). Nonetheless, the action modes of natural and food-waste polyphenols like gallic acid, caffeic acid, and tannic

acid may be inferred from previous studies (Kumar et al., 2021). These antimicrobial studies were evaluated using agar plate disk diffusion assays and colony-forming unit (CFU) counts of viable bacteria (Supplementary Tables S2–S5), while food-infection-associated microorganisms like *Bacillus cereus*, *L. monocytogenes*, *E. coli*, and *S. aureus* were used to confirm the antimicrobial properties (Supplementary Tables S2–S5). However, active packaging studies have demonstrated the antibacterial activities of natural polyphenols without using any standard antimicrobial substances as quality controls; hence, it may be necessary to include one or two positive controls while studying the antimicrobial properties of such polyphenols.



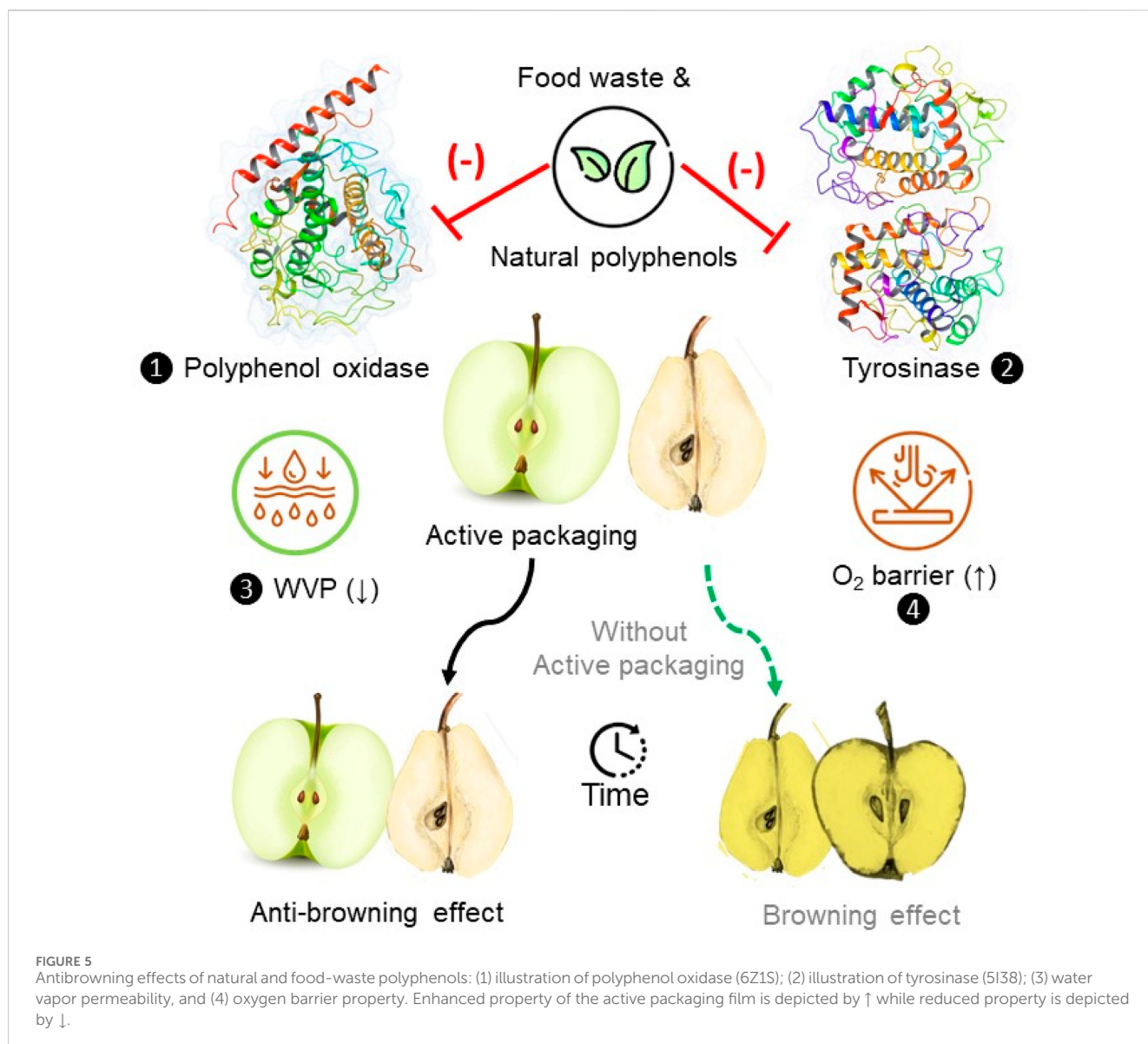
6.3 Antibrowning properties

Fruits and vegetables are commonly affected by enzymatic browning (Hamdan et al., 2022). Melanins are the compounds responsible for such browning (Djafarou et al., 2023) and are generated by the oxidation of phenolic compounds in damaged, sliced, peeled, and diseased fruits and vegetables. Melanins also cause the fruits and vegetables to darken faster when exposed to air. Enzymatic browning is primarily caused by polyphenol oxidase (PPO), while tyrosinase is responsible for melanin production (Djafarou et al., 2023) in most fruits, vegetables, and certain seafoods. Along with PPO (Moon et al., 2020), the related oxidative enzyme peroxidase may cause enzymatic browning of fruits and vegetables (Jiang et al., 2016). Active packaging films prepared using shallot waste extracts show excellent antibrowning effects against fresh-cut apples and potatoes through disruption of oxygen permeability, thereby facilitating longer storage (Thivya et al., 2021). Active packaging films prepared using shallot waste extracts were shown to accumulate CO₂ inside the packaging, while O₂ was consumed during respiration because of the O₂ barrier property of the film (Thivya et al., 2021). Conversely, fresh-cut fruits and vegetables packed with conventional plastic packaging films accumulate water and CO₂ inside the package, resulting in spoilage of the packaged food probably due to active anaerobic respiration (González et al., 2008). There are two possible approaches to inhibit the browning of fresh-cut fruits and vegetables, namely, by inhibition of oxygen permeability and addition of antioxidant substances (Arrieta et al., 2020). Nonetheless, poor WVP and gas barrier properties of the packaging films may contribute to browning of foods (Figure 5).

