Food Additives as Functional Ingredients in Food Products

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Abstract

In recent years, there has been a notable advancement in the field of food science and technology, with a growing emphasis on adopting sustainable practices in food production. This includes a focus on the selection and sourcing of food additives. Food additives are widely acknowledged for their significant contribution to enhancing the overall quality and stability of food products. These additives serve various purposes, such as imparting color, flavor, and texture, as well as preserving the food and enhancing its resistance to transportation and handling. The utilization of additives is deemed acceptable solely when they contribute to enhancing the overall quality and organoleptic characteristics of food while posing no threats to humans' health. The physicochemical and sensory properties of food products may undergo changes due to various deterioration processes, including microbiological, enzymatic, physical, and chemical factors. These processes can lead to a decline in both the nutritional quality and food safety of the products. In order to safeguard the well-being of consumers, preservatives (antimicrobials, and anti-browning agents), antioxidants from

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natural sources, natural pigments as food colorants (anthocyanins, carotenoids, betalains, and chlorophyll), and hydrocolloids (carboxymethylcellulose, xanthan, β-glucans) are included in the food. Unfortunately, depending on the dosage, there is a fine line between safe and hazardous. However, regulatory agencies and law enforcement organizations are responsible for overseeing the development of the food industry and have implemented rigorous laws to regulate the licensing and supervision of food additives.

Keywords

Functional foods · Antioxidants · Pigments · Food colorants · Hydrocolloids

1 Introduction

The global food system is kept under control by the national and international authorities responsible for food quality, safety, and security (those from the USA and Europe being the most important) (Wu et al. 2022b). One of the most significant roles of European legislation is laying down the rules on food additives used in the food industry, ensuring a high level of consumer protection, including human health. Even though there are some inconsistencies regarding the approval and use of certain food additives between the European Union (EU) and the USA (e.g., additives permitted in some countries are banned in others such as sodium sorbate, fast green, and fluorescein, which are permitted in the USA but prohibited in the EU, or amaranth and carmoisine dyes, which are prohibited in the USA but allowed in the EU [M'Arcio Carocho et al. 2014]), the responsible authorities have a common principle: to ensure a clean and safe alimentation for consumers worldwide. The European Food Safety Authority (EFSA) and the European Commission, based on EFSA assessment and regulations (Cox et al. 2021), define a food additive as a "substance not normally consumed as a food in itself and not normally used as a characteristic ingredient of food, whether or not it has nutritive value, the intentional addition of which to food for a technological purpose in the manufacture, processing, preparation, treatment, packaging, transport, or storage of such food results, or may be reasonably expected to result, in it or its by-products becoming directly or indirectly a component of such foods" (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008R1333 (EU), C. R. Regulation (EC) No 1333/2008 of the European Parliament and of the Council of 16 December 2008 on Food Additives).

The use of food additives has had ancient roots in history; in the time of Homer, Greeks used a mixture of salt and sodium nitrite to preserve meat, while, 3000 years ago, Egyptians used sulfur dioxide for wine preservation (Saltmarsh 2013). For preservation and to improve the look of meals, the Romans utilized potassium nitrate, spices, and colors (EUFIC 2021). Due to social, scientific, and technological evolution, nowadays food additives gained interest in society and the population is increasingly concerned about the composition of the food. Currently, in Europe over 330 authorized additives are used to increase the food's quality and shelf life (40 are colors, 19 are sweeteners, and 275 are other than colors and sweeteners) (Eloi Chazelas et al. 2020).

Food additives are recognized for their role in enhancing quality and stability, being used to color, flavor, preserve, or improve the texture of food, or conferring resistance to transportation and handling. Their use is justified only when they bring a benefit to the quality of the food and/or its organoleptic properties without presenting risks to public health.

Firstly, an additive can be considered suitable to be placed on the market and used in food only if it passes the approval process for new additives (Wu et al. 2022b). EFSA Panel on Food Additives and Nutrient Sources added to Food (ANS) from March 7, 2021, refers to the application for the authorization or re-authorization of a new additive, and of an already authorized additive, respectively. This document is built on four sections (European Food Safety Authority [EFSA] 2021):

(A) Chemistry and specifications: the section aims to identify the food additive, and potential hazards from its manufacturing, and to define the material tested through specifications.
(B) Existing authorizations and evaluation: the purpose of this section is to provide an overview of previous risk assessments on the additive and their conclusions.
(C) Proposed uses and exposure assessment: the section aims to estimate dietary exposure based on the proposed uses and use levels, as well as the consumption of the proposed foods by various age groups in the EU population.
(D) Toxicological studies: the purpose of this section is to describe the methods that can be used to identify and characterize hazards.

Notable is the fact that food additives permitted prior to January 20, 2009, are undergoing a risk assessment re-evaluation by the European Food Safety Authority (EFSA). This procedure was executed in three distinct phases, each with its own completion date. The first group, colorants and additives, must be evaluated by 2015; the second group, texturizing agents, must be evaluated by 2018; and, finally, the compliance of sweeteners must be evaluated by 2020 (EU; Claudia Pașca and Socaci 2018).

Depending on the dosage of additives used, there is a fine line between safe and hazardous, with the minimum dose required to achieve the desired effect being used the majority of the time (GA Blekas 2016). The "Acceptable Daily Intake" (ADI) represents the amount that can be safely consumed every day, throughout the entire life, without putting the consumer's health at risk. The ADI and acceptance rate of the additive are adjusted by EFSA's and World Health Organization-Food and Agriculture Organization (WHO–FAO) Joint FAO/WHO Expert Committee on Food Additives (JECFA) scientific panels (Saltmarsh 2013). This procedure can be applied to determine the maximum authorized amount of a specific additive or a chemically related group of additives. These concentrations are usually expressed in milligrams of additive per kilogram of body weight; ADI can also be unspecified at *quantum satis*, which is a Latin word that can be associated with the use of the additive in a suitable concentration to achieve the desired effect, but according to the Good Manufacturing Practice (Authority).

