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# New frontiers in the exploration of phenolic compounds and other bioactives as natural preservatives

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ABSTRACT

Phenolic compounds are secondary metabolites widely distributed in the plant kingdom, valued for their strong antioxidant and antimicrobial properties. These bioactive compounds are promising natural alternatives to artificial preservatives in the food industry, aligning with consumer demand for sustainable solutions that ensure food quality and safety. In this review, the structural complexity of bioactive phenolic compounds, which include their various subclasses and the chemical basis of their antioxidant and antimicrobial activity, is explored. This review examines innovative extraction methods designed to preserve the bioactivity of these compounds. Additionally, it examines their incorporation as natural preservatives, focusing on stability issues and applications in the food sector. The structural diversity of phenolic compounds underpins their broad applications in food preservation. These include antimicrobial and antioxidant properties, which contribute to food safety and offer potential health benefits. The use of agro-industrial biowastes as a sustainable supply of phenolics is a promising approach; however, standardization is necessary to obtain extracts with consistent and effective biological activity. Innovative techniques, such as encapsulation and integration into edible films, are being developed to improve the stability and effectiveness of these compounds, expanding their application in various food products.

## 1. Introduction

With over 8000 identified structures (Zhang et al., 2022a), phenolic compounds represent one of the most widely distributed families of secondary metabolites in plants (Borah et al., 2024). They play essential roles in plant defense against environmental stressors and pathogens (Chaachouay & Zidane, 2024; Vuolo et al., 2019). Rich in fruits, vegetables, grains, teas, coffees, and wines, phenolic compounds contribute to food quality from a sensory perspective by enhancing color, flavor, and aroma. From a health standpoint, they may help reduce the risk of chronic non-communicable diseases due to their antioxidant (Franco et al., 2019) and antimicrobial (Bouymajane et al., 2024) properties. Phenolic compounds have emerged as an alternative to artificial preservatives in the food sector (Martínez-zamora et al., 2020), in line with growing consumer concern for healthy alternatives with quality and safety (Sharma et al., 2020).

Artificial preservatives have been widely used for years due to their effectiveness in preventing food deterioration. However, prolonged consumption at high levels may pose health risks (Lorenzo et al., 2021). To overcome these issues, there is a need to search for new alternatives such as phenolic compounds that appear to serve as natural preservatives (Rathee et al., 2023). In addition to the antioxidant and antibacterial activities (Martinengo et al., 2021, p. 2469), bioactive actions of these compounds may offer other health benefits, increasing their acceptance (Rana et al., 2022).

Herein, we explore the sources, structural diversity, extraction methods, and modes of action of phenolic compounds as natural preservatives (Hernández-Montesinos et al., 2024). Additionally, we discuss the challenges of their application in the food industry and the advances of innovative delivery systems, focused on improving their stability and activity, such as encapsulation and active packaging technologies (Krepker et al., 2017). The review emphasizes the advantages of agro-industrial by-products as sustainable sources of phenolic compounds, facilitating a more ecologically friendly and economical

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**Table 1**
The European Food Safety Agency (EFSA) defines food additives and their duties under Regulation (EC) No 1333/2008.

| Function | Description |
|---|---|
| Acidity regulators | Modify the pH of a food product. |
| Acids | Enhance the acidity and/or introduce an acidic flavor. |
| Anti-caking agents | Decrease the agglomeration of particles. |
| Antioxidants | Inhibit oxidative deterioration (e.g., color changes or rancidity) to extend the shelf life. |
| Anti-foaming agents | Prevent or decrease foam generation. |
| Bulking agents | Increase the amount of a food without considerably increasing its energy value. |
| Carriers | Modify a compound in a physical manner to facilitate its application and management, while maintaining its activity. |
| Colors | Incorporate or recuperate color. |
| Emulsifiers | Facilitate the creation and maintenance of a homogeneous mixture of two immiscible phases. |
| Emulsifying salts | Convert cheese proteins into a dispersed state, leading to the homogeneous distribution of other components. |
| Firming agents | Maintain the firmness and crispness of fruits and vegetables or create and strengthen gels. |
| Flavor enhancers | Improve taste/odor. |
| Flour treatment agents | Enhance the culinary quality of flours and doughs that lack emulsifiers. |
| Foaming agents | Facilitate the dispersion of a gaseous phase in a liquid or solid. |
| Gelling agents | Improve the texture by forming a gel. |
| Glazing agents | Provide a protective coating or create an appearance of gloss. |
| Humectants | Prevent the drying of particles or facilitate their dissolution in an aqueous solution. |
| Modified starches | Edible carbohydrates that have been chemically treated. |
| Packaging gases | Before the foodstuff is placed in the containers, gases (not air) are introduced. |
| Preservatives | Inhibit the development of pathogens or the deterioration of microbial organisms to extend the shelf life. |
| Propellants | Foodstuffs are expelled from a container by gases, not air. |
| Raising agents | Therefore, the volume of a dough or batter is increased by the release of gas. |
| Sequestrants | Metallic ions that are complex. |
| Stabilizers | Preserve the physicochemical integrity of a culinary item. |
| Sweeteners | Increase the sweetness. |
| Thickeners | Enhance the viscosity. |

approach to food preservation (Sundaram et al., 2024). This review aims to highlight the significance of phenolic compounds, which may signify the future of food preservation and contribute to a more sustainable and health-focused economy.

## 2. Challenges of synthetic preservatives and the search for natural alternatives

Food additives can have a natural or synthetic origin and are classified (Kyriacou et al., 2020) as direct (those added to food on purpose) or indirect (i.e., substances migrating to food through the processing operations or packaging) (Martínez-zamora et al., 2020). Within the European Union, food additives are listed by a code that starts with the letter “E” (for Europe, Council Regulation (EC) 1129/2011) and is followed by three or four digits, as per the International Numbering System (INS), which is overseen by the Codex Alimentarius. These are known as food preservatives, commonly found as nitrates and nitrites (E249-E252) and used in meats to prevent bacteria such as *Clostridium botulinum* while also preserving color, sodium benzoate (E211), used in beverages and sauces against fungi, and sulfites (E220-E228), used in wines and dried fruits to inhibit oxidation (Lambert et al., 2017; R. Singh & Puniya, 2024). This principle is embedded in the concept described in Regulation (EC) No 1333/2008, Article 5 (Table 1), which allows a manufacturer to use these additives at concentrations that are necessary for the desired technological effect (following safety and good manufacturing practices) (Codex Alimentarius Commission, 2023). The FDA categorizes some additives as GRAS (generally recognized as safe) in the United States (U.S. Food and Drug Administration FDA, 2020; Lee & Paik, 2016; Shakil et al., 2022). Authorized additives are considered safe when consumed within the Acceptable Daily Intake (ADI), which represents the maximum amount of a substance that can be ingested daily over a lifetime without appreciable health risk (Zahmoul et al., 2019). Table 7, provided as supplementary material, presents the chemical additives commonly used in the food industry based on their main technological functions.

The use of additives is justified when they have the well-defined function of increasing stability, preserving nutritional quality, preventing deterioration caused by microorganisms and chemical processes such as oxidation (Zahmoul et al., 2019). Additives can be animal, plant, and mineral-based or synthetically created (Taylor et al., 2019). Low-cost synthetic preservatives are widely used due to their high efficacy at low concentrations; however, they raise concerns among consumers as they are associated with possible side effects such as allergies or gastrointestinal illnesses, especially in susceptible populations (for example, people allergic to sulfites or nitrites and children) (Garg & Thornton, 2025; Tung et al., 2024). In baby food, the presence of synthetic preservatives is particularly concerning, as infants have an immature detoxification system, making them more vulnerable to potential adverse effects (Garg & Thornton, 2025). Despite being considered safe for the general population when used within authorized limits, these concerns have driven a growing demand for natural alternatives (Chazelas et al., 2022; Di Nunzio et al., 2022; Lee & Paik, 2016; Shakil et al., 2022). The Acceptable Daily Intake (ADI) established by regulatory agencies includes 5 mg/kg body weight for benzoates (E210-E219), 25 mg/kg body weight for sorbates (E200-E209), and 0.07 mg/kg body weight for potassium nitrite (E249), which are commonly used in food preservation (Abedi-Firoozjah & Tavassoli, 2024a; J. Chen & Xia, 2024a; García-García & Searle, 2016a, pp. 505–509). These limits ensure their safety when properly regulated; however, increasing consumer awareness of potential health risks has stimulated the search for natural alternatives (Chen & Xia, 2024a). In contrast, natural preservatives are extracted from resources like microorganisms and plants, which prevent the development of yeast, molds, and bacteria. Naturally occurring preservatives include sorbic acid (E200), ascorbic acid (E300), and tocopherol (E306), which are widely used due to their antioxidant properties. E392 and other essential oils, including those from thyme and rosemary, have antimicrobial activities. Organic acids such as citric acid (E330) and lactic acid (E270) are commonly used, not only to lower the pH of foods, which in turn prevents the development of microorganisms, but also to chelate metals that catalyze oxidation reactions. However, some of these compounds, such as lactic acid, can also be produced synthetically for industrial Applications (Singh & Puniya, 2024). Conversely, natural plant-based preservatives still require large-scale studies for the optimization of production, which is widely related to the powder manufacturing processes, extraction techniques, and formulations ensuring them to be within affordable costs for small-, medium-, and large-scale producers (Vuolo et al., 2019). Specific requirements for natural preservatives to be accepted in the market are that they should be effective in low concentrations, should have stable antimicrobial activities, should have water solubility, should be non-toxic, should be homogeneous, should work at room temperature, should be penetrating, and should not alter the taste and aroma of the food. (Naufalin, 2019).

These preservatives can be natural or synthetic substances and are subdivided into three main groups: antimicrobials, antioxidants, and anti-browning agents. In addition to preservatives, food additives also include colorants (azo compounds, the chinophthalon derivatives, the triarylmethane compounds, the xanthenes, and the indigos); flavoring agents such as sweeteners, natural and synthetic flavors, and flavor enhancers; and texturizing agents, which are divided into emulsions and stabilizers (Taylor et al., 2019). Additionally, anti-browning agents are employed to prevent the browning of foods, which can occur at any stage of handling, processing, or storage. Antimicrobials are employed to control and prevent natural spoilage caused by microorganisms, while

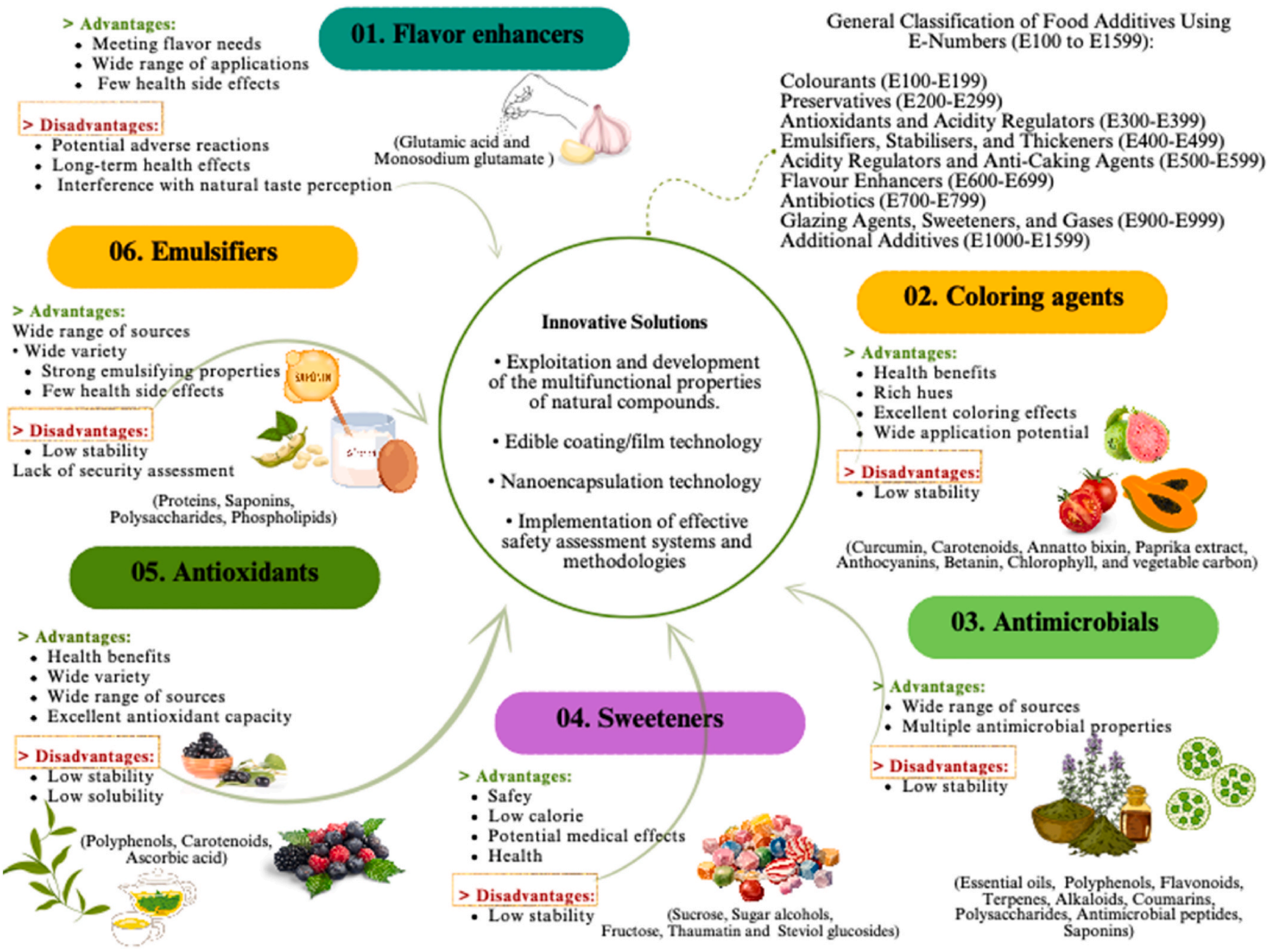

**Fig. 1.** Advantages, disadvantages of plant-based additives as an alternative to synthetic additives and their innovative solutions.

antioxidants are employed as preservatives to limit or delay the biological and chemical deterioration of foods, preventing the auto-oxidation of pigments, flavors, lipids, and vitamins (Carocho et al., 2015).