Active packaging films prepared using antioxidant extracts from the African horned melon (*Cucumis metuliferus*) have demonstrated excellent antibrowning effects by inhibiting the primary enzyme PPO (Arrieta et al., 2020). Moreover, as noted previously, tyrosinase is a member of the PPO family and is also very important for oxidative degradation of food items, especially fruits and vegetables (Loizzo et al., 2012). Remarkably, pecan nut shell hydroalcoholic extracts were recently reported to possess the ability to inhibit mushroom tyrosinase (Moccia et al., 2020).

6.4 Extending the shelf life of food

The shelf life of a food is the amount of time that the food is expected to be safe for eating and have intact organoleptic properties; it is primarily determined by four important aspects of food, namely, the formulation, processing, packaging, and storage conditions (Gallagher et al., 2011). WVP is a measure of the ease with which water vapor can move through a substance and is one of the main factors influencing high-quality food packaging and storage because water is crucial to spoiling reactions (Cazón et al., 2022). Thus, WVP plays a significant role in extending the shelf life of packaged foods (Kanatt et al., 2012). Active packaging films prepared using polyphenols from Chinese hawthorn (*Crataegus pinnatifida*) show excellent WVP, which may also help in extending the shelf lives of foods (Kan et al., 2019). Moreover, food packaging materials with better gas barrier (mainly O₂), added antioxidant, and antimicrobial properties could promote extension of the shelf lives of foods. The



effectiveness and quality of active packaging films in preventing microbial attacks on food are also linked to extending their shelf lives (Hanani et al., 2018). For example, the shelf lives of fresh-cut apples were shown to increase upon packaging them inside active films made of chitosan lychee pericarp powder (CHS-LPP). This may be attributed to the superior gas barrier and WVP properties, which inhibit O_2 and water from the outside environment into foods packed within the CHS-LPP films. Furthermore, CHS-LPP films are economically viable and environmentally friendly options as they are made from waste materials. CHS-LPP films were shown to exhibit excellent antioxidant properties and were successful in preventing oxidative degeneration of food, suggesting that they may also help in prolonging the shelf lives of foods by preventing oxidative degeneration (Jiang et al., 2021). Other films made of plasma-treated zein, pomegranate peel, and chitosan nanoparticle nanocomposites have been shown to be effective in reducing bacterial growth and prolonging the shelf lives of packed pork meat until the end of the prescribed storage period (Cui et al.,