According to their properties, the approved food additives are included in Annexes to Regulation EC No. 1333/2008. As such, Annex I contains classifications

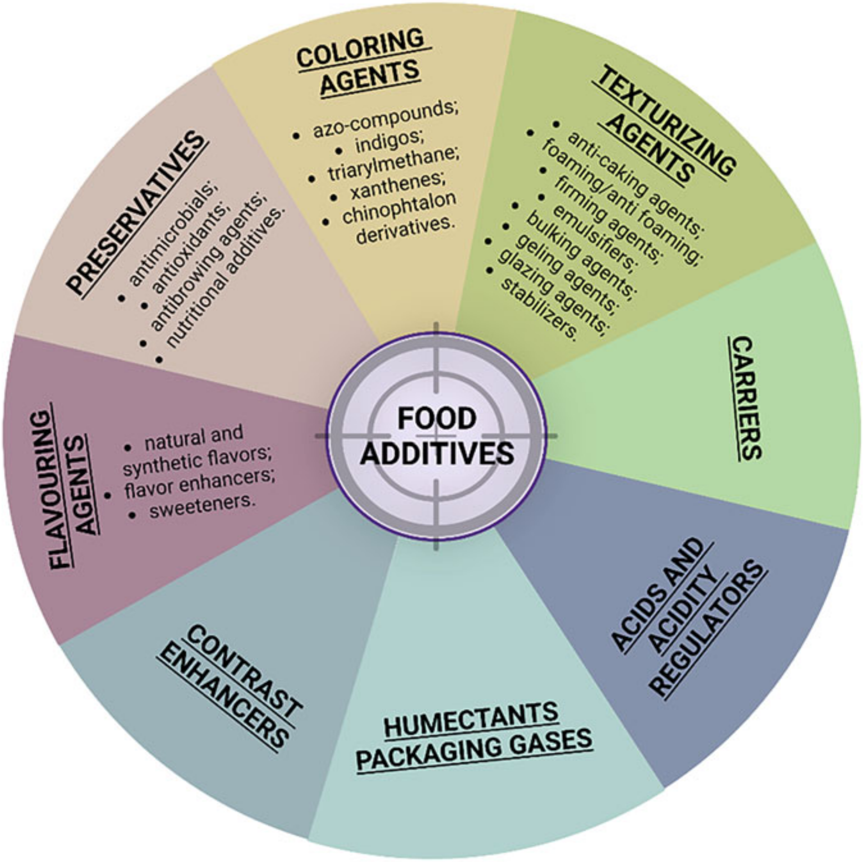

Fig. 1 Food additives classification based on their functionality

of food additives based on their functionality (27 functional classes): sweeteners, colors, preservatives, antioxidants, carriers, acids, acidity regulators, anti-caking agents, anti-foaming agents, bulking agents, emulsifiers, emulsifying salts, firming agents, flavor enhancers, foaming agents, gelling agents, glazing agents, humectants, stabilizers, and so on (Fig. 1). Also, the same regulation stipulates the Union list of food additives approved for use in foods and conditions of use (Annex II; EU). Additionally, food additives can be divided according to their origin as natural (as a result of plant or animal substrate purifying) and synthetic additives (as a result of chemical synthesis) (Wu et al. 2022b). Natural additives are an important future tool for food preservation due to their health benefits and synergistic properties (Márcio Carocho and Ferreira 2015).

In Europe, a scheme in which each additive receives a unique number called an "E-number" is used for the individualization and easiest classification of food additives. The label of each commercialized food product must include the

E-number or the name of the food additive and a specific reference for food use (e.g., acidulants and preservatives). Nowadays, numbering and coding additives is a key step in gaining consumers' trust, but this has not always been so. There was a campaign against "E-numbers" in the 1980s due to their irresponsible use; foods containing additives were considered dangerous, which is why they were as much to be avoided as foods containing genetically modified ingredients. The public's view of the relationship between "food additives" and "chemicals" has compounded matters. The focus on additives in the 1980s was prompted by a 1986 change in labeling laws that mandated the listing of each additive in the ingredient list of the majority of pre-packaged products. Prior to that, the use of additives was denoted by generic functional groups, such as "preservatives," "antioxidants," and "colors." As a consequence of the new labeling requirements, some food labels now contain lengthy inventories of additives, including lengthy chemical names. Some products appeared to be nothing more than a few basic constituents held together by a chemical dictionary. The "E" number system, which was intended as a short code for some of the longer chemical names and to indicate common European safety approval, became the focal point of the criticism against the use of additives, and consumers voted with their feet by abandoning products with lengthy "E" number lists. The anti-additives campaign and subsequent consumer pressure to eliminate or reduce the use of additives resulted in inevitable changes to manufacturing and marketing practices. It is therefore time to re-evaluate the role and application of additives in the food supply, keeping in mind that they will always be necessary for food preparation, quality, and preservation (M'Arcio Carocho et al. 2014). According to the EFSA's scientific forum, the introduction of government bodies that examine potential consumer dangers has caused these issues to dissipate and people's trust to rise (M'Arcio Carocho et al. 2014).

2 Preservatives

Food products' physicochemical and sensory properties can alter as a result of deterioration processes (microbiological, enzymatic, physical, and chemical), which also reduces the nutritional quality and food safety. To ensure the safety of food products for consumers, several methods (biological, physical, and chemical) have been developed to extend the shelf life of food products without changing any of the sensory properties. One of the most frequent conservation methods that sustains the quality of food items and decreases the incidence of foodborne diseases is the incorporation of preservatives into the technological processes of food production (Novais et al. 2022). Preservatives are one of the most important families of additives, with E values ranging from E200 to E399. The preservatives are classified into three functional groups: antioxidants, antimicrobials, and anti-browning agents (Carocho et al. 2018). Antimicrobials are substances that preserve food for a longer period of time by preventing natural spoilage and inhibiting spoilage caused by fungi, bacteria, and other microorganisms (Carocho et al. 2018; Wu et al. 2022a). Enzymatic and non-enzymatic food browning is often prevented by using

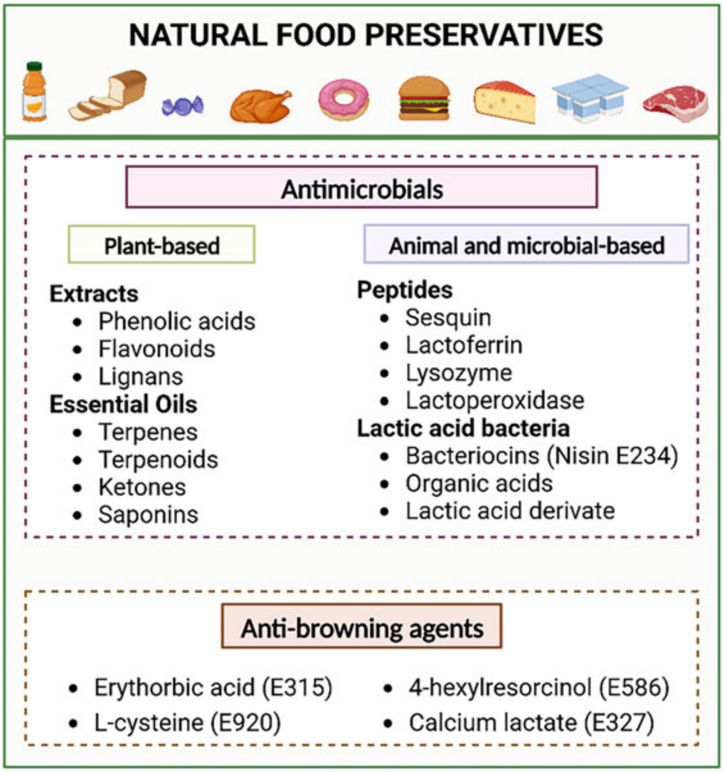

Fig. 2 Classification of natural food preservatives

anti-browning chemicals when handling, processing, and storing food products (Carocho et al. 2018). Compounds with an antioxidant action are a type of preservative used to extend the shelf life of food products by preventing oxidative processes such as rancidity, color and texture deterioration, and odor change (Carocho et al. 2018). In this book chapter, a special section is devoted to discuss the preservatives with antioxidant properties in more detail.