Fig. 1 illustrates the potential alternatives for natural preservatives against artificial ones.

### 2.1. *Antimicrobials*

Antimicrobial compounds are used in food for two reasons: (1) to prevent or reduce contamination by microorganisms, particularly pathogenic ones (which constitute a risk to food safety), and (2) to control natural food degradation (which can happen owing to the presence of bacteria, yeasts, and molds) (Abedi-Firoozjah & Tavassoli, 2024b). However, high antimicrobial concentrations can affect flavor, odor, viscosity, and color (J. Chen & Xia, 2024b). Their choice depends on antimicrobial spectrum, food matrix physicochemical composition and features, and storage and preservation methods (Abedi-Firoozjah & Tavassoli, 2024).

#### 2.1.1. *Artificial antimicrobials*

The principal chemical antimicrobials used in foods with *quantum satis* status include potassium acetate (E261), acetic acid (E260), calcium acetate (E263), carbon dioxide (E209), and propionic acid and propionates (E280-E289; *quantum satis*). Some organic acids, such as lactic acid (E270) and malic acid (E296), can be produced synthetically for use in food preservation, despite also being naturally present in various food sources. Sorbic acid and sorbates (E200-E209; ADI 25 mg/kg bw), benzoic acid and benzoates (E210-E219; ADI 5 mg/kg bw), nitrites (potassium nitrite E249; ADI 0.07 mg/kg bw, sodium nitrite E250; ADI 0.1 mg/kg bw), parabens (E214-E219; ADI 10 mg/kg bw), and nitrates are also widely used in food preservation (Abedi-Firoozjah & Tavassoli, 2024b).

The quantities needed for efficient antibacterial action differ substantially amongst acids (J. Chen & Xia, 2024b). The most frequent organic acids employed as preservatives are weak lipophilic organic acids such as (a) benzoates (sodium benzoate) at concentrations ranging from 0.01 % to 0.10 %, (b) sorbates (sorbic and potassium sorbate) at 0.03 %–0.10 %, and (c) propionates (sodium and calcium propionate) at 0.20 % - 0.5 %, or inorganic ones such as sulfite or nitrite, all of which are most effective at pH levels less than roughly 5.5 (García-García & Searle, 2016b, pp. 505–509). Acetic, citric, fumaric, lactic, and phosphoric acids are examples of common antibacterial acidulants. Although these acids serve primarily as preservatives, they also contribute to the overall sensory profile of foods. In particular, flavor profiles play a crucial role in consumer acceptance, as they are used in much larger quantities and can significantly influence the product's palatability (Chen & Xia, 2024b). To enhance antibacterial activity, acidulants are often combined with weak organic acids or their salts (García-García & Searle, 2016b, pp. 505–509). Organic acids and salts, such as benzoic acid, inhibit yeast at pH 4 at concentrations ranging from 2 to 6 mM, whereas acidulants, such as citric acid, are required at levels greater than 400 mM. Benzoic acid and its salts, such as sodium benzoate, potassium benzoate, and calcium benzoate, are classic antimicrobials that are frequently incorporated into acidic foods (e.g., carbonated beverages, fruit juices, mayonnaise, pickled vegetables, etc.) in order to inhibit the growth of molds, yeasts, and bacteria (Acar, 2021; Turnbull et al., 2021). Additionally, it has been noted that sodium benzoate has the potential to cause oxidative stress, genetic damage, and other toxic effects associated with enzyme interactions. These effects include a decrease in superoxide dismutase and catalase activity in human red blood cells and an elevated risk of myocardial infarction (Acar, 2021; J. Chen & Xia, 2024b). Sulfites, which inhibit most gram-negative and some gram-positive bacteria, are widely used as antimicrobial agents in alcoholic beverages (including wine and beer), soft drinks, seafood, fruit juices, fruits, and dry vegetables (EFSA, 2016; Hugo & Hugo, 2015). Sulfites can cause cleavage inactivation of various vitamins (e.g., B vitamins, vitamin C), and continuous exposure may lead to vitamin deficiency symptoms (e.g., tooth coloration, organ and tissue atrophy, and fibrosis) (J. Chen & Xia, 2024b). Additionally, sulfites can induce irreversible degradation of anthocyanins, which are important natural colorants in food systems (Do et al., 2023). Nitrites (potassium and sodium nitrite) and nitrates (sodium and potassium nitrate) are frequently used in meat processing (European Commission, 2008; 2023). Additives used in meat processing, such as sodium nitrite and monosodium glutamate, have been linked to a variety of degenerative alterations by harming brain cells, and they may also impact male fertility (Kyakma et al., 2022). Propionic acid and propionates, both carboxylic acid antimicrobials, effectively inhibit mold growth and are commonly utilized in foods such as bread and meat (J. Chen & Xia, 2024b).

Parabens are commonly found in processed vegetables, condiments, dairy products, baked goods, and fruit juices due to their broad-spectrum antibacterial and antifungal properties, odorlessness, soft burnt taste, and stability under normal conditions (European Commission, 2008; Soni et al., 2005). According to García-García and Searle, (2016) parabens' antibacterial activity is pH-independent at 8.0, when they are totally undissociated. Except for parabens, there are no antibacterial preservatives that are active across a wide range of pH levels. Concerns about the widespread use of these types of preservatives, their consequences on human health, and their inefficacy at pH values closer to neutrality have created a market need for natural alternatives (García-García & Searle, 2016b, pp. 505–509).

### 2.1.2. *Natural antimicrobials*

Consumer demands have spurred the use of alternate food processing and preservation methods. Natural antimicrobial substances prolong food shelf life by suppressing or destroying microbial development (Shi et al., 2024a). Antimicrobial substances are found in plants, animals, bacteria, fungi, and algae. Food processing uses natural preservatives such nisin, natamycin, and essential oils. Nisin and natamycin are bacterial metabolites, while essential oils are plant-based (García-García & Searle, 2016b, pp. 505–509).

*2.1.2.1. Plant-based antimicrobials.* Secondary metabolites in plants are bioactive compounds produced through secondary metabolism, originating as a response to environmental stress, attacks by microorganisms, and herbivores. These compounds include various chemical classes such as alkaloids, flavonoids, terpenoids, saponins, and phenolic compounds, which play different biological roles, including antimicrobial and antioxidant activity. Polyphenols, one of the most abundant classes in the plant kingdom (Abbas et al., 2017), are aromatic compounds biosynthesized through the shikimate and/or polyketide pathways and play an essential role in pathogen protection and pigment production in plants (Lyu et al., 2019). The chemical structure of polyphenols directly influences their bioactive properties, stability, and bioavailability (Gutiérrez-del-Río et al., 2018; Panić et al., 2019; Tomadoni et al., 2016).

Plant-based antimicrobials have been extensively studied due to their efficacy and application in the food industry. These compounds include essential oils, flavonoids, terpenes, alkaloids, coumarins, polysaccharides, antimicrobial peptides, saponins, and compounds such as anthraquinones and organic acids (S. Li et al., 2024). Among essential oils, the main antimicrobial compounds are thymol, carvacrol, and eugenol, belonging to the phenol and terpenoid classes. Although their mechanism of action is not fully understood, several studies indicate that these compounds act on the microbial cell membrane, resulting in structural destabilization and growth inhibition (J. Chen & Xia, 2024a). Moreover, the antimicrobial activity of essential oils is generally superior when used in crude form compared to their isolated compounds, suggesting that aldehydes such as cinnamaldehyde and other non-phenolic substances play a significant synergistic role (García-García & Searle, 2016a, pp. 505–509). Their antifungal, antibiotic, and antiviral properties make these oils potential natural preservatives in the food industry, frequently incorporated into products to control pathogenic organisms and prevent economic losses associated with food spoilage (Oladeji et al., 2024a; Shi et al., 2024b).

Polyphenols, produced by plants in response to stressors, exhibit significant antimicrobial activity against bacteria, yeasts, and fungi associated with food spoilage (Efenberger-Szmechtyk et al., 2021). The food industry has explored these compounds as natural preservatives, aiming to replace synthetic additives, which are often linked to adverse health effects. Additionally, when combined with other antimicrobials and antibiotics, polyphenols may act through various mechanisms, reducing the likelihood of bacterial resistance development. Polyphenol-rich plants such as oregano, clove, green tea, citronella, rosemary, thyme, grape, and sage have been tested individually or in combination with other preservation strategies against foodborne pathogens (Abbas et al., 2017; Fantini et al., 2015).

The antimicrobial mechanism of polyphenols involves their interaction with proteins in the bacterial cell wall, causing cell lysis, as well as their ability to bind to hydrophobic regions of extracellular microbial proteins, reducing their activity (S. Li et al., 2024b). Among the major polyphenols with antibacterial, antifungal, and antioxidant properties are flavonoids, curcumin, tannins, phenolic acids, tea polyphenols, chromones, and lignans (S. Li et al., 2024). Although polyphenols are known for their diverse biological effects on health, their use in coatings and films to demonstrate antibacterial activity remains relatively limited (Oladeji et al., 2024a).

In conclusion, plant-derived compounds possess enormous antimicrobial potential, yet challenges such as volatility and stability still limit their industrial application. Strategies such as nanoencapsulation and incorporation into edible films and coatings may be effective solutions to overcome these limitations, enabling the broader use of these compounds in food preservation (J. Chen & Xia, 2024a; S. Li et al., 2024).

*2.1.2.2. Animal and microbial based antimicrobials.* Animal products, such as milk and eggs, have natural antibacterial qualities from well-known components such lactoferrin, lactoperoxidase, and lysozyme. Polypeptides from various animal sources include chitosan, megainin, pleurocidin, curvacin A, and spheniscin (Juneja et al., 2012). Natural antimicrobials in animals serve as the first chemical barrier to bacterial and fungal diseases. All animals produce them, mostly as peptides, polysaccharides, sterols, terpenes, prostaglandins, and fatty acid derivatives. Some of these chemicals, including lysozyme, chitosan, and lactoferrin, are used as food preservatives. Lysozyme and lactoferrin are bioactive peptides obtained primarily from hen eggs and bovine milk, respectively, whereas chitosan is a polysaccharide derived from crab shells and fungal cell walls. Lysozyme is now the only permitted natural antibacterial generated from animals, and it is used in both the United States and the European Union (E−1105). The lysozyme used comes from eggs. This enzyme's antimicrobial activity is based on hydrolysis of the b-1,4 linkage site of peptidoglycan in bacterial walls. It is highly effective against Gram negative bacteria (which contain 90 % peptidoglycan), moderately effective against Gram positive bacteria (which contain less peptidoglycan), and inactive against yeasts and fungi (Barbiroli et al., 2012). The combination of phase-transitioned lysozyme and food-grade additive ε-poly-L-lysine (antimicrobial) showed a synergistic antimicrobial effect, inactivating 6 log CFU/mL of *Staphylococcus aureus* and *Escherichia coli*after only 30 min of exposure (Xu et al., 2025). Shabir et al. (2024) reported G-type lysozyme 2, an efficient antibacterial peptide, in *Cyprinus carpio mucus*. This peptide inhibits several bacterial and fungal infections. In addition to bioactive peptides, polysaccharides have garnered interest for their functional properties (Shabir et al., 2024; Xu et al., 2025). Srivatsa et al. (2024) tested phosphorylated chitosan for antibacterial properties. Phosphorylated chitosan inhibited *Candida tropicalis* at 100 % and *Pseudomonas aeruginosa* at 50 % and 100 %. The inhibitory effects on *Streptococcus mutans* and *E. coli* were weak (S. Zhang et al., 2025). describe antibacterial wound dressing using Chitosan-metallic scaffolds. Deacetylated chitosan, a natural antibacterial agent, may be used in food additives, processing aids, and active packaging (L. Li et al., 2023). Because it's insoluble at neutral or higher pH, chitosan's uses are limited (Srivatsa et al., 2024; S. Zhang et al., 2025).

Also, several bacteria have antimicrobial defenses. *Penicillin* is one of numerous mold-derived antibiotics. Lactic acid bacteria create antimicrobial peptides or proteins called bacteriocins. Their biological synthesis, application, spectrum, and mode of action differ from antibiotics. Bacteriocins, ribosomal peptides, have a narrow spectrum of activity and no known toxicity, unlike antibiotics, which are secondary metabolites. Bacteriocins are good food preservatives. Their extensive antibacterial spectrum and bactericidal effect against spoilage and pathogenic bacteria are inactivated by digestive proteases and do not harm eukaryotic cells. Despite many known bacteriocins, only nisin is allowed as a food preservative (García-García & Searle, 2016b, pp. 505–509).

### 2.2. Antioxidants

#### 2.2.1. Artificial antioxidants

Antioxidant chemicals are one of the most widely used preservation methods in the food industry. Their main role is to prevent oxidation-induced food spoilage by neutralizing free radicals, thus preserving color, taste, texture and extending shelf life (Carocho et al., 2018; Roca-Saavedra et al., 2018). The most common artificial antioxidants in the food industry are propyl gallate (PG, E310; ADI 1.4 mg/kg body weight), which regulates the oxidation of lipids, inhibits rancidity processes in meat products and preserves color and flavor in other food products (Javaheri-Ghezeldizaj et al., 2023). Tert-butylhydroquinone (TBHQ, E319; ADI 0.7 mg/kg bw), effective in preventing deterioration without affecting the flavor or (Khezerlou et al., 2022). Butylated hydroxyanisole (BHA, E320; ADI 0.5 mg/kg bw) and Butylated hydroxytoluene (BHT, E321; ADI 0.05 mg/kg bw) contain similar attributes for their function of inhibiting the oxidation of fatty acids in oil and general materials (Hew et al., 2024). In addition, BHA is commonly used in food packaging and is more functional in animal products than vegetable ones (Lemons et al., 2025; Yahaya et al., 2024)and ethoxyquin (EQ, E324; ADI 0.005 mg/kg bw), a quinolone-based antioxidant is often used in animal feed because of its low cost and high antioxidant potential (J. Chen & Xia, 2024b). However, BHA, BHT, and TBHQ are the most popular food antioxidants because of their inexpensive cost, great performance, and widespread availability, also have a significant benefit in terms of high-temperature stability, preserving antioxidant properties before and after baking and frying (Bazina et al., 2025). BHA and BHT are suggested for usage in fats, but TBHQ has a wider application in vegetable oils (Nooshkam & Varidi, 2024). In addition, other chemical antioxidants are widely used in the food industry, approved by EFSA, such as ascorbic acid and its derivatives (E300-E304), EDTA (E385), erythorbic acid (E315), sodium erythorbate (E316), citrates (E330-E380), lactates (E325-E327) and tartrates (E334-E354) (Caleja et al., 2017; Carocho et al., 2018). It is increasingly crucial to distinguish between synthetic and artificial food additives due to the growing interest in natural alternatives (Carocho et al., 2018). Some studies have suggested that synthetic antioxidants may have toxic and carcinogenic effects, particularly when consumed in high doses or over long periods of time (Nooshkam & Varidi, 2024) as a result, the food industry is improving its products in search of natural preservation alternatives (J. Chen & Xia, 2024b).