2020). Similarly, chitosan (CS) apple peel polyphenol (CS-APP) film was shown to improve WVP; mild changes in the mechanical characteristics of CS-APP films at low polyphenol concentrations suggest that they could be suitable substitutes for synthetic materials. The combined effects from CS and APP are also known to have antibacterial properties; thus, CS-APP films may be used as antimicrobial packaging materials to extend the shelf lives of foods (Riaz et al., 2018). The shelf lives of chicken samples packaged within curcumin with active films made of chitin and glucan complexes (CGCs) were significantly extended compared to control samples as the CGC active films demonstrate excellent capacity to inhibit viable counts of bacteria; thus, positive antimicrobial properties may improve the shelf lives of meat products (Kaya et al., 2022). Moreover, CGC active films are biodegradable, suggesting that they are sustainable and environment friendly. Slow emission of the active ingredients in active packaging films is another aspect that may help with extending the shelf lives of food products (Amjadi et al., 2019).

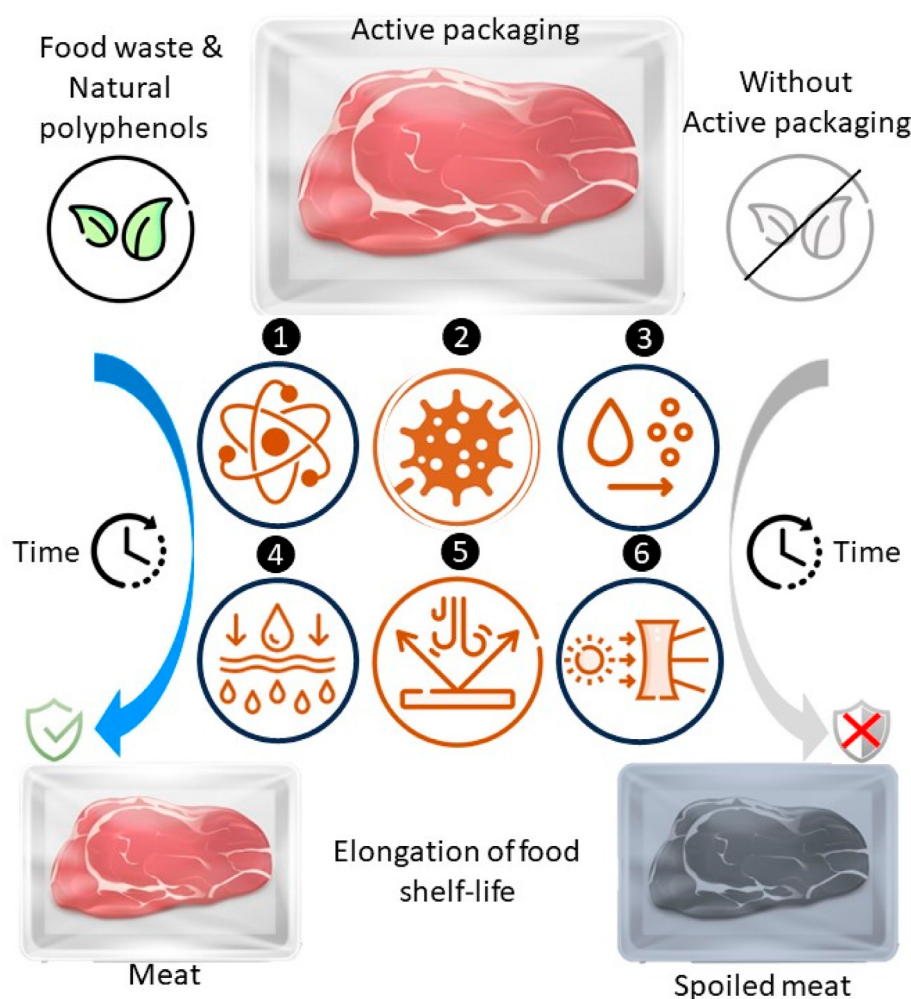


FIGURE 6

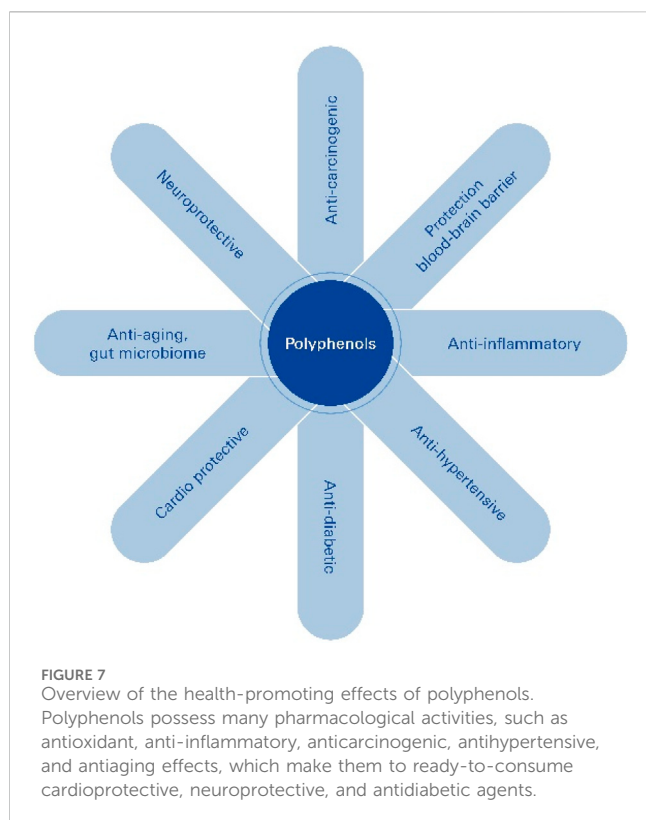
Extension of the shelf lives of food products using natural and food-waste polyphenols: (1) antioxidant property; (2) added antimicrobial property; (3) slow release of polyphenols; (4) improved water vapor permeability; (5) improved gas barrier property; (6) improved light barrier property.