Based on their origin, food preservatives are divided into two groups: artificial preservatives and natural preservatives. Food preservatives are most commonly found in synthetic forms in food products, such as sorbates, nitrates, and sulfites (Novais et al. 2022). However, the impact of artificial preservatives on the human body can produce an intestinal microbiota imbalance that may have consequences for human health (Ruiz-Rico et al. 2023). Improving food quality and safety is critical for human well-being, therefore, previous research articles have focused on finding alternatives to conventional food preservatives, such as plant-based and animal- or microbial-based antimicrobial compounds (Ruiz-Rico et al. 2023; Gokoglu 2019). A classification of natural preservatives is illustrated in Fig. 2.

Various plant parts, including the leaves, stems, flowers, fruits, and roots, are used to produce plant extracts that are rich in compounds with preserved functions. Herbs and spices extracts are significant examples of plant-based preservatives; depending on the species, habitat, and concentration, they may be used as natural preservatives (Gokoglu 2019). Polyphenols, flavonoids, tannins, alkaloids, terpenoids, isothiocyanates, lectins, and polypeptides are the main plant-based phytochemicals utilized as natural preservatives alongside essential oils (EOs) (Gokoglu 2019). Polyphenols represent a large class of natural compounds abundantly distributed in many plant sources, with more than 8000 phenolic structures known up to now. The primary industrial application of polyphenolic compounds is to prevent oxidative processes in food products, although studies demonstrate that polyphenolic compounds can also have an antibacterial effect on foods. The antimicrobial effect's mechanism of action is based on polyphenols' ability to change the permeability of the cell membrane, modify intracellular functions via links formed between phenolic compounds and enzymes, or degrade the cell wall via interactions between polyphenols and the cell membrane (Olszewska et al. 2020). The antibacterial potential of pomegranate extract, vanillin, and geraniol, which were utilized as food preservatives in strawberry juice, was examined by Tomadoni and colleagues (2016). Each antimicrobial preservative was used in two concentrations: pomegranate extract at 180 and 360 μg/mL; vanillin at 2.5 and 5 mg/mL; and geraniol at 0.6 and 1.2 μL/mL. The native microflora on strawberry juice was significantly reduced by more than three log cycles by geraniol and vanillin at both concentrations tested, increasing the product's microbiological shelf life. Additionally, both antimicrobials increased the security of the product by lowering inoculated *Escherichia coli* O157:H7. The highest concentration of pomegranate extract lowered the concentrations of mesophilic and psychrophilic bacteria, whereas it had no effect on yeasts, molds, and the inoculated *E. coli* bacterium (Tomadoni et al. 2016). Moreover, the leaf extract of *Basilicum polystachyon* rich in phenolic compounds (gallic acid, trans-cinnamic acid, ellagic acid, quercetin, vanillic acid, caffeic acid, *p*-coumaric acid, and rosmarinic acid) expressed antimicrobial activities against *Bacillus subtilis*, *Staphylococcus aureus*, *Mycobacterium smegmatis*, *E. coli*, and *Candida albicans* investigated through disk diffusion assay and minimum inhibitory concentration assay (Das et al. 2022). Furthermore, solvents such as methanol, ethanol, and acetone were utilized to extract bioactive chemicals having biological activity (antioxidant, antibacterial, and antimutagenic) from brewers' spent grain. All of the phenolic extracts have been found to have antibacterial properties on bacterial and fungal strains, particularly the *Candida albicans* fungus (Socaci et al. 2018). Natural food preservatives, on the other hand, such as phenolic extracts with antibacterial effects, may have a functional role in the human body due to their potential to reduce cellular damage or cellular death, lowering the incidence risk of chronic disease (Nemes et al. 2022). However, the bioavailability and bioaccessibility of phenolic compounds determine their efficiency in reaching target areas and performing any protective functionality on the human body (Nemes et al. 2022). Ferulic acid, one of the most abundant phenolic compounds in plant-based sources, is a high-value bioactive compound due to its preservation effects on food products and functional potential in the human body, such as anti-hyperlipidemic, anti-oxidative, and anti-inflammatory activities (Nemes et al. 2022; Bumrungpert et al. 2018). A recent study examined the impact of ferulic acid supplementation on lipid profiles, oxidative stress, and inflammation in hyperlipidemia patients, and found that it has the potential to lower cardiovascular diseases risk factors like total cholesterol, low-density lipoprotein (LDL)-cholesterol, triglycerides, oxidative stress biomarkers, and inflammatory markers (Bumrungpert et al. 2018).

Essential oils (EOs) are volatile oils with strong aromatic properties that provide a characteristic aroma and odor to aromatic plants (Pavela 2015). EOs are among the plant-based components that have been utilized since ancient times in fields such as medicine, flavoring agents, and food preservatives (Tiwari and Dubey 2022). More than 17,500 plant species, primarily from the angiospermic families Myrtaceae, Lamiaceae, Asteraceae, Rutaceae, and Zingiberaceae, have been identified to produce EO metabolites (Pavela 2015). Because of their antioxidant, antifungal, and antibacterial activities, EOs and their bioactive components are now widely used as novel green preservatives in the food industry. Aromatic phytoproducts are synthesized from many plant parts, including seeds, flowers, bark, rhizomes, roots, buds, fruits, and leaves (Tiwari and Dubey 2022). EOs contain a complex mix of bioactive chemical components such as terpenes, terpenoids, and phenolic compounds (Falleh et al. 2020). Terpenes, represented by pinene, myrcene, limonene, terpinene, or *p*-cymene, are hydrocarbons with a simple structure. Terpenoids are hydrocarbons that contain oxygen molecules and are derived from the structure of terpenes, by binding functional groups and methyl oxylated groups in various positions (Masyita et al. 2022). Mustard essential oil with allyl isothiocyanate (98.4%), thyme with linalool (14.6%), and Mexican oregano with carvacrol and *p*-cymene (26.9% and 20.0%, respectively) were found to have effective antibacterial properties against *Salmonella typhimurium* with minimum inhibitory concentration values ranging from 0.025 to >5 μg/mL (Meenu et al. 2023). Avocado leaf EOs indicated antibacterial activity against *Staphylococcus epidermidis* and *Staphylococcus aureus* (Nasri et al. 2022). Moreover, the bioactive components in EOs provide beneficial functional effects on the human body, including anti-inflammatory and antinociceptive effects (Huang et al. 2019), antibacterial and immunomodulatory activities (Valdivieso-Ugarte et al. 2021), and antioxidative and mucolytic effects on respiratory diseases (Li et al. 2023). Table 1 summarizes the plant-based, and animal and microbial-based food preservatives that provide a functional role in human health.