#### 2.2.2. Plant-based antioxidants

Phenolic chemicals are recognized for their antibacterial properties and significant antioxidant capability. They are prevalent in plants and represent a significant category of antioxidant compounds for potential utilization; however, other substances with significant antioxidant properties, including certain vitamins (C, E, and A), bioactive peptides, polysaccharides, select minerals, and enzymes, are also available (Caleja et al., 2017; McCusker et al., 2016). Colorimetric methods can be used to determine phenolic activity in extracts, wines, fruits and products into which they can be incorporated, however these methodologies lack specificity as they only quantify the total amount of reducing chemicals in the extracts (Johnson et al., 2024; Pérez et al., 2023). Due to their potential antioxidant and health-benefiting properties, coupled with good consumer acceptance, phenolic compounds are looking to effectively replace synthetic antioxidants (J. Chen & Xia, 2024b). The primary categories of polyphenols include phenolic acids (hydroxybenzoic and cinnamic acids), flavonoids (anthocyanidins, flavones, flavonols, isoflavones, flavanols, and flavanones), lignans, and stilbenes (Chiorcea-Paquim et al., 2020). Among these phenolic chemicals, certain ones are more prominent and can be incorporated into foods either individually, following the purification of the molecules, or utilized as plant extracts, leveraging the synergistic effects among them (Martins et al., 2019).

Moreover, other types of natural chemicals have antioxidant properties in foods; for instance, carotenoids, prevalent in fresh fruits and vegetables, possess considerable antioxidant activity but are prone to photo-oxidation. The predominant carotenoids in food are lycopene and β-carotene, extensively utilized in meat, fish, fruits, cereals, pastries, and dairy products (Rodriguez-Amaya, 2016). Furthermore, ascorbic acid (E300) serves as a significant antioxidant that stabilizes lipids and fats. EFSA has verified that the depletion of ascorbic acid is safe, so no acceptable daily intake (ADI) is established (J. Chen & Xia, 2024b).

Despite the challenges, many of them related to stability, various techniques have been developed and applied to get around this situation, including encapsulation systems for these bioactive molecules (J. Chen & Xia, 2024b; X. Li et al., 2019). Among all these compounds, the document will take a closer look at phenolic compounds as preservatives and their different classes in topic three, as well as ways of extracting and stabilizing them for use in the food industry in the following sections.

### 2.3. Antibrowning

Browning is caused by the enzymatic oxidation of phenolic components in fruits and vegetables by polyphenol oxidase (PPO), while oxidative rancidity is induced in lipid-containing foods by unsaturated fatty acid degradation (García-García & Searle, 2016b, pp. 505–509). Maillard reaction products (MRPs), which are naturally produced during food preparation and storage, may delay or prevent food lipid oxidation as typical, natural, and endogenous antioxidants (Nooshkam & Varidi, 2024). Melanoidins and Amadori rearrangement products (ARPs) from the Maillard reaction can chelate metals and scavenge oxygen radicals. PPO inhibition may prevent fruit and vegetable browning. PPO catalyzes raw fruit and vegetable browning. oxidation reaction that forms polymerized dark-colored pigments from o-quinones, which can significantly affect product functional, nutritional, and organoleptic qualities

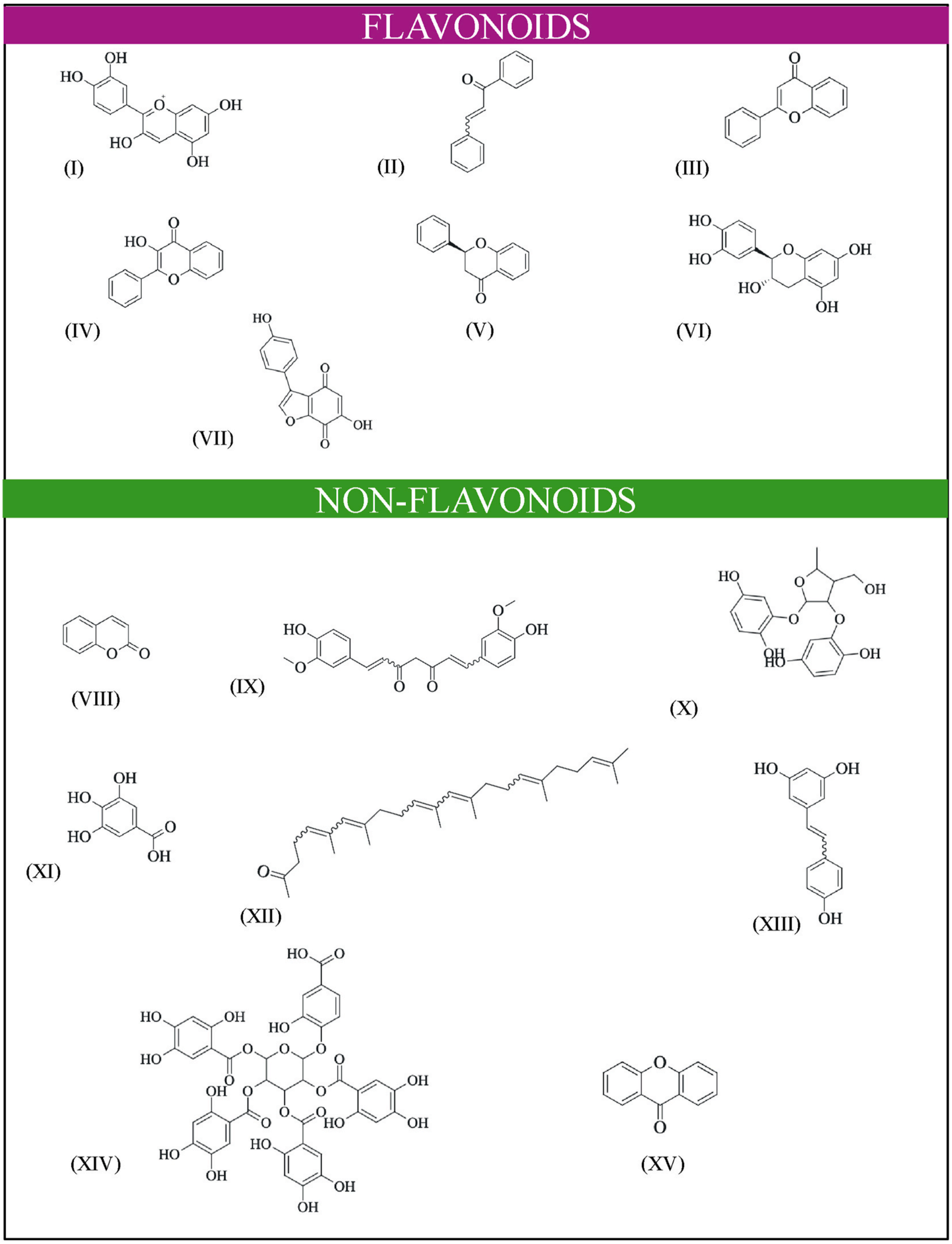

**Fig. 2.** Chemical structure of the different classes of flavonoids and non-flavonoids.

(Nooshkam et al., 2019). Ascorbic acid, its derivatives, SH-compounds, and sulfites are the principal reducing agents that reduce o-quinones to o-diphenols and create colorless compounds (Nooshkam & Varidi, 2024). As a natural alternative to sulphites, erythorbic acid (E315), used in beverages to preserve flavor, 4-hexylresorcinol (E586), an organic component allowed only in shrimp, and L-cysteine (E920) can be utilized. Natural antibrowning works by converting quinone intermediates to phenolics and inhibiting compound formation with quinolone intermediates (Cruzen et al., 2015).

### 2.4. Other bioactives

Natural colorants regulated by Regulation (EC) No 1129/2011 include anthocyanins (E163), betanin (E162), and carotenoids (E160), including β-carotene (E160a), lycopene (E160d) (obtained from tomato processing byproducts), lutein (E161b), canthaxanthin (E161g), chlorophyll and chlorophyllin (E140 and E141), and curcumin (E100). However, only grape skin extract (E163) is listed as an anthocyanin colorant in the Codex Alimentarius, but the FDA recognizes “grape color extract” and “grape skin extract” (enocyanin) (Bridle & Timberlake, 1997; Rodriguez-Amaya, 2016, 2019). The substitution of synthetic pigments with natural compounds is a current market trend (Iriondo-DeHond et al., 2018). The majority of commercial colorants are synthesized, such as erythrosine (red), cantaxanthin (orange), amaranth (azoic red), tartrazine (azoic yellow), and annatto bixine (yellow orange) (J. Chen & Xia, 2024b; Wu et al., 2022). Sources of natural colorants in the yellow-red spectrum include carotenoids (lycopene, lutein, β-carotene, astaxanthin, canthaxanthin and zeaxanthin) (Rodriguez-Amaya, 2016). Anthocyanins, which are natural plant pigments from the flavonoid family, are the most significant group of water-soluble plant pigments in the plant kingdom. They contribute to a color spectrum that ranges from red to blue, depending on pH, temperature, and the presence of metals (J. M. Lorenzo et al., 2018).

Also, texturizing agents, such as emulsifiers, stabilizers, thickeners, and bulking agents, are employed in the food industry to modify the overall texture and mouthfeel of foods (Saha & Bhattacharya, 2010). Therefore, the E-number system classifies emulsifiers, stabilizers, thickeners, and gelling agents as a singular category, with a range of E400 to E499 (Wu et al., 2022). Plant-based emulsifiers, such as polyglycerol esters, considerably improve food texture, stability, and mouthfeel) (J. Chen & Xia, 2024b). Emulsifiers, also known as emulgents, serve as a bridge between the opposing components in water and oil and are found in creams and sauces, bread, and dairy goods (McClements & Jafari, 2018). Plant-based emulsifiers commonly used in food items include proteins, saponins, polysaccharides, and phospholipids. (J. Chen & Xia, 2024b). Stabilizers are chemicals or substances that enable diverse culinary ingredients stay homogenous after being mixed. Agar, alginic acid, and their sodium, potassium, ammonium, and calcium salts are commonly used as food stabilizers (Tekin Pulatsü et al., 2018). Thickeners, when added to a food mixture, enhance the viscosity without changing other food features, whereas bulking agents, such as pectin, increase the bulk of a food without changing its nutritional value (Wu et al., 2022). Sorbitol, xylitol, and mannitol are natural sweeteners generated from sugars. They are commonly used in dairy, tea, alcoholic drinks, seasonings, confectionery, starch products, and processed fruits and vegetables (Wu et al., 2022).

Given the potential health concerns associated with synthetic preservatives, as well as the increasing consumer demand for clean-label and natural food products, the search for effective natural alternatives has gained significant momentum. Among these, phenolic compounds have emerged as promising candidates due to their well-documented antioxidant and antimicrobial properties, which can help extend shelf life while maintaining food quality and safety. The following sections will explore the diverse sources, structural diversity, extraction methods, and functional mechanisms of phenolic compounds, highlighting their potential as sustainable and efficient natural preservatives in the food industry.

## 3. Phenolic compounds

These are major classes of secondary metabolites in plants and are also the largest group of natural chemical compounds (Abbas et al., 2017). They are constituents of fruits, vegetables, grains, tea, coffee, and wine and are essential components of plant biology where they serve as defense agents against pathogens, ultraviolet radiation, and predation, while also providing the sensory characteristics of food, such as color, taste, and bitterness (Paissoni et al., 2018). These properties can be observed in the flavor intensity of wine and in the bitterness of certain fruits when the phenolics interact with salivary glycoproteins to produce sensory diversity (Y. Zhang et al., 2022b).

Polyphenols can be categorized into two classes, namely, flavonoids and non-flavonoids (Abbas et al., 2017), that encompass different subclasses, such as phenolic acids, tannins, as well as stilbenes (Fig. 2). The bioactive properties, such as antioxidant and antimicrobial activities (Taylor et al., 2019; Teshome et al., 2022a), of these compounds are dependent on their structure and chemical composition; in addition, many reported bioactive properties were claimed to be beneficial for human health (Alara et al., 2021a). Therefore, these properties in phenolic compounds are effective agents for the preservation and protection of plant cells from oxidative stresses. Protective effects against pathogens and free radicals are provided by phenolic acids, while tannins and stilbenes are also relevant in defense against microorganisms and in extending the shelf life of plant-derived products (Teshome et al., 2022b).

Due to their high structural diversity, phenolics exhibit a wide variety of bioactive properties, which can be explored in detail using resources such as the Phenol Explorer and the USDA. Thus, polyphenols not only add diversity to the sensory profile of plant foods but also have health implication benefits and consequently deserve attention in food science and nutrition disciplines (de la Rosa et al., 2019).

Flavonoids: I Anthocyanins (Cyanidin); II Chalcones (Chalcone); III Flavones (Flavone); IV Flavonols (3-Hydroxyflavone); V Flavanones ((2S)-Flavanone); VI Flavanol (Epicatechin); VII Isoflavones (Genistein); Non-flavonoids: VII Coumarins (Coumarin); IX Curcuminoids (Curcumin); X Lignans (Secoisolariciresinol); XI Phenolic acids (Gallic acid); XII Quinones (Coenzyme Q10); XIII Stilbenes (Resveratrol); XIV Hydrolyzable tannins (Pentagalloylglucose); XV Xanthanoids (Xanthone). The isomeric smiles for each structure can be found in the supplementary material, in Table 8.