An active compound can be applied as a surface coating to function at the surface level, which permits the use of active compounds at any point in the food supply chain (Arrieta et al., 2020). Therefore, to achieve prolonged shelf lives of food products, active compounds such as antioxidants and antibacterial agents may be applied to the surfaces of the packing materials. Furthermore, active packaging films containing fish gelatin and pomegranate peel powder have shown excellent antibacterial and antioxidant capabilities. The strongest protection against food pathogens during storage may be achieved through the active ingredients in the packaging materials, which could help in extending the shelf lives and maintaining the quality of foods (Hanani et al., 2019). Young apple polyphenol chitosan films have demonstrated antibacterial and antimold properties and may thus be useful as antimicrobial packaging materials to increase shelf lives of foods (Sun et al., 2017). Active packaging with edible-polyphenol-enriched plant extracts containing coatings could allow extension of the shelf lives of food products mainly because the ingredients are of natural origin and through the bioactive properties of the phytochemicals (Montero-Prado et al., 2011). In summary, the shelf lives of food

products could be extended through several attributes of active packaging films, such as antimicrobial properties (antiviral, antimold, and antifungal), antioxidant properties, lower WVP, reduced O_2 /gas permeability, light barrier properties, and slow release of active polyphenols (Figure 6). Notably, active packaging films prepared using natural and food-waste polyphenols show these important properties, suggesting that these films may be useful for better food preservation.