Another class of compounds with biological activity that can act as natural preservatives for food products are those derived from plants and microbial sources. Antimicrobial peptides, which are effective against bacteria, fungi, protozoa, and some viruses, are one of the animal-based natural preservatives (Novais et al. 2022). Specific bioactive peptides, such as Sesquin, are already in use in the food additives sector due to their ability to inhibit unwanted microorganisms' growth while preserving product quality and nutritional benefits. *Botrytis cinerea* and *Fusarium oxysporum*, which have the capacity to affect common products such as wheat and grapes, are the most critical microorganisms for which scientists are looking for

Table 1 Plant-based and animal- and microbial-based food preservatives with functional effects on the human body

Source		Bioactive constituent	Food application	Health benefits	References
Plant-based extracts	Leguminosae/ Fabaceae family	Prenylated isoflavonoids: Glabridin 6,8-Diprenylgenistein	Antimicrobial activity against *Listeria monocytogenes* in vitro tested on fresh-cut cantaloupe	Antidiabetic activity Obesity prevention Cardioprotection Immunomodulation Neuroprotection Osteoprotection	Bombelli et al. (2023), Chang et al. (2021)
	Asparagus Bean seeds *(Vigna sesquipedalis)*	Sesquin peptide	Food biopreservation Synergistic antimicrobial action	Hormone-like beneficial activities	Ramos-Martín et al. (2022), Hayes and Bleakley (2018)
	Lemon Basil leaf Mint leaf Lemongrass	Phenolic compounds	Sugarcane juice with a storage stability of 26 days at 4°C, preserved with natural preservatives Health/therapeutic drink	Prevention of diseases, like obesity, diabetes, and cardiovascular diseases	Bag et al. (2022), González-Molina et al. (2010)
	Kenaf seed	Peptide mixture	Antifungal effects on tomato puree Increased shelf life of tomato puree for up to 23 days at 4°C	Nutritional and physiological benefits	Arulrajah et al. (2021)
	Polyphenolic extracts	Eugenol Vanillin Ferulic acid	Food biopreservation	Free eugenol increased the Lachnospiraceae and Akkermansiaceae families Immobilized phenolics enhanced the Bacteroides and reduced the ratio of Firmicutes to Bacteroidetes	Ruiz-Rico et al. (2023)
	Sisymbrium officinale extract	Phenolic and flavonoids content	Strong antimicrobial activity against *Escherichia coli* and *Streptococcus* bacteria	Anticancer activity against breast cancer cell line	Khalid et al. (2022)

(continued)

Table 1 (continued)

Source		Bioactive constituent	Food application	Health benefits	References
	Henna (*Lawsonia inermis*) extract	Catechin acid Methyl gallate Ellagic acid Coumaric acid	High antibacterial efficacy against *Bacillus cereus*, *E. coli*, and *Pseudomonas aeruginosa* on yoghurt during 15 days of storage	Maintains beneficial probiotic concentrations at optimal levels	Ghazy et al. (2023)
Essential oils (EOs)	Cinnamon EOs Clove EOs White thyme EOs	Cinnamic aldehyde Thymol Eugenol	Extended food products' shelf life	Anti-inflammatory properties Immunomodulatory activities	Valdivieso-Ugarte et al. (2021)
	Anise *(Pimpinella anisum)* EOs	Anethole Estragole Fenchone	Green preservative in food and agricultural industries In situ minerals and macronutrient preservation of rice seeds Fungitoxic, aflatoxin inhibitory, and antioxidant potency	Ayurvedic treatments in intestinal parasitic infections Carminative Diuretic Stomachic Antispasmodic Expectorant	Das et al. (2021)
	Juniperus communis L. EOs	β-myrcene Monoterpene hydrocarbons	Antimicrobial activity against *Escherichia coli*, *Listeria monocytogenes*, *Salmonella* spp., and sulfite-reducing clostridia after 225 days of sausages fermentation Alternative for sodium nitrite in dry-fermented sausages	It reduced the risk of the formation of carcinogenic *N*-nitroso-compounds	Tomović et al. (2020)
	Acorus calamus EOs *Allium sativum* EOs *Mucuna pruriens* EOs	Hydroxylamine 1,2,4-Trimethoxy-5-1-propenyl Dodecanoic acid 1,2,3-Propanetriyl ester 2-Diisoprophylphosphinnoethane	In vitro antibacterial and antifungal properties against plum fruit spoilage microbes such as *Aspergillus niger*, *Aspergillus flavus*, and *Rhizopus microsporus*	Antiviral, antioxidant, and antimicrobial effects	Arasu et al. (2019)

	Sesamum indicum L. EOs				
	Sweet orange (*Citrus sinensis*) EOs Lemon (*Citrus limonum*) EOs	Limonene β-myrcene β-pinene α-pinene Citral Z Citral E Linalool	Preserving fresh-cut apples Weight loss, color, texture, and microbial growth of fresh-cut Jazz apples were reduced	Low toxicity Health benefits Pharmacological applications	Sumonsiri et al. (2020), Rasool et al. (2022)
Microbial-based sources	Antimicrobial enzymes	Lactoperoxidase Thiocyanate Hydrogen peroxide	The shelf life of trout fillets was extended by 4 days The growth of *Shewanella putrefaciens*, *Pseudomonas fluorescens*, and psychrotrophic and mesophilic bacteria was significantly reduced	A key component of the nonspecific immune response involved in oral health care	Jasour et al. (2015)
	Lactobacillus sakei subsp. *sakei* 2a	Bacteriocins	The growth of *Listeria monocytogenes serotypes* 4b and 1/2a was inhibited in three cheese spread trials	Potential probiotic effects	Martinez et al. (2015)
	Lactic acid bacteria *Lactococcus lactis* C15	*Lactococcin B* gene	Nisin-like bacteriocin Prevent food spoilage and inhibit foodborne pathogens The growth of *Escherichia coli* in Ultra Heat Treatment (UHT) milk was reduced	Improve intestinal diseases Increase immunity	Lei et al. (2022)
Animal-based sources	White shrimp (*Litopenaeus vannamei*)	C-type lysozyme	Antibacterial activities against *Escherichia coli*, *Vibrio splendidus*, *Micrococcus luteus*, *Vibrio parahaemolyticus*, and *Staphylococcus aureus*	Increased immune response against invading pathogens	Hu et al. (2022)

(continued)

Table 1 (continued)

Source		Bioactive constituent	Food application	Health benefits	References
	Chicken egg white	Lysozyme	*L. monocytogenes*, total aerobic microbial, yeasts, and molds in smoked salmon samples were inactivated	–	Min et al. (2005)

bio-preservative alternatives. Fungi's capacity to affect every part of the plant, such as grapes, tomatoes, and strawberries, at any stage of development limits the use of synthetic fungicides (Ramos-Martín et al. 2022). Brisha Arulrajah and colleagues created a microbial-based preservative with antifungal activity by fermenting kenaf seeds to produce a mixture of antifungal peptides (Arulrajah et al. 2021). The peptide mixture produced during lacto-fermentation with *Lactobacillus pentosus* RK3 presented fungicidal effects against *Aspergillus niger* and *Fusarium* sp. when tested on tomato puree (Arulrajah et al. 2021).