### 3.1. Chemical structure

Generally, phenolic compounds can be further classified as simple phenols (one phenol unit) or polyphenols (many linked phenol units) (Abbas et al., 2017). In which, flavonoids largely exist as bioactive compounds due to a high level of phenyl benzopyran and a phenillen-ene-stilbeni structure conformed as follows: walks of the basis of two adjacent aromatic rings (rings A and B) with the connection pyran-ring (C6-C3-C6 core structure), and where between members among them exist with the structural molecular between their members to occur in quantity with a heterocyclic pyran, which describes them to be highly reactive. The hydroxyl and methoxyl groups of their structure allow them bioactivity (Chiorcea-Paquim et al., 2020). Flavonoles, like quercetin, are known for their antioxidant stability, whereas anthocyanins are natural pigments sensitive to pH, which contribute to the dyeing and conservation of foods. Polymeric phenolic compounds also belong to the class of flavonoids that were identified, condensed tannins (i.e., proanthocyanidins), and provide astringent properties, but may add stabilizing qualities within food systems. These flavonoid subclasses are widely employed as natural antioxidants, stabilizers, and dyes (Goławska et al., 2023; Zhang et al., 2021).

Non-flavonoid components, such as phenolic acids, stilbenes, lignans, coumarins, hydrolyzable tannins, quinones, curcuminoids, and xanthones, are important in the aspects of food preservation and quality. They include, for example, phenolic acids with a C6-C1 structure that are abundant in fruits and grains, and hydrolyzable tannins, whose structure is more complicated and derives from phenolic acids (gallic and ellagic acids). C6-C2-C6 structures are characteristic of stilbenes (Rana et al., 2022; Singla et al., 2019) (Fig. 1). Hydroxybenzoic and hydroxycinnamic acids are phenolic acids (Goławska et al., 2023; Saleem et al., 2005)with a wide range of antioxidant properties (Poljsak et al., 2021), while the stilbene resveratrol has cardioprotective properties. Lignans are mentioned for their effects on hormones, coumarins for aroma and antioxidant activity (Saleem et al., 2005). In addition, these compounds satisfy the need for functional and natural ingredients that contribute to enhanced safety, stability, and sensory aspects of food products (Hassan et al., 2022; Vuolo et al., 2019).

Structural diversity is an important factor which also complements the individual reactivity and bioactive function of phenolic compounds along with contributing to the sensory properties of food (Keshavarzi et al., 2021). These chemical structures too give antioxidant (Franco et al., 2019) and antimicrobial properties basic (Pinto et al., 2023) for the plant defense reaction against natural stresses, such as UV radiation and pathogen contamination. In this way, this basic and utilitarian complexity makes phenolic compounds imperative constituents in human sustenance and nourishment conservation (Singla et al., 2019). This concern has provoked more noteworthy intrigued in substituting engineered added substances with phenolics from common sources,

**Table 2**
Different dietary phenolic compounds in addition to their sources and biological functions.

| Class | Phenolic Compounds in the Diet | Sources | Disease Management and Biological Activities | References |
|---|---|---|---|---|
| Phenolic acids | Ferulic acid<br>Caffeic acid<br>Gallic acid<br>*p*-Coumaric acid<br>Vanillic acid | Oilseeds, cereals, coffee, cowpeas, black currants, raspberries, cherries, peaches, blackberries, plums, citrus juices and fruits, squash shells and seeds, spinach, tomatoes, potatoes, and almonds. | Diabetes (by enzyme inhibition); cancer; neuroprotection; antibacterial and antiviral characteristics. | Goławska et al. (2023); Kovač et al. (2022); Skroza et al. (2022); Welc et al. (2022) |
| Flavonoids | Curcumin<br>Quercetin<br>Rutin<br>Kaempferol<br>Luteolin<br>Cyanidin<br>Catechin<br>Epicatechin | Whole grains, coffee, green tea, berries, apples, citrus fruits, tomatoes, onions, garlic, carrots, and cruciferous vegetables (cabbage, broccoli, cauliflower, Brussels sprouts). | Properties that are anti-inflammatory, antiviral, antiallergic, and anticarcinogenic; prevention of toxin-mediated stress and chronic diseases; breast cancer, coronary heart disease, cataracts, diabetes, and Alzheimer's disease. | Che et al. (2021); Čižmárová et al. (2023); Goławska et al. (2023); N. Shen et al. (2022) |
| Stilbenes | Resveratrol<br>Pterostilbene<br>ε-Viniferin<br>Raloxifene<br>Tamoxifen | Cocoa, grapes, hops, peanuts, sugarcane, tomatoes, bilberries, blueberries, strawberries, mulberries, deerberries | Allergies, inflammation of many tissues (cardiac, connective, neurological), intestinal, hepatic, and pulmonary inflammations, enzyme inhibition, obesity. | (X. Chen et al., 2024; Duta-Bratu et al., 2023; Navarro et al., 2018; Salehi et al., 2018) |
| Tannins | Gallotannins<br>Ellagotannins | Jack bean, pigeon pea, yam bean, babul, black myrobalan, blackberry, pomegranate, walnut. | Management of diabetes, obesity, dyslipidemia; infections control; treatment of diarrhea and skin burn; antioxidant, antibacterial, anti-inflammatory, and anti-diabetic qualities. | Ekambaram et al. (2016); Fraga-Corral et al. (2021); Li et al. (2020); Rinaldi et al. (2016) |
| Coumarins | Osthole<br>Dicoumarol<br>Thunberginols<br>Psoralen | Orange, clementine, lemon, propolis products, oils (olive, soy, peanut, maize), coffee, almonds, wine, green tea, cinnamon, citrus fruit peels. | Anti-inflammatory, anti-mutagenic, anti-tumorigenic, antioxidant qualities, spasmolysis, reduction of insulin-induced lipogenesis, antibacterial and anticancer action | Lončar et al. (2020); Yerer et al. (2020) |
| Lignans | Sevanol<br>Isoguaiacin<br>Carinol<br>Gomisin | Cereals, barley, buckwheat, chickpeas, asparagus, avocado, eggplant, pineapple, orange, kiwi, lemon, grapes; flaxseed, sesame seeds, coffee, tea (black, green). | Anti-inflammatory, antioxidant, and anticancer actions, cancer treatment, cardiovascular disease control, chronic inflammation | Berenshtein et al. (2024); Dadáková et al. (2021); Saleem et al. (2005; Teodor et al. (2020) |

**Table 3**
Emerging and conventional strategies for extracting phenolic compounds.

| Extraction Method | Advantages | Disadvantages | Affecting Factors | Applications | References |
|---|---|---|---|---|---|
| Solid–Liquid Extraction (SLE) | Simplicity, low cost, applicable to various materials. | High solvent consumption, long extraction time, degradation of heat-sensitive compounds. | Type of solvent, extraction time, temperature. | Extraction of compounds from plants, fruits, seeds. | Machado et al. (2024); Perra et al. (2023) |
| Ultrasound-Assisted Extraction (UAE) | Increased yield, reduced solvent consumption, shorter extraction time, simple operation. | Potential degradation of compounds sensitive to ultrasound. | Ultrasound frequency and intensity, exposure time, temperature. | Extraction of antioxidants, polyphenols, essential oils. | Devi et al. (2024); Lameirão et al., 2020 |
| Supercritical Fluid Extraction (SFE) | High selectivity, no toxic solvents, ideal for heat-sensitive compounds. | Expensive equipment, requires strict control of temperature and pressure. | Temperature, pressure, $CO_2$ purity. | Extraction of essential oils, carotenoids, lipophilic compounds. | Herzyk et al. (2024) |
| Microwave-Assisted Extraction (MAE) | Reduced extraction time, higher efficiency, lower solvent consumption. | Risk of degradation of heat-sensitive compounds, requires special containers. | Microwave power, irradiation time, type of solvent. | Extraction of polyphenols, flavonoids, bioactive compounds from plants. | Apicella et al. (2023) |
| Enhanced Solvent Extraction (ESE)/ Pressurized Liquid Extraction (PLE) | High efficiency, shorter extraction time, lower solvent consumption. | Expensive equipment, requires precise control of operating conditions. | Temperature, pressure, type of solvent. | Extraction of compounds in foods, lipid extraction, antioxidants. | (Kovač et al., 2022; Machado et al., 2024; Perra et al., 2023) |
| Liquid–liquid Extraction (LLE) | Wide application, easy and efficient | Low selectivity, low yields, emulsion formation, and excessive organic solvent usage. | Solubility, Polarity, Time. | Process temperature-sensitive chemicals and azeotropic combinations. | Lama-Muñoz and Contreras (2022) |
| Maceration | Simple method, low-cost, suitable for heat-sensitive compounds. | Time-consuming, high solvent consumption, lower extraction efficiency. | Type of solvent, duration of extraction, temperature. | Extraction of essential oils, herbal extracts, and aromatic compounds. | de Oliveira et al. (2024b) de Oliveira et al., 2024a |

counting green tea, rosemary, and natural product peels, to realize additive and useful properties. They can be employed for oils, drinks, and processed foods, which match up with the trend for sustainability as well as customer desire for healthier, additive-cost-free items (Ben Said et al., 2019; Lima et al., 2021).

The flavonoid class (flavonol, flavone, anthocyanin, among others) is known for its antioxidant properties and impact on color (Shen et al., 2022). Also, many other non-flavonoids, including phenolic acids, tannins, and stilbenes, improve sensory quality and stability of food (Poljsak et al., 2021). The use of phenolic compounds and other projection towards food not only pinpoints socio-economic issues but also as an enriched bioactive compound with added-on benefits, also giving a commercial benefit (Table 2) (Albuquerque et al., 2018; R. C. Lima et al., 2021).

### 3.2. *Extraction methods and emerging analyses of phenolic compounds*

#### 3.2.1. *Extraction methods*

There are numerous emerging methodologies for extracting bioactive compounds, particularly phenolic compounds, using pre-established techniques (Table 3). However, the yield, quality, and ultimate effectiveness of the extracts may be compromised. Extract quality, and the chemicals obtained (Apicella et al., 2023, p. 4247; de Oliveira et al., 2024a; Lameirão et al., 2020a; Skenderidis et al., 2021). These techniques vary widely, from classical methods such as maceration (de Oliveira et al. (2024b) de Oliveira et al., 2024a and solid-liquid extraction (SLE) (Perra et al., 2023) to more contemporary and rapid ones, including ultrasound-assisted extraction (UAE) (Devi et al., 2024), microwave-assisted extraction (MAE) (Garofulić et al., 2020), or supercritical fluid extraction (SFE) (Herzyk et al., 2024). Depending on the matrix and the compound to be extracted, as well as the efficiency required and the temperature sensitivity of the compounds, an extraction method can be chosen. These methodologies help to optimize the extraction amount of a targeted component that also must remain functional and sensorially supported (Alara et al., 2021a; Lameirão et al., 2020a; Lefebvre et al., 2021; Zhang et al., 2022).

The extraction of phenolic compounds from plant materials typically begins with a solid-liquid extraction, followed by a direct liquid-liquid extraction (LLE) of the clarified primary aqueous extract using organic solvents such as petroleum ether and ethyl acetate to fractionate the phenolic compound fraction (Lama-Muñoz & Contreras, 2022). Although LLE employing organic-aqueous liquid-liquid biphasic systems remains one of the most used solvent extraction strategies for recovering phenolic chemicals from plant sources. However, due to the difficulties of using volatile and organic solvents, these methods are being replaced with aqueous two-phase extractions (ATPE), which lower toxicity (Sánchez-Rangel et al., 2016).

Solid-liquid extraction (SLE) is a conventional technique for isolating bioactive compounds from solid matrices such as fruits, plants, and seeds (Perra et al., 2023). This consists of soaking the powdered solid into a certain solvent (water, ethanol, methanol), mixing it, and filtering to separate the extract. Although this approach is rapid, inexpensive, and broadly applicable to a lot of materials, it often uses massive volumes of solvent and can destroy heat-sensitive compounds (e.g., studies such as those by Machado et al. (2024) and Perra et al. (2023)).

Ultrasound-assisted extraction (UAE) is a process known as cavitation, in which ultrasonic waves contribute to the extraction efficiency of bioactive compounds from cells. Compared to traditional SLE methods, UAE is a much easier approach, using less solvent and shorter extraction time. On the other hand, its decomposition of sensitive compounds under extreme conditions needs to be controlled (Christou et al., 2023; Devi et al., 2024). The research performed by Lameirão et al. (2020b) and Terenzi et al. (2024) underlines its potential to valorize bio-waste generated during the production of high-value crops according to chestnut shells or the fruit processing industry as a green option along the food chain.

Supercritical Fluid Extraction (SFE) is another application, where supercritical carbon dioxide ($CO_2$) acts as the solvent (high pressure and temperature) and features with high diffusivity (promotion of mass transfer) and low viscosity (so that a larger mass of solvent can be used with no time delay), promoting the effective extraction of the compounds. It is well suited for heat-sensitive compounds and has low toxicity and selectivity. Although offering an environmentally friendly alternative to traditional solvents, it necessitates costly equipment and precise operational management (Herzyk et al., 2024). Despite these disadvantages, its advantages make it one of the promising techniques used to extract natural compounds in food and pharmaceutical industries, although its use is more appropriate for lipophilic compounds, and cosolvents such as methanol are needed to improve the extraction performance for more hydrophilic compounds. The utilization of enhanced dissolvable extraction (ESE) and pressurized fluid extraction (PLE) (Machado et al., 2024) can enhance extraction efficiency through the influence of temperature and pressure; elevated temperatures (up to 200 °C) may facilitate increased extraction with a reduced risk of solvent evaporation (Perra et al., 2023).

Microwave-assisted extraction (MAE) (Apicella et al., 2023, p. 4247), in which microwave radiation is applied to heat the matrix and solvent, allows the components to escape by disrupting the cell wall. This method decreases time, and solvent use, and increases utilization. Still, it can risk heat-sensitive compound decay and generate high pressure in closed systems (Apicella et al., 2023, p. 4247).

Soxhlet extraction is frequently employed when the solid sample has limited solubility in a solvent and there are intractable impurities present in the sample. The “like dissolve like” principle allows for the use of a variety of solvents with varying polarities in Soxhlet extraction (Wong et al., 2023). The extraction of hydrophilic flavonoids and hydroxycinnamic acids is feasible with a highly polar solvent, such as water (Reis et al., 2012). Ethyl acetate, a solvent with intermediate polarity, is effective in the extraction of phenolic compounds (Babbar et al., 2014). Until the sample is transformed into a desiccated and fine solid, the process is continuous and can last for several hour. This technique permits the use of a smaller volume of extracting solvent than the maceration method; however, the extraction solvents must be of high purity. The solvents employed, including methanol and ethyl acetate, may pose a risk to human health (Wong et al., 2023).