6.5 Health-promoting effects

The polyphenols found in fruits and plants are considered highly important functional foods. Thus, the use of polyphenols from fruit and food wastes may also have health-promoting properties alongside sustainability. To date, several *in vitro* and *in vivo* studies have been conducted to evaluate the effects of these chemicals on health (Agarwal et al., 2013; Afrin et al., 2016; Rana et al., 2022). Herein, we describe the anti-inflammatory, antihypertensive, and antidiabetic actions of polyphenols as well



as their antioxidant and anticarcinogenic capacities based on experimental evidence (Figure 7). Research has shown that polyphenols serve important roles in protecting the body from external stimuli and eliminating reactive oxygen species, which are responsible for several illnesses (Abolaji et al., 2018). Tea, chocolate, fruits, and vegetables contain polyphenols, which have the potential to boost the health of the human cardiovascular system positively. For example, the flavan-3-ols of cocoa have been associated with decreased risk of myocardial infarction, stroke, and type 2 diabetes in both animal and human studies. Additionally, resveratrol as a flavonoid and stilbene has been linked to a healthier heart (Abolaji et al., 2018; Lüscher, 2021). In addition to improving blood pressure, lipid profile, and insulin resistance, diets high in polyphenols can also lower cholesterol levels. Polyphenols from dietary sources may exert therapeutic effects on the gut microbiome through multifactorial characteristics. There is an increasing body of evidence on how the human gut microbiome intercedes feedback between our diet and health; the gut microbiome is also an important mediator of gut and systemic inflammation (Singh et al., 2017). It is important to note that polyphenols are converted into bioactive compounds by the gut microbiome. Expanding on this point, research on aging and longevity support the notion that the gut microbiome is at the core of many age-related disorders, including immune system dysregulation and susceptibility to major diseases (Badal et al., 2020). Recent studies have suggested that the intestinal microbiome has vital influence on modulating susceptibility to several chronic and common diseases, including inflammatory bowel disease, obesity, type 2 diabetes, cardiovascular diseases, and cancer.

7 Biodegradable smart, intelligent, and active food packaging

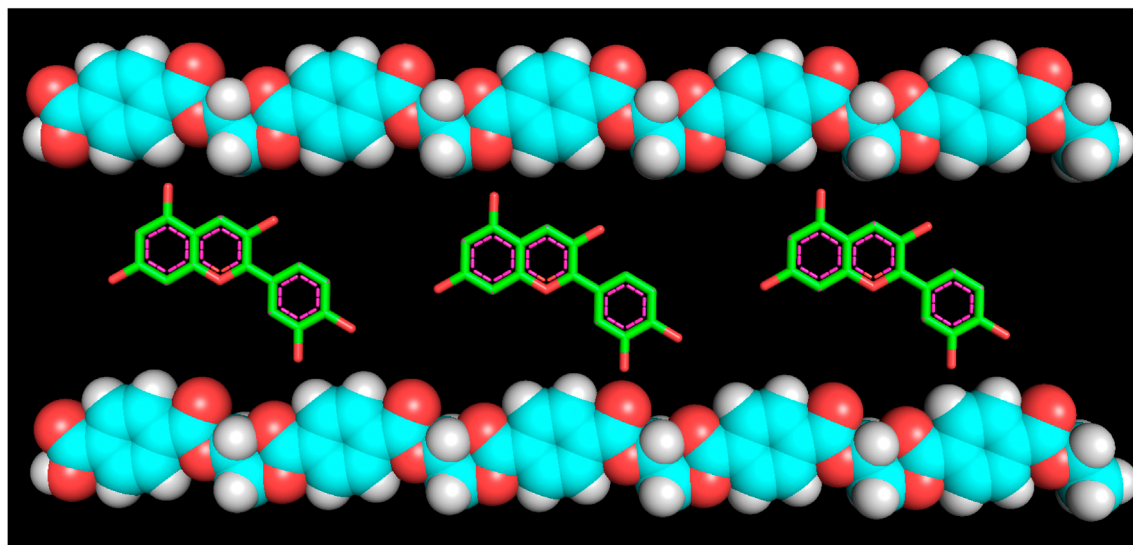
Biodegradable food packaging refers to packaging materials that are designed to break down naturally and return to the environment without leaving harmful residues. This type of packaging is increasingly being recognized for its potential to reduce environmental impact and promote sustainability in the food industry. The key feature of biodegradable packaging is natural decomposition of the material; thus, biodegradable nanocomposite food packaging can reduce reliance on fossil fuels by utilizing renewable resources (Qasim et al., 2021). It also diminishes plastic wastes in landfills and contributes to a circular economy where packaging wastes can be composted to enrich soil, meet the growing consumer demands for sustainable products, and enhance brand loyalty. In the food industry, biodegradable packaging is suitable for various food products, including fresh produce and baked goods, as well as takeout containers; it also ensures safe handling and preservation while minimizing the environmental impact (Dilkes-Hoffman et al., 2018). Overall, biodegradable food packaging represents a significant advancement in sustainable practices within the food industry (As'ad Mahpuz et al., 2022).