3 Antioxidants from Natural Sources

Plants or plant extracts rich in polyphenols can be used as antimicrobial and antioxidant food additives, as flavoring agents, or as natural sources of antioxidants with health benefits. With the ability to interact with free radicals and antimicrobial effect, phenolic compounds have antibacterial, antioxidant, anti-hyperlipidemic, antitumoral, antidiabetic, cardioprotective, and neuroprotective properties (Zeb 2020). Antioxidants of natural origin are "generally recognized as safe" (GRAS) by regulatory bodies, but they need to meet some criteria: low-concentration efficacy, maintaining stability during food preparation and storage, compatibility with food, and consumer safety regarding mutagenicity, carcinogenicity, teratogenicity, and toxicity due to higher amounts used than synthetic antioxidants (Lourenço et al. 2019). Table 2 presents examples of natural sources of antioxidants with applications in food products, along with their biological activities.

A method to assure stability and bioavailability of phenolic compounds in functional food products (bread, butter, yogurt, cake, biscuits) or beverages (milk, juice) is nano-formulation using various matrices and carriers that are non-toxic for consumers (Jampilek et al. 2019). Phenolic compounds with antioxidant properties like phenolic acids, flavonoids, stilbenes, coumarins, lignans, and tannins may be found in all parts of the plant: fruits, roots, leaves, seeds, and barks (Shahidi and Ambigaipalan 2015). Alasalvar et al. (2021) reviewed eight specialty seeds—black cumin, chia, hemp, flax, perilla, pumpkin, quinoa, and sesame—to assess nutrients, bioactive compounds, health benefits, and consumer safety. Rich in essential nutrients like amino acids, minerals, and vitamins, specialty seeds contain bioactive ingredients such as tocopherols, carotenoids, phytosterols, and polyphenols (flavonoids, phenolic acids, lignans, and isoflavones) that have anti-inflammatory, hypoglycemic, blood pressure and lipid metabolism regulation, antioxidant, and antimicrobial activities with multiple health benefits (Alasalvar et al. 2021).

Functional foods enriched with plant antioxidants may contribute to dementia and Alzheimer's disease treatment as well as maintaining a proper renal, hepatic, cardiovascular, and digestive status in older patients (Wilson et al. 2017). Red raspberries possess anthocyanins and ellagitannins, polyphenol compounds that can reduce the risk of metabolism or oxidative-related diseases, increasing cardiovascular and brain health (Burton-Freeman et al. 2016). Green coffee and tea antioxidants (chlorogenic and caffeic acids, caffeine, and trigonelline) can be incorporated in various

Table 2 Examples of natural sources of antioxidants, biological activities, and applications in food products

Antioxidant	Source	Food application	Effects/benefits for human health	Studies (in vitro/ in vivo)	Functional properties	References
Polyphenols	Green coffee bean	Bread	Improved the serum levels of fasting blood sugar, insulin, triglycerides, and high-density lipoprotein (HDL)-cholesterol	In vivo	↑ Phenolic content and antioxidant properties	Zain et al. (2018), Morvaridi et al. (2020)
Anthocyanins, procyanidins, flavan-3-ol	Blueberry	Biscuits	Antioxidant, anti-inflammatory, antihypertensive, and antidiabetic activities with cardiovascular effects and gut-microbiome modulation with prebiotic activity and decrease in pro-inflammatory cytokines	In vitro and in vivo	↑ Phenolic content	Aksoylu et al. (2015), Pap et al. (2021)
Carnosic acid, carnosol, rosmarinic acid, diterpenoids, flavonoids	Rosemary	Yoghurt	Decrease post-prandial glycemia	In vivo	↑ Antioxidant properties and α-amylase activity	Shori (2020)
Caffeoylquinic acid derivatives	Sweet potato	Bread	Hepato- and cardio-protective, anti-inflammatory, antihypertensive properties; modulate lipid metabolism and glucose	In vitro	↑ Phenolic content, antioxidant properties, and dietary fibers	Mau et al. (2020), Sun et al. (2014)
Isoflavones	Soy	Bread	↓ Pro-inflammatory cytokines in patients with chronic pancreatitis and modulate gut microbiota,	In vivo on humans	↑ Isoflavones content with the anti-inflammatory role	Ahn-Jarvis et al. (2020)

			gut immune function, and gut integrity			
Phenolic acids (ferulic acid, *p*-hydroxybenzoic acid) and anthocyanins (luteolinidin and apigeninidin)	Sorghum	Pasta	Prevention of diabetes type 2 and improved intestinal health; increased antioxidant and superoxide dismutase (SOD) activity and decreased oxidative stress markers	In vivo on humans	Enhanced antioxidant potential	Khan et al. (2015), Khan et al. (2013)
Phenolic compounds, condensed tannins (proanthocyanidins), flavonoids (luteolinidin, 5-methoxyluteolinidine)	Sorghum	Cereals	Improved inflammation and oxidative stress in individuals with chronic kidney disease on hemodialysis	In vivo on humans	↑ Phenolic content and antioxidant properties	Lopes et al. (2018)
Phenolic compounds (secoiridoid derivatives—hydroxytyrosol, tyrosol, and verbascoside)	Olive oil by-products	Refined oils	Inhibition of lipid peroxidation on LDL molecules; antiproliferative effects; scavenging activity	In vitro	Preserving α-tocopherol content and ↓ negative volatile compounds during frying	Esposto et al. (2015), Araújo et al. (2015)
Polyphenols, flavonoids	Pollen	Kombucha beverage	Cytotoxic and antitumoral activities; antimicrobial, antimutagenic, antioxidant properties	In vitro	Enhancement of pollen phytonutrients bioavailability due to Kombucha fermentation	Uțoiu et al. (2018), Pascoal et al. (2014)
Furanocoumarins, quercetin 3-*O*- or 7-*O*-glucosides	Pollen	Sheep, goat, and cow milk yoghurt	Antioxidant	In vitro	Increased TPC and antioxidant capacity	Karabagias et al. (2018)
Phenolic compounds	Bamboo shoots	Crackers	Antioxidant; modulate the composition of the human gut microbiome	In vivo	Increased TPC, vitamin C and E, and phytosterols	Santosh et al. (2021), Fraga et al. (2019)
	Walnut green husk	Sausages	Increased paraoxonase (PON-1), catalase (CAT),	In vivo		Salejda et al. (2016),