Maceration and hydrodistillation are conventional extraction technologies that are frequently employed to recover bioactive compounds (Zhang et al., 2018). Maceration is a method that relies on the use of organic solvents, agitation, temperature, and time for extraction. This extraction technology is the most prevalent due to its straightforward and cost-effective procedure (Albuquerque et al., 2018; de Oliveira et al., 2024b). The recovery of bioactive compounds necessitates a subsequent concentration process, typically evaporation, and the use of potentially toxic solvents (Azmir et al., 2013). The quality of these green technologies, which have replaced conventional technologies such as maceration and hydrodistillation, is maintained by the high yield, reduced extraction process time, and benign conditions that prevent or reduce the degradation of the antioxidant molecules. The most significant factor is the recovery of the compounds of interest from sustainable processes (Lizárraga-Velázquez et al., 2020).

#### 3.2.2. *Methods for phenolic compound analysis*

Phenolic compounds are crucial secondary metabolites, while analytical methodologies are crucial for the characterization, quantification, and analysis of polyphenols in a variety of matrices such as food, beverages, and plant extracts (Welc et al., 2022). These technologies include both general, broad measures, such as UV–vis spectrophotometry, and complex, high-sensitivity techniques, such as High-Performance Liquid Chromatography coupled with Mass Spectrometry (HPLC-MS) (Ferreira et al., 2016). In addition, among the other popular ones, gas chromatography (GC-MS), nuclear magnetic resonance (NMR), and capillary electrophoresis (CE) each offer specific advantages, depending on the type of compounds being analyzed and the nature of the sample. Also, the molecular structure contributes to factors such as polarity, conjugation and interaction with food matrix and a number of high-molecular-weight phenolics are insoluble and thus require suitable extraction methods in order to prevent their chemical transformation and preserve bioactive properties (Berenshtein et al., 2024; Riaz & Masud, 2013).

Phytochemical characterization is essential to characterize extracts in terms of their chemical structure, molecular weight, surface charges, size and functional groups. There is a range of analytical equipment that can be used to analyze these compounds. gas chromatography-mass spectrometry (GCMS) to identify compounds (Tran et al., 2024), Fourier transform infrared spectroscopy (FTIR) to characterize functional groups (Gong et al., 2024), the Zetasizer to analyze surface charge and particle size (Fierri et al., 2024), and ultraviolet–visible spectroscopy

**Table 4**
Phenolic compound analysis methods.

| Analysis Method | Advantages | Disadvantages | Affecting Factors | Application | References |
|---|---|---|---|---|---|
| UV–Vis Spectrophotometry | Simple, low cost, fast, suitable for total phenolic quantification. | Not specific for individual compounds, only provides total content. | Wavelength selection, reagent quality, sample preparation. | Quantification of total phenolic content in plant extracts, fruits, wines. | Johnson et al. (2024); Pérez et al. (2023) |
| High-Performance Liquid Chromatography (HPLC) | High sensitivity and specificity, precise quantification of individual compounds. | Expensive equipment, requires expertise and careful calibration. | Column type, mobile phase composition, flow rate, detection wavelength. | Identification and quantification of specific phenolic acids, flavonoids, tannins. | Felegyi-Tóth et al. (2022); Russo et al. (2018) |
| Liquid Chromatography-Mass Spectrometry (HPLC-MS/MS or UPLC-MS/MS) | Highly sensitive, capable of identifying and quantifying low-concentration compounds in complex samples. | High equipment cost, complex sample preparation, and data interpretation. | Ionization mode, sample preparation, chromatographic conditions. | Detailed profiling of phenolic compounds in complex matrices like foods and beverages. | Felegyi-Tóth et al. (2022); Magda R. A. Ferreira et al. (2016) |
| Gas Chromatography-Mass Spectrometry (GC-MS) | Excellent resolution for volatile compounds, suitable for phenolics that can be derivatized. | Requires derivatization for non-volatile phenolics, expensive setup. | Derivatization process, column type, temperature, carrier gas flow. | Analysis of volatile phenolic compounds in beverages and essential oils. | de Oliveira et al. (2024c) de Oliveira et al., 2024a |
| Capillary Electrophoresis (CE) | High resolution, low solvent consumption compared to HPLC. | Complex operation, less common use due to technical challenges. | Buffer composition, voltage, capillary type. | Analysis of phenolic compounds in plant extracts and food products. | Carbonell-Rozas et al. (2024); Stolz et al. (2019); Zheng et al. (2016) |
| Nuclear Magnetic Resonance (NMR) | Non-destructive, provides detailed structural information. | Lower sensitivity | | | |
| Other Techniques (FTIR, Raman spectroscopy) | Rapid, non-destructive, useful for functional group identification. | Less specific for quantification, provides more qualitative than quantitative data. | Wavelength range, sample preparation, interaction with light. | Qualitative analysis of phenolic functional groups in extracts. | Ji et al. (2015); Maher et al. (2021) |

(UV–Vis) to measure the light absorbance value of samples (Liu et al., 2024). These technologies include high-sensitivity techniques, such as High-Performance Liquid Chromatography coupled with Mass Spectrometry (HPLC-MS) (Ferreira et al., 2016). In addition, NMR, and CE each offer specific advantages, depending on the type of compounds being analyzed and the nature of the sample.

It is thus an important step to choose the right technique (such as Table 4) to acquire accurate and reproducible results, enabling improved understanding of the composition and potential activity offered by phenolic compounds (Delgado et al., 2019; Khoddami et al., 2013; Zhang et al., 2022) (Table 2). UV–vis spectrophotometry is a simple, cheap, and common technique for the quantification of total phenolic compounds, usually using the Folin–Ciocalteu method (Abedi-Firoozjah & Tavassoli, 2024b). Complex components are analyzed using high-performance liquid chromatography (HPLC), which does not require derivatization or sample preparation. In recent years, HPLC has been combined with spectroscopic techniques or detectors such as mass spectrometers, which produce spectra containing structural information (molecular weight and UV–Vis absorption bands) once analytes are separated. This approach provides exact and sensitive identification of known phytoconstituents, especially for compounds that have accessible databases (Oladeji et al., 2024b). Especially, it is very practical when the qualitative and quantitative composition of food, beverages, and plant extracts are of interest, and among the techniques, this method provides unrivaled accuracy (Felegyi-Tóth et al., 2022; Russo et al., 2018).

Most commonly used techniques for the identification and quantification of phenolic compounds in complex samples include Liquid Chromatography Coupled with Mass Spectrometry (HPLC-MS/MS or UPLC-MS/MS) (Felegyi-Tóth et al., 2022). In particular, it is applicable to detailed polyphenol characterization, as shown by Hernández-Montesinos et al. (2024), for example, coffee grounds and fruit peels, which potentially act as a green supply of natural antioxidants (Felegyi-Tóth et al., 2022; Magda R. A. Ferreira et al., 2016; Russo et al., 2018). Volatile phenolic compounds are converted into volatile forms, indicating that the identification of these compounds via gas chromatography-mass spectrometry (GC-MS) de Oliveira et al. (2024c) de Oliveira et al., 2024a is highly appropriate for food and beverages, including wines and teas. Although it has been successfully applied for the resolution of volatile compounds, a different derivatization step is necessary for non-volatile phenolics, which are the dominant species of phenolics (de Oliveira et al., 2024b, de Oliveira et al., 2024a).

CE, a higher resolution technique compared to HPLC and lower solvent demand, separates phenolic compounds according to size and/or charge in an electric field and is combined with UV–visible or mass spectrometry for diagnostic use, the complexity of its operation restricts its application and widespread acceptance (Carbonell-Rozas et al., 2024; Stolz et al., 2019).

Other methodologies, such as nuclear magnetic resonance (NMR), offer substantial structural insights and are especially useful for elucidating structures and characterizing complex mixtures (Consonni & Cagliani, 2019; Mahrous & Farag, 2015). At last, FTIR and Raman spectroscopy can be used to identify (Maher et al., 2021) the functional groups in phenolic compounds by non-destructive approaches. These approaches are quick and useful for qualitative analysis but are lower in specificity for quantification (Ji et al., 2015; Maher et al., 2021).

### 3.3. *Phenolic compounds and their importance to food industry*

Numerous applications in the food industry have been suggested in relation to the technological potential of phenolic Compounds. However, it is critical to note that food manufacturers must not only understand the technology of combining ingredients to meet sensory and safety requirements, but also develop a new framework for food recommendations based on physics, storage and preservation techniques, nutrient restoration, and food fortification, allowing for the development of new products with functional claims and improved quality (de Araújo et al., 2021a), given its significant antioxidant potential (Franco et al., 2019) and antibacterial capabilities (Martinengo et al., 2021, p. 2469).

However, direct inclusion poses certain obstacles. The engagement of phenolic compounds with dietary constituents may diminish their efficacy, complicating the attainment of uniform distribution and the assurance of antibacterial and antioxidant activity (de Araújo et al.,

**Table 5**
The employing of phenolic compounds in the food industry.

| Food Additives | Source | Product | Effects | Reference |
|---|---|---|---|---|
| Phenolic extracts | Yerba mate (Ilex paraguariensis) | Frozen burgers with natural antioxidant | Reduced lipid oxidation, increased antioxidant activity, maintained sensory acceptance, healthier alternative to synthetic antioxidants. | Feihrmann et al. (2022) |
| Phenolic extracts | Strawberry tree (Arbutus unedo L.) and dog rose (Rosa canina L.) | Frankfurters | Enhanced oxidative stability, reduced lipid oxidation and protein carbonyl formation, preserved color and texture during storage. | Armenteros et al. (2013) |
| Quercetin derivatives (quercetin-4′-O-glucoside, quercetin-3-O-rutinoside, etc.), luteolin-7-O-glucoside | Capers, red-skinned onion, red radish, olives | Co-digested starchy foods (pasta with vegetable foods) | Inhibited starch hydrolysis (21.5 %–31.7 %), reduced post-prandial glucose levels, potential anti-diabetic effect through α-glucosidase inhibition. | Cattivelli et al. (2024) |
| Phenolic compounds at Grape pomace and olive pomace pâté | By-products of wine and olive oil production | Fortified pasta (tagliatelle) | Increased fiber content (~3 %), retention of phenolic compounds (6.21–9 mg/100 g), maintained cooking resistance and texture, improved nutritional profile. | Balli et al. (2021) |
| Hull-less barley flour, buckwheat flour | Highland crops (hull-less barley, buckwheat) | Nutritionally enhanced pasta | Enhanced nutrition, increased protein and phenolic content, reduced brightness, high acceptability at 20 % barley and buckwheat incorporation. | Kumari and Gupta (2022) |
| Ferulic acid (major), vanillic acid, caffeic acid, p-coumaric acid, p-hydroxybenzoic acid | Barley flour | Fresh and dried spaghetti with barley flour | Increased phenolic content, maintained antioxidant capacity, variable impact of drying on individual phenolic acids, minimal loss during cooking. | De Paula et al. (2017) |
| Phenolic extracts | Matricaria recutita L.<br>Foeniculum vulgare Mill. | Yogurt | Antioxidant activity | Caleja et al. (2016) |
| Anthocyanins | Euterpe edulis M. | Fermented and unfermented beverages | Improvement of the color. | (E. M. F. Lima et al., 2019) |
| | Phaseolus vulgaris L. | Sport beverage | Stable color and fortification with bioactive molecules. | Aguilera et al. (2016) |
| Chlorogenic acid, rutin, and others | Roasted yerba mate | Infusions prepared with water, whole, semi-skimmed, and skimmed milk | Increased bioavailability, preserved phenolic content, enhanced antioxidant activity, and bioactive peptides with health benefits. | Kautzmann et al. (2024) |
| Purified phenolics and green tea extract (GTE) | Green tea | Milk and cheese with GTE addition | Reduced milk coagulation efficiency, decreased primary proteolysis, hindered micelle aggregation, and altered peptide profiles in cheese. | Yildirim-Elikoglu et al. (2021) |
| Caffeic acid and other phenolic acids | Regular and decaffeinated espresso coffee capsules | Coffee beverages with or without milk | Reduced phenolic content post-digestion, 48 % intestinal recovery of caffeic acid, prooxidative action in regular coffee, and lipid peroxidation prevention by decaffeinated coffee. | Soares et al. (2021) |
| Total and individual phenolics | Pomelo juice (PJ) and kiwi juice (KJ) | Juices processed with high-pressure homogenization (HPHP), thermal treatment (TT), and mixed with milk matrices | Increased phenolics, reduced bioaccessibility, improved with milk, best with skimmed/whole milk. | Quan et al. (2020) |

2021a). The efficacy of phenolic compounds can be affected by several factors: intrinsic food properties (including pH, water activity, and composition), external conditions (such as temperature, humidity, and ambient atmosphere), microbiological elements (comprising initial microorganism count, growth rate, antimicrobial resistance, and microbial interactions), and processing parameters (including cooking stages and oxygen exposure) (Calo et al., 2015).

Codina-Torrella et al. (2021) investigated the use of selected brewing industry (potential) by-products, i.e., brewer's spent grain (BSG) and spent hops (BSH), as potential sources of natural antioxidants. BSG exhibited a higher polyphenol content and antioxidant capacity than BSH upon extraction optimization using NaOH in terms of polyphenols and antioxidant capacity (1.45 %, 80 °C).

Recent studies on solid-state fermentation techniques have shown potential for phenolic component recovery. According to Martí-Quijal et al. (2021) fermented food waste, such as fruits, vegetables, and grains, created bioactive molecules with antioxidant and antibacterial properties. Although promising, this material method is constrained by optimizing bioreactor conditions and purification costs, requiring transfer to an industrial platform.