8 *In silico* molecular modeling of food packaging

In silico modeling has emerged as a powerful tool in the field of biotechnology to predict the molecular behaviors and improve the physicochemical properties of different materials, including drug-like molecules, supramolecular complexes, and polymers (Wang et al., 2010; Shityakov et al., 2014; Fateminasab et al., 2019). This innovative approach leverages computational techniques that may be useful for simulating active packaging systems, where materials interact with the packaged food to extend its shelf life and maintain freshness. One study successfully reported the development and validation of a comprehensive mathematical model to manage moisture condensation in active packaging through a moisture absorber during avocado storage; the model demonstrated high correlations ($R^2 = 0.97\text{--}0.99$) among moisture accumulation, adsorber efficiency, and fruit weight loss (Gaona-Forero et al., 2018).

Similarly, molecular dynamics (MD) simulations offer another avenue for exploration, particularly in investigating the interactions between polymers and antioxidant molecules. For instance, MD simulations have been used as ecofriendly antioxidant screening strategies to identify thymol, α -tocopherol, and lotus-seed-starch-EGCG as promising alternatives to enhance the oxidative resistances of natural rubber composites (Lu et al., 2020). In theory, polymers can also be analyzed *in silico* as molecules bound to polyphenols to form active packaging systems, such as the polyethylene terephthalate and epicatechin complex; this complex can be computationally designed in two dimensions as a “sandwich” model (Figure 8A) or as a three-dimensional polymer–ligand model (Figure 8B). By employing mathematical equations and MD simulations, *in silico* modeling provides valuable insights into how different packaging materials, designs, and active components can influence food preservation. This approach may help to reduce the need for costly and time-consuming experimental trials while contributing to more sustainable and efficient packaging solutions in the food industry.

(A)



(B)