(continued)

Table 2 (continued)

Antioxidant	Source	Food application	Effects/benefits for human health	Studies (in vitro/ in vivo)	Functional properties	References
Rosmarinic acid, chlorogenic acid, quercetin derivatives			and superoxide dismutase (SOD) enzymatic activities and γ-tocopherol levels and decreased lipoperoxides in patients with high cardiovascular risk		Increased polyphenol content; increased sensory acceptability	Sánchez-Muniz et al. (2012)
Hydroxycinnamic acids (danshensu, caftaric acid, fertaric acid, salviaflaside, and rosmarinic acid), Flavonoids (quercetin dihexoside, kaempferol dihexoside, quercetin hexoside)	Chia	Cookies	Antioxidant properties; prebiotic capacity	In vitro	Increased antioxidant capacity and polyphenol content	Lucini Mas et al. (2020)
Low-molecular-weight peptides	Flaxseed	Bakery products	Lower total and LDL-cholesterol; antioxidant properties	In vivo, patients with cardiovascular disease	Increased antioxidant capacity	Edel et al. (2015), Wu et al. (2019)

TPC total phenolic content

matrices—muffins, bread, and donuts—offering increased antioxidant levels and lower levels of acrylamide formed during the frying process of donuts. Sensory acceptability and polyphenol bioavailability are increased when the extracts are micro- or nano-encapsulated (Aguiar et al. 2016). Epicatechin derivatives found in green tea may increase bone mineral density due to the inhibition of bone resorption and apoptosis of the osteoclasts, and it can represent a good source of antioxidants for osteoporosis prevention (Arnold et al. 2021).

Several plants used as traditional herbal medicines can be included in functional foods with human health benefits. *Angelica dahurica* root contains coumarins and furanocoumarins with in vitro antioxidant and antiproliferative activities (Bai et al. 2016). *Moringa oleifera* leaves contain ascorbic acid, flavonoids, phenolics, carotenoids with antioxidant properties, and calcium, iron, copper, potassium, and folate with good bioavailability (Peñalver et al. 2022). Powdered fruits and vegetables like mango, apple, carrot, pumpkin, jaboticaba, guava, pomegranate, blueberry, grape, orange, mushroom, and grapefruit can be added to biscuits as functional ingredients, increasing mineral and fiber content but also carotenoids and polyphenols levels, with human health benefits (Salehi 2020). Antioxidant additives also contribute to an efficient production process. The addition of pollen to beverages or dairy products as a fermentation activator, natural antioxidant, or fermentation feedstock improved the final product, with an increase in polyphenols and flavonoids content, an improvement in sensory and textural or rheological properties, and increased alcohol formation (Kostić et al. 2020). The incorporation of plant antioxidants into meat products increased shelf life and inhibited the formation of chemical toxins produced during preparation (Jiang and Xiong 2016).

4 Natural Pigments as Food Colorants

Colorants are used in the food industry to increase consumer acceptability (Solymosi et al. 2015). Plants, especially fruits, are good sources of natural colorants. The main natural pigments in the plant kingdom are anthocyanins, carotenoids, betalains, and chlorophyll, and their use in the food industry is challenged by low stability, which can be increased by micro- and nano-encapsulation (Rodriguez-Amaya 2019). Anthocyanins are a family of natural pigments responsible for the purple, red, blue, and orange colors of fruits, vegetables, and flowers (Zhang et al. 2014). The most common anthocyanidins are pelargonidin, cyanidin, peonidin, delphinidin, petunidin, and malvidin.

Fortified food with anthocyanins has multiple health benefits: anticancer, anti-inflammatory, neuroprotective, cardioprotective, anti-obesity, and antidiabetic activities (Li et al. 2017). The selection of a specific colorant is made considering its solubility and the matrix that needs to incorporate it: anthocyanins, which offer the red-blue-purple color, and betalains, which offer the red color, are water soluble, while carotenoids, which offer the yellow-orange-red color, and chlorophylls, which offer the green color, are lipid soluble (Sharma et al. 2021). Most natural origin colorants also have antioxidant effects. García-Cruz et al. (2017) compared two different species of pitaya fruit, one with white pulp and one with red pulp, and found different amounts of betalains and phenolic compounds, with similar antioxidant capacities. Carotenoids are also colorants with antioxidant properties and can be found in mango, pumpkin, carrots (β-carotene), tomatoes (lycopene), green leafy vegetables, or algae (lutein and zeaxanthin) (Xu et al. 2017). Flavonoids and anthocyanins are added to bakery products, biscuits, dairy products, or beverages for increasing antioxidant properties and stability, or improving the final product color (like yellow or orange-colored cheeses) (Neri-Numa et al. 2020). In the process of making naturally colored foods, other beneficial compounds are made. Red yeast rice receives its red color after rice fermentation by the *Monascus purpureus* fungus.

During the fermentation, a series of molecules that inhibit cholesterol (monacolin A and KA) are formed, and their effect is identical to that of lovastatin, a drug that inhibits 3-hydroxy-3-methyl-glutaryl-coenzyme A (HMG-CoA)-CoA reductase and lowers serum cholesterol levels, especially LDL-cholesterol (Poli et al. 2018). Bioactive compounds may also be found in by-products, and their use is encouraged to contribute to sustainable production. Veneziani et al. (2017) reviewed the application of recovered bioactive compounds in food products with a focus on olive oil production wastes. Olive mill wastewater is rich in phenolic compounds such as phenolic acids, comselogoside, secoiridoids, flavonoids, and verbascoside and can be used as a fortifier in oil, milk beverages, and meat products with antioxidant and antimicrobial activities (Veneziani et al. 2017). Anthocyanins, carotenoids, anthoxanthins, and chlorophyll can be extracted from wine pomace, rice bran, tomato by-products, berries, potatoes, citrus peels, or green leafy vegetables, and used as natural-source colorants in the food industry (Faustino et al. 2019). Lombardelli et al. (2021) efficiently extracted betalains from unsold red beets, which can be further used as a food colorant in desserts and confectioneries, dry mixes, and dairy and meat products (Lombardelli et al. 2021). Bagasse, skin, and seeds of kiwi are wasted, which are rich in bioactive compounds such as flavonoids, tocopherols, phenolic compounds, and anthocyanins, with antioxidant, antitumoral, and anti-inflammatory activities and gastrointestinal benefits (Chamorro et al. 2022). Ooi et al. (2021) analyzed the carotenoids and phenolic compounds content of the skin of various sweet potato species. The orange peel had the highest carotenoid content while the purple peel had the highest phenolic compounds content, both with high antioxidant capacity, being a sustainable option for food colorant or antioxidant (Ooi et al. 2021). Table 3 presents examples of natural sources of colorants with applications in food products, along with their biological activities.