In the field of beverage preservation, Ma et al. (2023), p. 5255 examined the prospective application of some polyphenols (dihydromyricetin, resveratrol, and catechins) in wine, as an alternative to the more commonly used preservative sulfur dioxide ($SO_2$), the presence of which poses a health threat to sensitive individuals. Dihydromyricetin exhibited the greatest antioxidant activity; resveratrol improved aromatic compounds; and catechins produced the best sensory response. The study results point to the opportunity of using polyphenols as additives to enhance food and beverage quality and safety, potentially replacing or minimizing the use of synthetic additives while offering targeted quality benefits in different types of products. Besides their application in different food matrices, these bioactive compounds have also been incorporated into edible films, a type of protective barrier which functions to prevent microbial growth and delay oxidation, enabling sustainable food preservation. The use of natural preservatives in edible films is noteworthy due to their dual role: alongside providing surfaces against an external attack, this type of films prevents losing sensory and nutritional properties of products (Iversen et al., 2022; Singh, 2024; Kumar et al., 2022). Studies by Mazzucotelli et al., (2022) studied a mixed salad (i.e., red cabbage, arugula, parsley, and beet leaves), which after *in vitro* digestion showed losses in both phenolic content and antioxidant capacity, with the microbiological shelf life of up to five days (Elejalde et al., 2024).

The antimicrobial activity of plant polyphenols is validated, highlighting their potential as food preservatives. Each bioactive polyphenol acts in a different manner and thus, bacteria should not be able to develop resistance when used in combination with other antimicrobials and antibiotics. Indeed, such a use could potentially lower exposure to

**Table 6**
Strategies for enhancing the bioavailability and stability of phenolic compounds.

| Encapsulation technique | Carrier materials | Phenolic compounds | Source | Effects | References |
|---|---|---|---|---|---|
| Emulsions | Pectin, wastewater, limonene | Orange peel phenolics | Orange peel wastewater | Enhanced emulsion stability, essential oil retention, film flexibility, improved physicochemical and mechanical properties, increased water vapor permeability, and effective waste valorization for eco-friendly food packaging applications. | Bocker and Silva (2024) |
| Loading phenolic compounds into lignin nanoparticles (LNPs) and chitosan nanoparticles (DLECNPs) | Soy protein isolate (SPI), lignin nanoparticles (LNPs), chitosan nanoparticles (DLECNPs) | Phenolic compounds extracted from date palm leaves | Date palm leaves | Improved antioxidant and antibacterial properties, enhanced mechanical strength, reduced water vapor permeability, altered color, and biodegradable packaging potential | Mostafa et al. (2024) |
| None (extraction and purification) | None | Polyphenols (3.3 g/L TPC) | Orange peel biomass | Bioactive compound recovery, food-grade applications, sustainability, and waste valorization | Niglio et al. (2024) |
| Supercritical fluid impregnation (SFI) | Corn starch aerogels | Piceatannol | Ethanolic extract of passion fruit bagasse (EEPFB) | Enhanced antioxidant capacity (FRAP and ORAC), incorporation of phenolic compounds into aerogels, and effective pore filling through precipitation. | de Araujo et al. (2024) |
| Nanoprecipitation | Whey protein isolate (EPWI), whey protein concentrate (EPWC), soy protein isolate (EPSP) | Procyanidin B1, fumaric acid | Pulp flour of Cantaloupe melon (Cucumis melo L.) | Increased antioxidant activity (up to 6x), high incorporation efficiency (74.10–90.60 %), formation of stable spherical particles with smooth surfaces and amorphous structure. | da Silva et al. (2025) |
| Liposomes | Liposomes loaded with extracts | Extracts from Cinnamomum verum and Syzygium aromaticum | Cinnamomum verum (cinnamon) and Syzygium aromaticum (clove) | Increased phenolic content and antioxidant activity, reduced yeast and mold growth, reduced moisture and water uptake, acceptable sensory quality, and extended shelf life of fresh pasta. | Aslan et al. (2024) |
| Microencapsulation | Dairy beverage matrices (fermented and unfermented) | Anthocyanins | Juçara palm fruit | Stable pigment and bioactive compound content, minimal color change, improved nutritional and sensory value. | (E. M. F. Lima et al., 2019) |
| Nanoemulsions (NEs) and acidified milk gels (MGs) | Sodium caseinate (NEs) and glucono delta-lactone acidified milk gels (MGs) | Yarrow phenolics | Yarrow extract (YE) | MGs provided better phenolic stability and antioxidant activity post-digestion compared to NEs, highlighting the potential of MGs for dairy product enrichment. | Villalva et al. (2020) |
| Incorporation into starch-PVA films | Starch-PVA matrix | Polyphenols from Clitoria ternatea flower extract (ECT) | Clitoria ternatea flowers | Dose-dependent antioxidant activity, reduced tensile strength, 70 % compostability, enhanced polyphenol release in water-based fluids, suitable for active food packaging. | (do Nascimento et al., 2024) |
| Incorporation into starch-based films | Cassava starch matrix | Secondary metabolites with antioxidant activity | Aspergillus niger MgF2 fungal extract | Maximum release in 25 min at 37 °C, maintained antioxidant activity, non-toxic, with potential for pharmacological and cosmetic applications. | Falcão et al. (2024) |
| Incorporation into SPI edible films | Soy protein isolate (SPI), cellulose nanoparticles (NC) | Green extracted phenolics from date palm leaves (DLE) | Date palm leaves | Improved mechanical and barrier properties with NC; enhanced antioxidant and antibacterial properties with DLE powder (DLPE); development of biodegradable, active food packaging materials. | Mostafa et al. (2023) |
| Incorporation into maize starch-based films | Maize starch | Protocatechuic acid, naringin, tannic acid | Synthetic or natural phenolics | Enhanced mechanical, thermal, antioxidant, and barrier properties; influenced film structure, crystallinity, and compatibility based on phenolic complexity. | (N. Chen et al., 2023) |

(*continued on next page*)

**Table 6** (*continued*)

| Encapsulation technique | Carrier materials | Phenolic compounds | Source | Effects | References |
|---|---|---|---|---|---|
| Cross-linking | Chicken gelatin, glycerol (GLY) | Caffeic acid (CA), rutin (RUT) | Poultry by-products | Improved thermal stability, tensile strength, reduced water solubility (up to 50 %), enhanced opacity and barrier properties, suitable for biodegradable packaging films. | Erge et al. (2024) |
| Interfacial self-assembly | Zein films (ZF) | Curcumin, resveratrol, quercetin | Natural polyphenols | Efficient loading, controlled release kinetics, hydrogen bonding and hydrophobic interactions, and modulation of film surface micromorphology. | Lu et al. (2023) |
| Casting-laminated method | Gelatin and myofibrillar protein multilayer films | Phenols from clove (Eugenia spp.) essential oil | Clove (Eugenia spp.) essential oil | Improved barrier properties, increased transparency, reduced elongation at break, protein-phenolic interactions, good antioxidant activity, fastest release in water, and highest efficiency in 50 % ethanol. | Jiang et al. (2022) |
| Incorporation into poly (vinyl alcohol) (PVA) layer via thermocompression lamination | Multilayer films of poly(lactic acid) (PLA) and PVA | Carvacrol, ferulic acid | Natural phenolic compounds | Improved tensile and barrier properties, effective microbial growth control, enhanced meat preservation during cold storage. | Andrade et al. (2022) |
| Incorporation into k-carrageenan edible films | k-Carrageenan matrix | Bee pollen and honey extracts (ulmo and quillay honey) | Bee pollen and honey | Enhanced physical and antioxidant properties, increased hydrophilicity, unchanged thermal stability, no significant antibacterial enhancement, but improved antioxidant and antiradical activity in films and beef. | Velásquez et al. (2022) |
| Cross-linking with phenolic substances | Turmeric (Curcuma longa) and gelatin films | Tannic acid, caffeic acid, green tea extract | Natural phenolics | Increased tensile strength, reduced elongation-at-break, improved barrier properties, antioxidant activity, prevention of lipid oxidation, extended shelf life of pork, and maintained sensory acceptability. | Choi et al. (2018) |
| Incorporation into gellan gum films | Gellan gum matrix | Gallic acid, chlorogenic acid, p-coumaric acid, sinapic acid, caffeine | Coffee parchment waste (Coffea arabica) | Antifungal activity, modified physicochemical, mechanical, and structural properties, and potential application in bioactive food packaging. | Mirón-Mérida et al. (2019) |
| Incorporation into soy protein isolate (SPI) films | Soy protein isolate (SPI) | Rutin and epicatechin | Natural phenolic compounds | Increased tensile strength and puncture strength (with rutin), enhanced water vapor barrier (with rutin), increased water vapor permeability (with epicatechin), and higher opacity for phenolic-added films. | Friesen et al. (2015) |
| Microencapsulation | Inulin and OSA-starch (octenyl succinic anhydride modified starch) | Gallic acid, protocatechuic acid, p-hydroxybenzoic acid, 2,4-dihydroxybenzoic acid, p-coumaric acid, sinapinic acid, 2-hydroxybenzoic acid, quercetin 3-β-D-glucoside, (+)-catechin, (−)-epicatechin, myricetin, quercetin | Brazil nut (Bertholletia excelsa) cake extract | Stabilized phenolic compounds and antioxidant capacity for 120 days, high selenium content (4.95 μg/g), functional food-grade powder with prebiotic and bioactive properties. | Gomes et al. (2019) |
| Microencapsulation | Maltodextrin | Pomegranate peel phenolics | Pomegranate peel | Stable phenolic content (90 days at 4 °C), improved antioxidant and α-glucosidase inhibitory activities, high sensory acceptance, functional food potential. | Çam et al. (2014) |
| Freeze-drying | Maltodextrin, arabic gum | Anthocyanins | Cherry juice | Superior stability of monomeric anthocyanins and color retention at 38 °C, attributed to the protective encapsulation in an amorphous matrix with reduced water activity. | Sanchez et al. (2015) |
| Microencapsulation | Soy protein (S), whey protein (W), maltodextrin (M) | Anthocyanins, flavonols, hydroxycinnamates, flavan-3-ols | BRS Violeta red grape juice | Preserved anthocyanins in 1SM treatment, decreased hydroxycinnamates and flavan-3-ols at 35 °C, stable antioxidant | Moser et al. (2017) |

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**Table 6** (*continued*)

| Encapsulation technique | Carrier materials | Phenolic compounds | Source | Effects | References |
|---|---|---|---|---|---|
| | | | | activity and color after 150 days of storage. | |
| Complex coacervation | Gelatin with gum arabic, κ-carrageenan, cashew tree gum, pectin, or carboxymethylcellulose | Proanthocyanidins and other polyphenols | Ceylon cinnamon extract | Improved stability of phenolic compounds (up to 80 % retention), masked flavor and astringency in ice cream, resistance to stress conditions except at pH < 2 and temperatures >50 °C, enhanced applicability in food products. | Brito de Souza et al. (2020) |
| Freeze drying and spray drying | Maltodextrin (MD), β-cyclodextrin (CD), MD + CD | Green tea polyphenols | Green tea extract | Improved stability and antioxidant activity (higher in freeze-dried MD encapsulates), retained bread quality (volume, crumb firmness), and preserved total polyphenol content in encapsulated bread. | Pasrija et al. (2015) |
| Freeze-drying | Maltodextrin, pectin, soy protein isolate | Anthocyanins | Jaboticaba pomace | High protection of total phenolics (>90 %), monomeric anthocyanins (76 %), and antioxidant activity (73 %) after 90 days, stability under UV light, and encapsulation confirmed by thermal analysis. | Pereira Souza et al. (2017) |
| Ethanol injection method (EIM) | Nanovesicles (transfersomes, niosomes, liposomes) formulated with soybean lecithin, Tween 80, Span 60, and cholesterol | Taxifolin (flavanonol) | Natural antioxidant | High encapsulation efficiency (72 %–75 %), controlled release (90 % in gastrointestinal conditions), improved bioavailability, stable formulations, and potential application in fortified apple juice. | Hasibi et al. (2020) |
| High-pressure homogenization and layer-by-layer coating | Liposomes coated with chitosan and mixed with maltodextrin | Anthocyanins from black mulberry extract (BME) | Black mulberry (Morus nigra) | Enhanced anthocyanin stability at high temperatures and pH, improved bioaccessibility, and successful fortification of chocolate with up to 76.8 % anthocyanin retention. | Gültekin-Özgüven et al. (2016) |
| Freeze drying with ultrasonication | Soy protein isolate (SPI), gum arabic (AG), and their combination | Anthocyanins | Red raspberry | High encapsulation efficiency (93.05 %–98.87 %), enhanced thermal stability (80–114 °C), retention of anthocyanins (up to 48 % at 37 °C for 60 days), and improved release behavior under gastrointestinal conditions. | Mansour et al. (2020) |

drug-resistant bacteria, evo-king a new resource for food preservation (Efenberger-Szmechtyk et al., 2021; Álvarez-Martínez et al., 2020). Though synthetic preservatives continue to be used to suppress microbial growth and extend the shelf life of foods (Teshome et al., 2022a), pathogens such as *Salmonella* spp., *E. coli*, *Listeria monocytogenes*, etc., remain hot topics in the domain of food safety, leading to a quest for efficient natural alternatives. However, the effectiveness of natural antimicrobials, including essential oils (EOs) was limited in the complex food system owing to their interaction with various components, including proteins, lipids, carbohydrates, and even ions contained in foods. Such interactions diminish the antimicrobial action of natural components, requiring specific testing under the conditions of each food before application (Asbahani et al., 2015; Tongnuanchan & Benjakul, 2014).

Hydrophobic and hydrophilic segments are combined for amphiphilic nature of natural antimicrobials; therefore, they exert effect on microbial cell membranes, such as essential oils. However, this amphiphilic attribute can also result in undesirable interactions with hydrophobic food constituents, as lipids, compromising their efficiency (Asbahani et al., 2015). When applying these antimicrobials in foods, for development of more effective formulations, the microbial flora of the product, could be a potential resistance of these microorganisms to the extreme conditions as pH shift and high temperatures employed during its processing, describes the use of other substances as preservation techniques these methods in addition to this. This may result in reduced antimicrobial activity or microbial adaptive responses (for example, synthesis of acid-shock proteins and cell protective defenses), making it difficult to control microbial contamination. Others, in addition to this antimicrobials can influence sensorial properties of food due to their strong aroma and flavour that might be compatible with meat products rather than dairy (e.g. garlic extracts). By using combinations, an attempt can be made to keep a balance between food preservation and unwanted sensory effects as demonstrated by studies combining mustard essential oil with extracts of citrus and olive (Calo et al., 2015; Lima et al., 2021b; Lopes & Brandelli, 2018; Taylor et al., 2019).