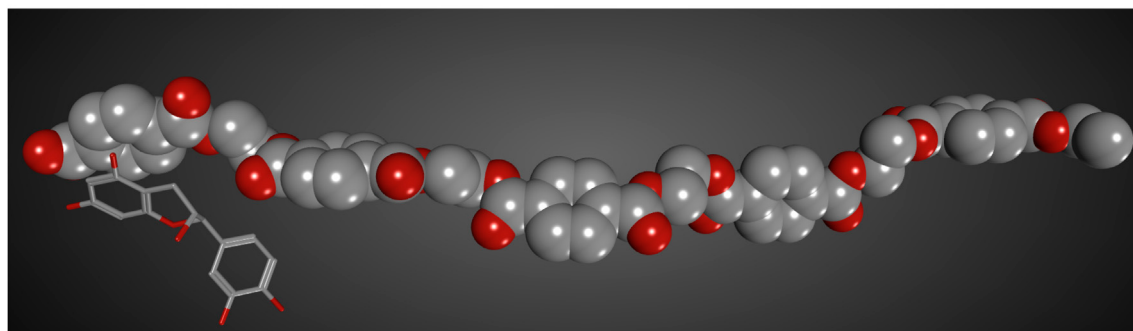


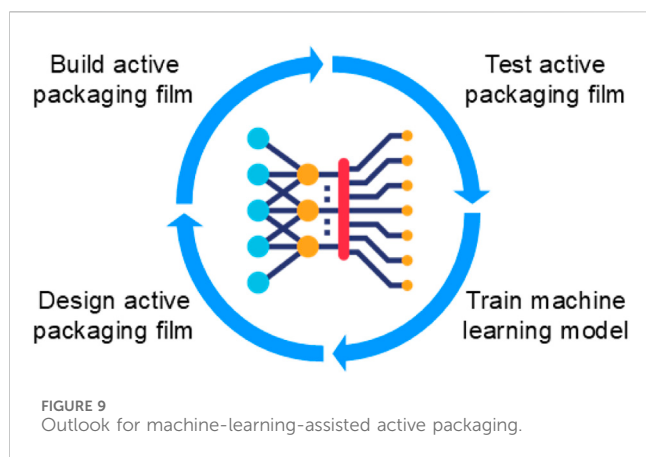
FIGURE 8

Illustration of the application of molecular modeling in the design and simulation of active packaging systems. In these models, polyphenols are analyzed *in silico* as complexes between polymers and polyphenols, such as between polyethylene terephthalate and epicatechin. These complexes can be visualized in (A) two dimensions as a “sandwich” model or (B) three dimensions as a polymer–ligand model. The polymer molecules are represented using van der Waals spheres, while the polyphenol molecules are depicted as stick models.

9 Machine-learning-aided food packaging with natural polyphenols

One of the fundamental components of material science is the process of “trial-and-error” to design the best-possible material (Figure 9). However, utilizing machine learning for material designs may be a little daunting (Meyer et al., 2022) yet useful to a material scientist. Similarly, data science can be utilized to design active food packaging materials. There are several properties of biocomposite or nanocomposite active packaging films that may be tuned for best performances. Machine learning and artificial intelligence offer excellent opportunities for big-data handling to provide optimized solutions. Notably, there are very limited numbers of studies that have harnessed the power of machine learning to optimize the properties of active food packaging films. For example, Özkan et al. (2019) used machine learning to

design tailor-made nanocellulose films; here, machine learning was used to assist with tuning the crosslinking properties of the nanocellulose composite films to achieve higher tensile strength and Young’s modulus values as well as different elongation profiles under stress. Özkan et al. (2019) also showed that a prediction model based on artificial neural networks performs better than those based on random forest and multiple linear regression. Artificial neural network models have also been reported to help with highly accurate predictions of moisture content in coated pineapple cubes during drying (Meerasri and Sothornvit, 2022). In addition to offering antioxidant features, the antimicrobial properties of active food packaging could be improved by adding food safety properties. Pandey et al. (2023) have summarized an excellent review on machine learning algorithms to ensure food quality, safety, and preservation of fruits and vegetables. Integrating artificial intelligence methods could significantly improve food quality and



safety properties through real-time monitoring, predictive analytics, enhanced formulations, quality control, consumer interactions, and supply chain optimization.

10 Conclusion and future perspectives

The uncertainties associated with local weather and global climate change dynamics can critically impact food security and agricultural output as considerable amounts of food are currently known to deteriorate along the supply chain. While regular food packaging methods only provide a physical barrier, active food packaging using natural polyphenols can provide numerous benefits while extending the shelf lives of food products. Moreover, recent advancements in the extraction of natural polyphenols from food wastes and their applications in active packaging can support sustainable use of food-waste materials (Ly and Sothornvit, 2024). In the present review, we surveyed research articles documenting the use of natural and food-waste polyphenols for active food packaging applications. Tea polyphenols are the most frequently reported active components among various sources of polyphenols, including fruits, vegetables, and associated food-waste materials. Antimicrobial, antioxidant, and antibrowning capabilities are the most significant characteristics of an efficient active packaging film. In addition, the water barrier, gas barrier, light barrier, and oxidative damage properties all have impacts on the shelf lives of packaged foods. The antibacterial, antioxidant, and antibrowning profiles are favorably associated with extending the shelf lives of packaged foods; notably, packaging films made from natural and food-waste polyphenols have demonstrated these beneficial qualities, indicating their sustainable use in active food packaging. The present review is thus expected to be a valuable guide for encouraging research on the sustainable extraction and use of natural and food-waste polyphenols in active food packaging applications.

Author contributions

KD: Data curation, Writing – original draft, Writing – review and editing. CF: Writing – original draft, Writing – review and editing. OO: Writing – original draft, Writing – review and editing.

TD: Writing – original draft, Writing – review and editing. ES: Writing – original draft, Writing – review and editing, Funding acquisition. SS: Conceptualization, Investigation, Supervision, Validation, Writing – original draft, Writing – review and editing, Project administration, Resources.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frfst.2025.1604816/full#supplementary-material>.

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