5 Hydrocolloids' Functionality in Foods

Hydrocolloids are high-molecular-weight, long-chain hydrophilic polymers having amino and carbonyl functional groups. They are used in the food industry to thicken, gel, replace fat, and produce films (Zhang et al. 2021). Starch, xanthan gum, agar, pectin, gellan gum, alginate, inulin, carob bean gum, gum Arabic, and carrageenan are some of the most well-known hydrocolloids (Zhang et al. 2021; Pirsa and Hafezi

Table 3 Examples of natural sources of colorants, biological activities, and applications in food products

Colorant	Source	Food application	Effects/benefits for human health	Studies (in vitro/ in vivo)	Functional properties	References
Anthocyanins (cyanidin 3-rutinoside, cyanidin 3-glucoside, peonidin 3-rutinoside, peonidin 3-glucoside, and pelargonidin 3-rutinoside)	Sweet cherry skins	Yoghurt; marshmallows	Prebiotic effect for yoghurt; antioxidant activity	In vitro	↑ Antioxidant activity; anthocyanins levels ↓ after 2 days of storage of yoghurt while ↑ for marshmallows	Milea et al. (2019), Kumar and Kumar (2016)
Carotenoids (β-carotene)	Carrot pomace	Biscuits; pasta	Contribute to eye, skin, and mucosal membrane health; antioxidant; maintain immunity	In vitro + in vivo	↑ Carotenoid retention with good sensory acceptability for 8% pomace powder addition in biscuits ↑ Fiber content; ↑ nutritional value of pasta; good sensory acceptability of orange color given by carotenoids	Bellur Nagarajaiah and Prakash (2015), Gull et al. (2015), Ahmad et al. (2019)
Anthocyanins (cyanidin-based, cyanidin-3-xylosyl-sinapoyl-glucosyl-galactoside being predominant)	Black carrot pomace	Cake	Antioxidant, cardioprotective, antidiabetic, anticancer effects; contribute to visual health	In vitro + in vivo	↑ Phenolic content and antioxidant capacity	Kamiloglu et al. (2017), Khoo et al. (2017)
Anthocyanins (glycosylated derivative of delphinidin)	Eggplant (fruit, pulp, epicarp)	Pastry cream	Antioxidant, antimicrobial, cytotoxic, and	In vitro	Stable purple-colored cream with antioxidant activity and ↑ phenolic	Pantuzza Silva et al. (2021), Horincar et al. (2020)

(continued)

Table 3 (continued)

Colorant	Source	Food application	Effects/benefits for human health	Studies (in vitro/ in vivo)	Functional properties	References
			hepatoprotective effects		content, with good rheological behavior	
Anthocyanins (cyanidin 3-rutinoside, peonidin 3-rutinoside)	Fig peels and blackthorn fruits	Beijinho—Brazilian traditional pastry and donuts icings	Antioxidant; antimicrobial; cytotoxic	In vitro	↑ Firmness and consistency of doughnuts ↑ Softness and chewiness of beijinho Stable pink color for fig extract	Backes et al. (2020)
Anthocyanins (delphinidin-3-*O*-glucoside, petunidin-3-*O*-glucoside, malvidin-3-*O*-glucoside)	Black beans; blue maize; chard	Snacks	Reactive oxygen species (ROS) inhibition; decreased glucose uptake	In vitro	Dark red color snacks with good retention of health beneficial compounds due to extrusion cooking and microwave heating	Mojica et al. (2017), Neder-Suárez et al. (2021)
Anthocyanins (cyanidin-3-*O*-glucoside)	Passion fruit epicarp	Cake	Antioxidant, antimicrobial, and cytotoxic activities	In vitro	Good sensory acceptability with increase of dietary fibers	Ghada et al. (2020), Oliveira et al. (2016)
Carotenoids (β-carotene, α-carotene, β-cryptoxanthin, zeaxanthin, lycopene)	Mandarin epicarp	Bakery products (cake and bread)	Anticancer (by anti-inflammatory and antioxidant mechanisms)	In vitro	Stable orange color of the final product; may be used instead of tartrazine in bakery products	Ordóñez-Santos et al. (2021), Saini et al. (2022)
Betaxanthines	Pitayas	Gummies; beverages	Antioxidant	In vitro	Match the yellow color of commercially available products (synthetically colored); increased stability of color in	Rodríguez-Sánchez et al. (2017)

					gummies than in beverages	
Chlorophyll a	*Spirulina* sp. and *Chlorella* sp.	Breadsticks	Antioxidant; anti-inflammatory; gut microbiota modulator	In vitro	Spirulina pigments have lower stability than *Chlorella* pigments for breadsticks' final green color	Igual et al. (2022), Zhou et al. (2023)
Anthocyanins (cyanidin-3-*O*-sambubioside)	Black elder flowers and fruits	Jellies	Scavenging activities; antioxidant	In vitro	A combination of fruit and flower dye had the best sensory acceptability with good antioxidant capacity (due to phenolic acids from flowers) and a pleasant purple color	Salejda et al. (2016)
Betalains (betacyanins, betaxanthins); anthocyanins (pelargonidin mainly)	Red beetroot, opuntia; Hibiscus, red radish	Soy-based yoghurt alternative	Beneficial in oxidative stress-, inflammation-, and dyslipidemia-related diseases	In vitro and in vivo	Non-encapsulated red radish extract offered an appealing pink color while encapsulated opuntia extract had increased health benefits, maintaining the pink color	Dias et al. (2020), Rahimi et al. (2019)
Carotenoids; chlorophyll	Pumpkin pulp and peel	Biscuits	Antioxidant; anti-fatigue; antibacterial	In vitro and in vivo *(mice)*	Sensory acceptability was the best at 3% pumpkin pulp flower addition to the biscuits	Abdulaali and George (2020), Hussain et al. (2022)
Anthocyanins (delphinidin)	*Clitoria ternatea* flowers	Muffins	Antioxidant, antimicrobial, anticancer, and antidiabetic activities	In vitro and in vivo	Encapsulated *C. ternatea* with maltodextrin assured blue color stability and improved shelf life of the muffins	Ab Rashid et al. (2021), Jeyaraj et al. (2021)

(continued)

Table 3 (continued)