Table 5 shows some applications of phenolic compounds derived from natural sources and their possible effects on the food products tested.

### 3.3.1. *Bioavailability of phenolic compounds*

The beneficial health effects of phenolic compounds are primarily due to their metabolites. Bioavailability of phenolic compounds is influenced by digestion, absorption, metabolism, chemical structure, release in food matrix, conjugation with other compounds, size molecular, degree of polymerization, and solubility (de Araújo et al., 2021). The food matrix has been reported as a factor influencing the bioaccessibility of phenolic compounds, since the -OH radical of phenolics may interact with parts of dietary fiber or proteins (Matsumura et al., 2023; Mihaylova et al., 2024).

The small intestine absorbs only around 5–10 % of the total polyphenols consumed, depending on their chemical complexity (Mihaylova et al., 2024). The liver deglycosylates and converts less complex phenolic compounds into methylation, glucuronidation, and sulfonation reactions before they are absorbed and distributed to other organs (Loarca-Piña et al., 2022). It is crucial to consider bioaccessibility when consuming a personal computer, which is the quantity of a compound that is released from the food matrix and accessible for absorption in the gut (Domínguez-Avila et al., 2017).

Improving phenolic compound bioavailability is critical for maximizing their therapeutic potential in disease prevention. Chemical and technological modification, the use of prodrugs, polymers (for example, chitosan, dendrimers, and cyclodextrins), and nanotechnology can all be used to increase the bioavailability of these compounds and alter parameters such as solubility, absorption, and metabolism (L. Chen et al., 2019).

### 3.3.2. *Encapsulation of phenolic compounds for food applications*

Encapsulation is a technique used to resolve the problems related to bioavailability (C. Di Lorenzo et al., 2021) and stability (Berenshtein et al., 2024) of phenolic compounds present in food products. This can be achieved by entrapping these compounds in carrier molecules (liposomes, cyclodextrins and biocompatible polymers) that protect them against degradation and guarantee controlled and progressive release, increasing their efficacy and duration in food applications (Atarés & Chiralt, (s.d.). Essential oils as additives in biodegradable films and 1 coatings for active food packaging 2 3; Gyawali & Ibrahim, 2014). This technique is especially useful for hydrophobic compounds, which tend to accumulate in the lipid fraction of foods, while their antimicrobial activity is more effective in the hydrophilic portion, where they act to prevent microbial growth (Guo et al., 2018; Song et al., 2017).

Common encapsulation systems include spray drying, emulsification, solvent precipitation, electrospinning, and liposome forms, producing micro or nanocapsules (Riaz & Masud, 2013). Hydrophilic compounds can be encapsulated in starch, alginate, gelatin, carrageenan and milk proteins, while phospholipids can be used to form liposomes for hydrophobic compounds — human safety and properties of the bioactive compound should take the highest priority when choosing encapsulating agents (Asbahani et al., 2015).

Temperature, pH, water activity, food ingredients (Khoo et al., 2017), preparation method (Irakli et al., 2023), and storage conditions (Król et al., 2020) directly affect the release of the active chemical (Bhargava et al., 2015). The selection of coating material, encapsulation technique, and particle size is essential (Falguera et al., 2011) for maximizing antimicrobial efficacy, with materials with antimicrobial characteristics, such as chitosan, frequently producing optimal outcomes (Riaz & Masud, 2013; Zimet et al., 2018). Devi et al. (2024) used ultrasound-assisted extraction to optimize the phytochemicals, in particular the anthocyanin from black rice bran and after microencapsulating these compounds obtained the potential to serve as a stable nutraceutical source.

Improved methods for the controlled release of phenolic compounds in nanostructures has been especially important to beverages, meats, dairy products, and other minimally processed foods, in which antioxidants and antimicrobials released slowly can prolong shelf life without synthetic preservatives (Bouarab Chibane et al., 2019; Franco et al., 2019; Lavanya et al., 2024a). The reduction of undesirable properties in food (among them odor, smell and taste) can be minimized with nanoparticles ranging from 1 to 100 nm, generating stability and increased activity in food products against microorganisms in food systems (Pinto et al., 2023; Teshome et al., 2022a; Tsiraki et al., 2017).

Challenges remain to be addressed, particularly in legislation and consumer acceptance, with a demand for guarantees about the safety and transparency of nanoparticles in food products. Nanotechnology research on phenolic chemical release and industrial applications is

**Table 7**
Chemical compounds are employed in the food industry based on their primary technological functions (FDA-U.S. Food Administ., 2018); (Food and Agriculture Organization of the United Nations World Health Organization, 2016).

| Class | Additives |
|---|---|
| Anticaking agent | Calcium silicate; Carnauba wax; Castor oil; Ferric ammonium citrate; Ferrocyanides; Magnesium hydroxide carbonate; Magnesium oxide; Magnesium silicate, synthetic; Mannitol; Microcrystalline celulose (cellulose gel); Phosphates; Polydimethylsiloxane; Powdered cellulose; Salts of myristic, palmitic and stearic acids with ammonia, calcium, potassium and sodium; Salts of oleic acid with calcium, potassium and sodium; Silicon dioxide, amorphous; Sodium aluminosilicate; Sodium carbonate; Sodium hydrogen carbonate; Sodium sesquicarbonate; Talc. |
| Antifoaming agent | Calcium alginate; Microcrystalline wax; Mono- and di-glycerides of fatty acids; Polydimethylsiloxane; Polyethylene glycol; Polysorbates; Silicon dioxide, amorphous. |
| Antioxidant | Ascorbic acid, L; Ascorbyl esters; Butylated hydroxyanisole; Butylated hydroxytoluene; Calcium ascorbate; Citric acid; Citric and fatty acid esters of glycerol; Erythorbic acid (isoascorbic acid); Ethylene diamine tetra acetates; Guaiac resin; Isopropyl citrates; Nitrous oxide; Phosphoric acid; Potassium lactate; Propyl gallate; Sodium ascorbate; Sodium erythorbate (sodium isoascorbate); Sodium lactate; Stannous chloride; Stearyl citrate; Sulfites; Tartrates; Tertiary butylhydroquinone; Thiodipropionates; Tocopherols. |
| Bulking agent | Hydroxypropyl methyl cellulose; Mannitol; Methyl cellulose; Microcrystalline cellulose (cellulose gel); Polydextroses; Powdered cellulose; Processed Euchema sea weed (PES); Propylene glycol alginate; Sodium alginate; Sodium carboxymethyl cellulose (cellulose gum); Sodium lactate. |
| Carbonating agent | Carbon dioxide. |
| Carrier | Castor oil; Cyclodextrin, Beta-; Dextrins, roasted starch; Gum Arabic (Acacia gum); Magnesium hydroxide carbonate; Polyethylene glycol; Processed Euchema sea weed (PES); Silicon dioxide, amorphous. |
| Color | Allura red AC; Amaranth; Annato extracts, Bixin-based; Annato extracts, Norbixin-based; Azorubine (Carmoisine); Brilliant black (Black PN); Brilliant blue FCF; Brown HT; Canthaxanthin; Caramel I – Plain caramel; Caramel II – Sulfite caramel; Caramel III – Ammonia caramel; Caramel IV – Sulfite ammonia caramel; Carmine; Carotenes, Beta-, vegetable; Carotenoids; Chlorophylls and Chlorophyllins, copper complexes; Curcumin; Erythrosine; Fast green FCF; Grape skin extract; Indigotine (Indigo Carmine); Iron oxides; Lutein from tagetes erecta; Ponceau 4R (Cochineal red A); Riboflavins; Sunset yellow FCF; Tartrazine; Zeaxanthin, synthetic. |
| Color retention agent | Aluminum ammonium sulfate; Ethylene diamine tetra acetates; Ferrous gluconate; Ferrous lactate; Magnesium carbonate; Magnesium chloride; Magnesium hydroxide; Magnesium hydroxide carbonate; Nitrites; Stannous chloride. |
| Emulsifier | Acetic and fatty acid esters of glycerol; Agar; Alginic acid; Ammonium alginate; Ammonium salts of phosphatidic acid; Beeswax; Candelilla wax; Carob bean gum; Carrageenan; Castor oil; Citric and fatty acid esters of glycerol; Dextrins, roasted starch; Diacetyltartaric and fatty acid esters of glycerol; Dioctyl sodium sulfosuccinate; Glycerol ester of wood rosin; Guar gum; Gum Arabic (Acacia gum); Hydroxypropyl cellulose; Hydroxypropyl starch; Karaya gum; Konjac flour; Lactic and fatty acid esters of glycerol; Lecithin; Methyl cellulose; Methyl ethyl cellulose; Microcrystalline cellulose (cellulose gel); Mono- and di-glycerides of fatty acids; Monostarch phosphate; Oxidized starch; Pectins; Phosphated distarch phosphate; Sodium dihydrogen phosphate; Trisodium phosphate; Phosphates; Polyethylene glycol; Polyglycerol esters of fatty acids; Polyglycerol esters of interesterified ricinoleic acid; Polyoxyethylene stearates; Polysorbates; Polyvinylpyrrolidone; Potassium alginate; Powdered cellulose; Processed Euchema sea weed (PES); Propylene glycol; Propylene glycol alginate; Propylene glycol esters of fatty acids; Salts of myristic, palmitic and stearic acids with ammonia, calcium, potassium and sodium; Salts of oleic acid with calcium, potassium and sodium; Sodium alginate; Sodium aluminium phosphates; Sodium dihydrogen citrate; Sodium lactate; Sorbitan esters of fatty acids; Starch acetate; Starch sodium octenyl succinate; |

(*continued on next page*)

**Table 7** (*continued*)

| Class | Additives |
|---|---|
|  | Starches, enzyme treated; Stearoyl lactylates; Sucroglycerides; Sucrose acetate isobutyrate; Sucrose esters of fatty acids; Sucrose oligoesters, type I and type II; Tragacanth gum; Trisodium citrate; Xanthan gum. |
| Emulsifying salt | Sodium dihydrogen phosphate; Phosphates; Potassium dihydrogen citrate; Sodium aluminium phosphates; Sodium lactate; Tripotassium citrate; Trisodium citrate. |
| Firming agent | Aluminium ammonium sulfate; Calcium chloride; Calcium hydroxide; Calcium lactate; Calcium sulfate; Curdlan; Magnesium sulfate; Phosphates; Potassium chloride; Tricalcium citrate. |
| Flavor enhancer | Benzoyl peroxide; Calcium 5′-guanylate; Calcium 5′-inosinate; Calcium 5′-ribonucleotides; Calcium di-L-glutamate; Dipotassium 5′-guanylate;<br>Disodium5′-guanylate; Disodium 5′-inosinate; Disodium 5′-ribonucleotides; Ethyl maltol; Glutamic acid, L (+); Guanylic acid, 5′; Inosinic acid, 5′; Magnesium di-L-glutamate; Magnesium sulfate; Maltol; Monoammonium L-glutamate; Monopotassium L-glutamate; Monosodium L-glutamate; Neotame; Potassium 5′-inosinate; Sulfites; Tartrates. |
| Flour treatment agent | Alpha amylase from Aspergillus oryzae var.; Alpha amylase from Bacillus subtilis; Azodicarbonamide; Benzoyl peroxide; Bromelain; Calcium lactate; Calcium oxide; Calcium sulfate; Carbohydrase from Bacillus licheniforms; Chlorine; Citric and fatty acid esters of glycerol; Phosphates; Polysorbates; Sulfites. |
| Foaming agent | Ammonium alginate; Calcium alginate; Carbon dioxide; Methyl ethyl cellulose; Microcrystalline cellulose (cellulose gel); Nitrogen; Nitrous oxide; Polysorbates; Sucrose esters of fatty acids; Xanthan gum. |
| Gelling agent | Agar; Alginic acid; Ammonium alginate; Calcium alginate; Carrageenan; Curdlan; Konjac flour; Pectins; Potassium alginate; Processed Euchema sea weed (PES); Sodium alginate; Sodium carboxymethyl cellulose (cellulose gum); Tara gum. |
| Glazing agent | Beeswax; Candelilla wax; Carnauba wax; Carrageenan; Castor oil; Gum Arabic (Acacia gum); Hydrogenated poly-1-decenes; Konjac flour;<br>Microcrystalline wax; Mineral oil, high viscosity; Mineral oil, medium viscosity; Polyethylene glycol; Polyvinyl alcohol; Polyvinylpyrrolidone;<br>Processed Euchema sea weed (PES); Propylene glycol; Pullulan; Shellac, bleached; Sucrose esters of fatty acids; Sucrose oligoesters, type I and type II; Talc. |
| Humectant | Glycerol; Mannitol; Sodium dihydrogen phosphate; Trisodium phosphate; Phosphates; Polydextroses; Processed Euchema sea weed (PES); Propylene glycol; Sodium DL-malate; Sodium lactate |
| Preservative | Benzoates, Calcium acetate; Calcium propionate; Carbon dioxide; Dimethyl dicarbonate; Ethylene diamine tetra acetates; Hexamethylene tetramine; Hidroxybenzoates, para; Isopropyl citrates; Lauric arginate ethyl ester; Lysozyme; Natamycin (Pimaricin); Nisin; Nitrites; Ortho-phenylphenols; Trisodium phosphate; Potassium acetate; Propionic acid; Sodium acetate; Sodium diacetate; Sorbates; Sulfites; Carbon dioxide; Nitrogen; Nitrous oxide. |
| Raising agent | Ammonium carbonate; Ammonium hydrogen carbonate; Glucono delta-lactone; Sodium dihydrogen phosphate; Phosphates; Sodium aluminium phosphates; Sodium carbonate; Sodium hydrogen carbonate; Sodium sesquicarbonate. |
| Sequestrant | Calcium sulfate; Citric Acid; Citric and fatty acid esters of glycerol; Diacetyltartaric and fatty acid esters of glycerol; Ethylene diamine tetra acetates;<br>Glucono delta-lactone; Isopropyl citrates; Lactic and fatty acid esters of glycerol; Phosphoric acid; Sodium dihydrogen phosphate; Trisodium phosphate; Potassium dihydrogen citrate; Sodium acetate; Sodium diacetate; Sodium dihydrogen citrate; Sodium gluconate; Stearyl citrate; Tartrates; Tricalcium citrate; Triethyl citrate; Tri-potassium citrate; Trisodium citrate |
| Stabilizer | Acetylated distarch adipate; Acetylated distarch phosphate; Acetylated oxidized starch; Acid-treated starch; Agar; Alginic acid; Alkaline treated starch; Aluminium ammonium sulfate; Ammonium alginate; Beeswax; Bleached starch; Calcium alginate; Calcium chloride; Carob bean gum; Citric and fatty acid esters of glycerol; Curdlan; Cyclodextrin, Beta-; Dextrins, roasted starch; Diacetyltartaric and fatty acid esters of glycerol; Ethylene diamine tetra acetates; Glycerol ester of wood rosin; Guar gum; Gum Arabic (Acacia gum); Hydroxypropyl cellulose; Hydroxypropyl distarch phosphate; Hydroxypropyl methyl cellulose; Hydroxypropyl starch; Karaya gum; Konjac flour; Lactic and fatty acid esters of glycerol; Magnesium chloride; Mannitol; Methyl cellulose; Methyl ethyl cellulose; Microcrystalline cellulose (cellulose gel); Mono- and di-glycerides of fatty acids; Monostarch phosphate; Oxidized starch; Pectins; Phosphated distarch phosphate; Sodium dihydrogen phosphate; Trisodium phosphate; Phosphates; Polydextroses; Polyglycerol esters of fatty acids; Polysorbates; Polyvinylpyrrolidone; Potassium alginate; Potassium carbonate; Potassium chloride; Potassium dihydrogen citrate; Potassium hydrogen carbonate; Powdered cellulose; Processed Euchema sea weed (PES); Propylene glycol alginate;<br>Salts of myristic, palmitic and stearic acids with ammonia, calcium, potassium and sodium; Salts of oleic acid with calcium, potassium and sodium; Sodium alginate; Sodium aluminium phosphates; Sodium carbonate; Sodium carboxymethyl cellulose (cellulose gum); Sodium dihydrogen citrate; Sodium hydrogen carbonate; Sorbitan esters of fatty acids; Starch acetate; Starch sodium octenyl succinate; Starches, enzyme treated; Stearoyl lactylates; Sucrose acetate isobutyrate; Sucrose esters of fatty acids; Sucrose oligoesters, type I and type II; Tara gum; Tartrates; Tragacanth gum; Triethyl citrate; Tripotassium citrate; Trisodium citrate; Xanthan gum. |
| Sweetener | Acesulfame potassium; Alitame; Aspartame; Aspartame-acesulfame salt; Cyclamates; Mannitol; Neotame; Saccharins; Steviol glycosides; Sucralose (Trichlorogalactosucrose). |
| Thickener | Acetylated distarch adipate; Acetylated distarch phosphate; Acetylated oxidized starch; Acid-treated starch; Agar; Alginic acid; Alkaline treated starch; Ammonium alginate; Bleached starch; Calcium alginate; Candelilla wax; Carob bean gum; Carrageenan; Curdlan; Cyclodextrin, Beta-; Dextrins, roasted starch; Distarch phosphate; Glycerol; Guar gum; Gum Arabic (Acacia gum); Hydroxypropyl cellulose; Hydroxypropyl distarch phosphate; Hydroxypropyl methyl cellulose; Hydroxypropyl starch; Karaya gum; Konjac flour; Mannitol; Methyl cellulose; Methyl ethyl cellulose; Microcrystalline cellulose (cellulose gel); Monostarch phosphate; Oxidized starch; Pectins; Phosphated distarch phosphate; Sodium dihydrogen phosphate; Trisodium phosphate; Phosphates; Polydextroses; Polyethylene glycol; Polyvinyl alcohol; Polyvinylpyrrolidone; Potassium alginate;<br>Potassium chloride; Powdered cellulose; Processed Euchema sea weed (PES); Propylene glycol alginate; Pullulan; Sodium alginate; Sodium aluminum phosphates; Sodium carboxymethyl cellulose (cellulose gum); Sodium lactate; Starch acetate; Starch sodium octenyl succinate; Starches, enzyme treated; Talc; Tara gum; Tragacanth gum; Xanthan gum. |