Colorant	Source	Food application	Effects/benefits for human health	Studies (in vitro/ in vivo)	Functional properties	References
Anthocyanins (delphinidin-3-*O*-glucoside, cyanidin-3-*O*-glucoside)	*Jabuticaba* epicarp	Macarons	Anticancer activity; hepatic protection; effects on metabolic syndrome	In vitro and in vivo	Stable color of the final product	Albuquerque et al. (2020), Fernandes et al. (2022)

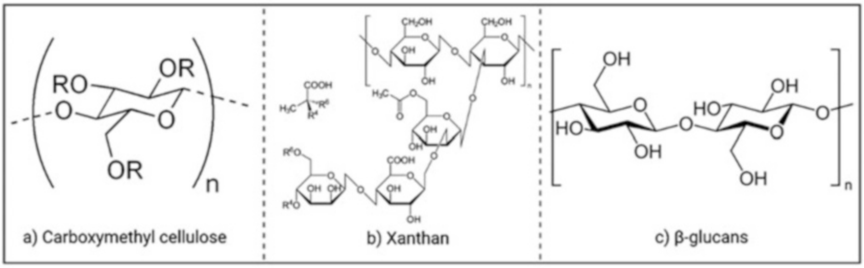

Fig. 3 Structure of functional hydrocolloids

2023). Furthermore, because of their preservation properties, several hydrocolloids are used in the food additives industry.

Carboxymethylcellulose (Fig. 3a) is nowadays one of the most commonly used food additives in foods such as ice cream, sweets, biscuits, cakes, cookies, candies, juices, liquid beverages, dairy and meat products, frozen foods, instant pasta, and fruit compotes (Pirsa and Hafezi 2023). Carboxymethylcellulose can perform numerous roles in food products, including thickening, emulsification, water retention, and stabilization. Carboxymethylcellulose also has rheological properties, which makes it a viable alternative for gelatins. Therefore, carboxymethylcellulose is economical, improves the sensory properties of foods, and increases their shelf life (Pirsa and Hafezi 2023).

Xanthan (Fig. 3b) is another potential additive hydrocolloid. Xanthan is an anionic bacterial heteropolysaccharide derived from *Xanthomonas campestris* fermentation. It has a linear cellulose backbone consisting of β-*d*-glucose substituted on every two units with a pendant trisaccharidic side chain containing a β-*d*-glucuronic acid between an inner α-*d*-mannose and a terminal β-*d*-mannose (Abou Dib et al. 2023). The antimicrobial properties of xanthan gum-based edible coatings on fresh-cut lotus root were recently analyzed (Lara et al. 2020). The findings of the experiments indicated that the spray-coating treatments with xanthan gum solutions successfully reduced the enzymatic browning of fresh-cut lotus root during storage, and potentially improved its market shelf life. Throughout the first 24 hours of incubation, the xanthan gum-based spray-coating significantly inhibited the growth of *Bacillus subtilis* (Lara et al. 2020).

β-glucans (Fig. 3c) are polymers of glucose that are found in numerous bacteria, fungi, algae, and higher plants. One of the largest amounts of β-glucans is found in *Saccharomyces* sp., where the cell walls contain 55–65% of β-glucan (Caruso et al. 2022). The beer industry is one of the richest sources of yeasts. Moreover, brewer's spent yeast is one of the main by-products of the technological process of beer manufacturing, accounting for around 1.5–2.5% of total beer produced annually (1.82 billion hL in 2020) (Caruso et al. 2022). Regarding their functional role, the European Food Safety Authority has recognized β-glucans as safe food additives since 2011. Also, the Food and Drug Administration (FDA) classifies β-glucans as nutritional supplements and food additives in the USA, and there is precedent in

Argentina for the inclusion of the first beer by-product in the Argentinian Codex Alimentarius CAA (Caruso et al. 2022). Therefore, many research works are underlining the use of β-glucans as a thickener or stabilizer in food products, such as salad dressing, soups, sauces, and dairy products (Kayanna et al. 2022). In a recent study performed by Shuya Xu and colleagues, various concentrations (0%, 1%, 3%, and 5%) of oat β-glucan were added to Chinese steamed bread as food additives, and the effect on water mobility, starch retrogradation characteristics, and product quality was investigated (Xu et al. 2021). The properties of β-glucan slow the staling processes of bread by inhibiting the migration of water and the retrogradation of starch, sustaining its use as a natural food additive (Xu et al. 2021). Another study investigated the effect of carboxymethylcellulose, locust bean gum, and psyllium husk powder on wheat dough rheological behavior and bread quality (Sim et al. 2015). A 0.2% concentration of psyllium husk powder ensured the strength and extensibility of the dough, creating a balanced ratio between bread stretch and volume. The study's findings highlighted that the addition of non-starch polysaccharides, such as hydrocolloids, in the dough production process, improves the quality of the resulting bread, slows the aging process, and extends the shelf life (Sim et al. 2015).

In addition to the role of natural food additives, hydrocolloids have many beneficial effects on the human body, such as lowering blood cholesterol, regulating blood lipids and blood sugar (Xu et al. 2021), and prebiotic, immunomodulatory (Nemes et al. 2022), antitumoral, anti-inflammatory, and antioxidant effects (Caruso et al. 2022). A meta-analysis conducted in the USA, Canada, and Europe included 15 randomized controlled studies on human subjects that attempted to measure the effect of consuming β-glucan-rich oatmeal in individuals in the early stages of diabetes. Following the analysis, it was revealed that consuming 3 mg of oat β-glucans for at least eight weeks can considerably reduce insulin, blood sugar, and glycosylated hemoglobin (Bao et al. 2014). The health benefits of beta-glucans, including their ability to reduce serum LDL-cholesterol in humans, were also highlighted in a randomized clinical trial conducted by Wolever Thomas and colleagues. The physicochemical properties of β-glucans influence their effects on lowering cholesterol. An extruded breakfast cereal containing 3 g oat-glucan, consumed daily, with a high molecular weight (2,210,000 g/mol) or a medium molecular weight (530,000 g/mol), similarly reduced LDL-cholesterol (Wolever et al. 2010). However, hydrocolloids represent a valuable class of bioactive compounds that can act as both natural food additives and functional compounds with a beneficial role for the human body.

6 Conclusions

Over the last decades, food science and technology have progressed toward greener and environmentally friendly ways of producing foods, thus including the types of food additives and their sources of origin. The current trend is focused on finding new sources of natural compounds that can be used in foods and feed due to their bioactive properties. Besides their protective role in products, they also have beneficial effects on human health. The large number of chemicals in nature, the biological activities of natural extracts, and the synergies with other compounds provide limitless sources of novel compounds with potential uses in foods and feeds. Nonetheless, the development in the food industry is being overseen by regulatory agencies and law enforcement organizations that have developed stringent laws controlling the licensing and supervision of all food additives.

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