needed to improve encapsulation systems' efficacy, affordability, and practicality (Ashique et al., 2023; Lavanya et al., 2024b; Rosales & Fabi, 2022).

Table 6 shows some results of the application of phenolic compounds in encapsulation systems to improve the bioavailability and stability of phenolic compounds.

### 3.3.3. *Potential bioactivities of phenolic compounds and their effects on health promotion*

The polyphenols present in plant extracts have advantages over synthetic preservatives due to their chemical characteristics, which are potential promoters of antioxidant and antimicrobial bioactivities (Amiri et al., 2021). They also act as health promoters with anti-inflammatory (Liu et al., 2023) anti-cancer (Maheshwari & Sharma, 2023) and cytotoxicity activity (Lopez-Corona et al., 2022) neuroprotective (Nájera-Maldonado et al., 2024; Rojas-García et al., 2023), treating metabolic illnesses such as diabetes (de Paulo Farias et al., 2021) cardiovascular disease (Torres-Fuentes et al., 2022), hypertension (de Araújo et al., 2021b) and infections (Ecevit et al., 2022). The anticancer and anti-inflammatory activities of phenolic substances

**Table 8**
Isomeric smiles.

| Phenolic Class | Isomeric Smiles |
|---|---|
| Flavonoids | |
| Anthocyanins | (Cyanidin) C1=CC(=C(C=C1C2 = [O+]C3=CC(=CC(=C3C=C2O)O)O)O)O |
| Chalcones | (Chalcone) C1=CC=C(C=C1)/C=C/C(=O)C2=CC=CC=C2 |
| Flavones | (Flavone) C1=CC=C(C=C1)C2=CC(=O)C3=CC=CC=C3O2 |
| Flavonols | (3-Hydroxyflavone) C1=CC=C(C=C1)C2=C(C(=O)C3=CC=CC=C3O2)O |
| Flavanones | ((2S)-Flavanone) C1[C@H](OC2=CC=CC=C2C1 = O)C3=CC=CC=C3 |
| Flavanol | (Epicatechin) C1[C@@H]([C@H](OC2=CC(=CC(=C21)O)O)C3=CC(=C(C=C3)O)O)O |
| Isoflavones | (Genistein) C1=CC(=CC=C1C2 = COC3=C2C(=O)C=C(C3=O)O)O |
| **Non-Flavonoids** | |
| Cumarines | (Coumarin) C1=CC=C2C(=C1)C=CC(=O)O2 |
| Curcuminoids | (Curcumin) COC1=C(C=CC(=C1)/C=C/C(=O)CC(=O)/C=C/C2=CC(=C(C=C2)O)OC)O |
| Lignans | (Secoisolariciresinol) CC1C(C(C(O1)OC2=C(C=CC(=C2)O)O)OC3=C(C=CC(=C3)O)O)CO |
| Phenolic Acids | (Gallic acid) C1=C(C=C(C(=C1O)O)O)C(=O)O |
| Quinonas | (Coenzyme Q10) CC(C)=CCCC(C)=CCCC(C)=CC(C)=CCCC(C)=CC(C)=CCCC(C)=O |
| Stilbenes | (Resveratrol) C1=CC(=CC=C1/C=C/C2=CC(=CC(=C2)O)O)O |
| Tannins | (Pentagalloylglucose) C1=CC(=C(C=C1C(=O)O)O)OC2C(C(C(C(O2)OC(=O)C3=CC(=C(C=C3O)O)O)OC(=O)C4=CC(=C(C=C4O)O)O)OC(=O)C5=CC(=C(C=C5O)O)O)OC(=O)C6=CC(=C(C=C6O)O)O |
| Xanthanoids | (Xanthone) C1=CC2=C(C(=O)C3=CC=CC=C3O2)C=C1 |

*Isomeric smiles acquired on the platform https://pubchem.ncbi.nlm.nih.gov/to draw the chemical structures in Fig. 2.

(anthocyanins, epigallocatechin-3-gallate (EGGC), and resveratrol) are linked to their antioxidant (free radical scavenger) and pro-oxidant processes (Khan et al., 2020). Phenolic chemicals' antibacterial activity is linked to membrane damage in bacteria. This process involves changing the membrane permeability, resulting in the loss of cell wall integrity and changes in intracellular processes (Lizárraga-Velázquez et al., 2020).

Despite the fact that most of the data supporting phenolic compound antioxidant activity is derived from *in vitro* studies, there is evidence that phenolic compounds are recognized as active antioxidants even at low concentrations (Edo et al., 2025). Because of their redox properties and ability to self-oxidize at higher concentrations, phenolic compounds can exhibit pro-oxidant activities *in vivo* under certain conditions, such as high dose supplementation, high concentrations of transition metal ions (e.g., Cu, Fe, Zn), alkaline pH, and the presence of molecular oxygen (Ashok et al., 2022). Biopsies revealed elevated levels of bilirubin, serum transaminase, necrosis, and inflammation in individuals taking large dosages of green tea supplements (Bešlo et al., 2023).

According to the research, exogenous antioxidants, including antioxidant enzymes contained in food, neutralize free radicals and ROS/RNS while also eliminating or repairing damaged biomolecules (Carrillo-Martinez et al., 2024). Free radicals including $O_2\cdot$, HO·, peroxyl radical (ROO·), and NO·, as well as non-radical species made of molecular oxygen like $H_2O_2$ and HOCl, are regularly generated during ordinary physiological processes in small amounts. Phenolic chemicals act as both antioxidants and prooxidants (Fig. 3) (Carrillo-Martinez et al., 2024).

Polyphenols affect the activities of a range of enzymes and cellular receptors as demonstrated by Alara et al. (2021b, )Alara et al., 2021a both *in vivo* and *in vitro* studies, suggesting that their biological effects are not limited to antioxidant protection. Therefore, their extraction efficacy changes in accordance with their solubility and stability properties, which are influenced by their chemical structure (Mavai et al., 2025).

A study by Poljsak et al. (2021) reviews the course of subject, citing the way that many naturally occurring close relatives of biochemical antioxidants are converted, through food processing methods (heat, UV, drying, etc.), into oxidized forms whose health impacts are less well-described. In contrast to the well-established positive effects of reduced antioxidants, their oxidized counterparts may also modulate cellular signal processes and gene expression, and at low doses might induce protective responses through a hormetic mechanism (Lizárraga-Velázquez et al., 2020). Further functional studies are needed to elucidate potential synergistic actions of reduced, oxidized and antioxidant metabolites (Edo et al., 2025).

## 4. Conclusion

Phenolic chemicals are emerging as a unique food preservation solution, combining the safety, efficacy, and natural attributes that consumers and businesses value. These compounds are appealing as multifunctional alternatives to synthetic preservatives because of their antioxidant and antibacterial capabilities, as well as potential health benefits. The use of phenolic compounds as natural preservatives enhances food by providing functional, long-term benefits and an extended shelf life, coinciding with consumers' need for transparency and naturalness in products. However, the widespread use of these chemicals

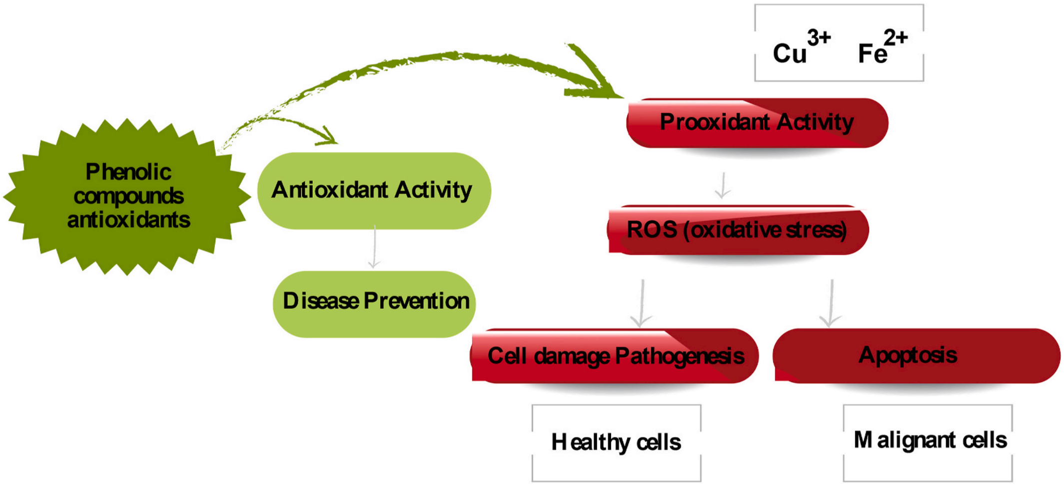

**Fig. 3.** Phenolic chemicals and ROS-derived antibacterial agents. The green box represents the adverse effects of phenolic compounds as pro-oxidants (Ashok et al., 2022; Edo et al., 2025; Rajashekar, 2023).

faces technological challenges, including the difficulty of incorporating them into multiple food matrices and their intrinsic instability under different storage conditions. Innovation like epitome and dynamic bundling can fathom these issues. These strategies permit controlled bioactive discharge and long-term viability. These advances offer assistance make maintainable, inventive bundling that fulfills advertise needs and boost phenolic compounds' antibacterial and antioxidant impacts. Moreover, the application of phenolic-rich agro-industrial squander as renewable additives speaks to an imaginative and conservative approach, decreasing squander and advancing a more feasible nourishment generation demonstrate. Consequently, phenolic compounds, when effectively utilized and integrated with technological advancements, possess the capacity to transform food preservation benchmarks. The food industry's future may be enhanced by a transition to natural preservatives, offering goods that comply with safety and quality standards while satisfying customer preferences for natural and sustainable ingredients. In conclusion, the utilization of phenolic compounds as preservatives represents a strategic and promising advancement, capable of significantly influencing public health and the environment, thereby fostering a new era of innovation in the food industry.

## CRediT authorship contribution statement

**Izamara de Oliveira:** Writing – original draft, Investigation. **Celestino Santos-Buelga:** Writing – review & editing. **Yara Aquino:** Writing – original draft. **Lillian Barros:** Writing – review & editing. **Sandrina A. Heleno:** Writing – review & editing, Supervision, Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

No data was used for the research described in the article.

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