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Review

Natural Compounds from Food By-Products in Preservation Processes: An Overview

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Abstract: Food spoilage is a natural process that influences the quality and safety of food products, negatively affecting their nutritional and organoleptic composition. In these regards, traditional industrial food preservation processes often rely on the use of traditional preservation techniques to extend food shelf life, while ensuring microbiological and chemical stability without compromising the product's sensory characteristics. However, in recent years, consumers have become increasingly wary of chemical food additives; they often associate their use with potential health risks and negative impact on product appeal. In addition, this is compounded by an increasingly compellent European regulatory framework, as well as efforts in the search of natural and sustainable alternatives for food preservation. In this context, this review explores the potential of natural additives, such as polyphenols, flavonoids, and antioxidants, derived from agro-industrial waste, including fruit peels, vegetable by-products, and seeds. These compounds exhibit strong antioxidant and antimicrobial properties, which not only extend the shelf life of food products but also enhance their safety and quality. Considering vegetable wastes (i.e., pomegranate peels, olive leaves, olive mill wastewater, and grape pomace) as the main by-products from which natural additives can be extracted, this study provides an overview of their efficacy in preventing lipid oxidation and reducing microbial growth, while maintaining sensory properties. This could represent an opportunity both for maintaining food quality and prolonging food shelf life by valorizing by-products to be otherwise disposed of, and also contribute to mitigating the environmental impact associated with the food industry and to optimize food preservation processes. In addition, it highlights the possibility of employing sustainable alternatives to synthetic additives, capable of extending the shelf life of food products while ensuring their safety for human consumption.

Keywords: food by-products; food shelf life; sustainable processes; food preservation; natural additives

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1. Introduction

Food represents the basis for human nutrition and well-being, making effective methods to reduce food spoilage crucial. Food spoilage occurs when a food item's nutritional value, texture, and flavor degrade to the point of becoming unsafe for consumption. In this sense, ensuring food safety while extending shelf life are critical challenges within the food industry, especially as consumer demand shifts toward natural and sustainable solutions [1].

The need for preservation techniques emerged when food surpluses became available and food globalization spread, allowing storage for food security and quality along the food supply chain. In particular, maintaining food quality from production to consumer requires substantial energy, typically through refrigeration, controlled packaging, or the use of additives to prevent spoilage and minimize alterations. In a competitive global market, cost-effective preservation methods are prioritized, with food additives often being the preferred choice [2,3].

The European Food Safety Authority (EFSA) defines a food additive as *"any substance not typically consumed as food on its own, nor commonly used as a characteristic ingredient of food, regardless of whether it has nutritional value. Its deliberate addition to food for a technological purpose during manufacturing, processing, preparation, treatment, packaging, transport, or storage results, or could reasonably be expected to result, in the substance or its by-products becoming a direct or indirect component of the food"* [4,5]. Food additives can be classified into six main categories: preservatives, nutritional additives, coloring agents, flavoring agents, texturizing agents, and miscellaneous agents, which can be composed of both synthetic and natural substances [3,6].

Food additives are common across all types of foods, ranging from minimally processed to highly processed and transformed products. The public's perception of food additive use has often been contentious. In the 1980s, additives were widely regarded as potentially hazardous, which led to widespread concern and the removal of certain additives, particularly colorants, from processed foods. Although the relationship between consumers and additives has improved since then, some skepticism persists [7,8]. Today, despite periodic reviews by authorities to ensure safety and establish acceptable daily intake (ADI) levels, some researchers continue to report health concerns related to the consumption of food additives. Numerous reports in the existing literature highlight the potential dangers of consuming synthetic food additives [9]. Ensuring that the ADI of synthetic additives is not exceeded has always been a significant concern for regulatory authorities. In this sense, Regulation (EC) No. 1333/2008 of the European Parliament establishes the rules for the approval, use, and labeling of food additives to ensure a high level of consumer protection and safeguard public health [10].

In recent years, the use of natural food additives has gained significant attention as a promising alternative to synthetic ones. This shift is driven by increasing consumer demand for healthier, cleaner-label products and growing awareness about potential health risks associated with synthetic additives (https://doi.org/10.3390/foods12030556). Natural additives, derived from plant, animal, or microbial sources, offer a way to enhance the taste, color, texture, and shelf life of foods while aligning with current trends in environmental sustainability and human wellness. There are no distinct classifications for natural additives; in the EU, they are followed under the same "E" number system as their synthetic additives (Council Regulation (EC) 1129/2011) [11]. Nonetheless, the most extensively studied natural additives include antioxidants, antimicrobials, colorants, and sweeteners [12].

Recently, agri-food by-products have presented a promising solution for advancing circular and sustainable practices in the food industry. With the rising global demand for food, optimizing the most agricultural resources and minimizing waste has become essential. Agri-food by-products, such as fruit peels, seeds, husks, stems, and other plant residues, often contain valuable bioactive compounds that can be extracted and used as natural food additives. These compounds, such as antioxidants, preservatives, flavor enhancers, and colorants, not only help enhance food quality and extend shelf life but also decrease addiction to synthetic additives, providing "*safer and greener alternatives*" [1,12]. Quantitative analysis and economic evaluation of these applications are necessary to assess their feasibility and competitiveness with synthetic additives.

Many of these phytochemicals, such as tocopherols, ascorbic acid, terpenes, phenolic acids, and polyphenols, have antioxidant and antimicrobial properties, making them viable alternatives to conventional additives [13–15]. As such, valorizing bio-waste and other co-products from agricultural production for use in food preservation processes not only supports circular economy principles but also aligns with growing consumer demand for "natural" ingredients and "clean-label" foods [16].

From this perspective, this study aims to provide an overview of natural by-product compounds and their potential applications in food preservation processes. However, this review needs to address the quantity of natural additives required for efficacy, their impact on food safety, and their structural stability during food preservation processes. These aspects are crucial for evaluating the feasibility of natural additives in practical applications. A detailed comparison of natural and synthetic additives, particularly regarding cost, scalability, and convenience in large-scale production, would enhance the understanding of their industrial applicability. The review also aims to highlight the benefits of using these natural by-product compounds as alternatives to synthetic additives, while emphasizing their role in supporting circular economy practices by valorizing waste materials from the food industry.

2. Literature Review Methodologies

In this study, a systematic and rigorous methodology was applied to the literature review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [17]. The review process consisted of multiple stages:

- Database Identification: Major reference databases—PubMed, Scopus, Web of Science, and Google Scholar—were selected for the search.
- Search Strategy: Specific and comprehensive search terms were developed, including keywords such as "*Food Preservation*", "*Food By-products*", "*Shelf-life*", "*Natural Additives*", "*Additives*", "*Phenolics*", "*Bioactive Compounds*", "*Plant Extracts*", "*Antioxidants*" and "*Antimicrobial Activity*" and combined terms like "*Natural Compounds AND By-products AND Food Preservation*". Medical Subject Headings (MeSH) terms were also incorporated to enhance the search relevance [18].
- Inclusion Criteria: Studies were included based on the following criteria: peer-reviewed, published in the last 20 years, written in English, and directly related to the research topic.
- Article Selection: The initial search yielded 527 articles. These were screened for methodological quality and content relevance, and duplicates or unrelated studies were excluded.

The final selection resulted in 60 articles specifically addressing the application of natural extracts derived from food by-products as substitutes for synthetic additives to prolong the shelf life of various foods. The article selection process is depicted in Figure 1, following the methodology outlined by Liberati et al. (2009) [17]. Finally, the selected articles were analyzed and synthesized to provide a comprehensive and up-to-date overview of the state of the art on this topic.

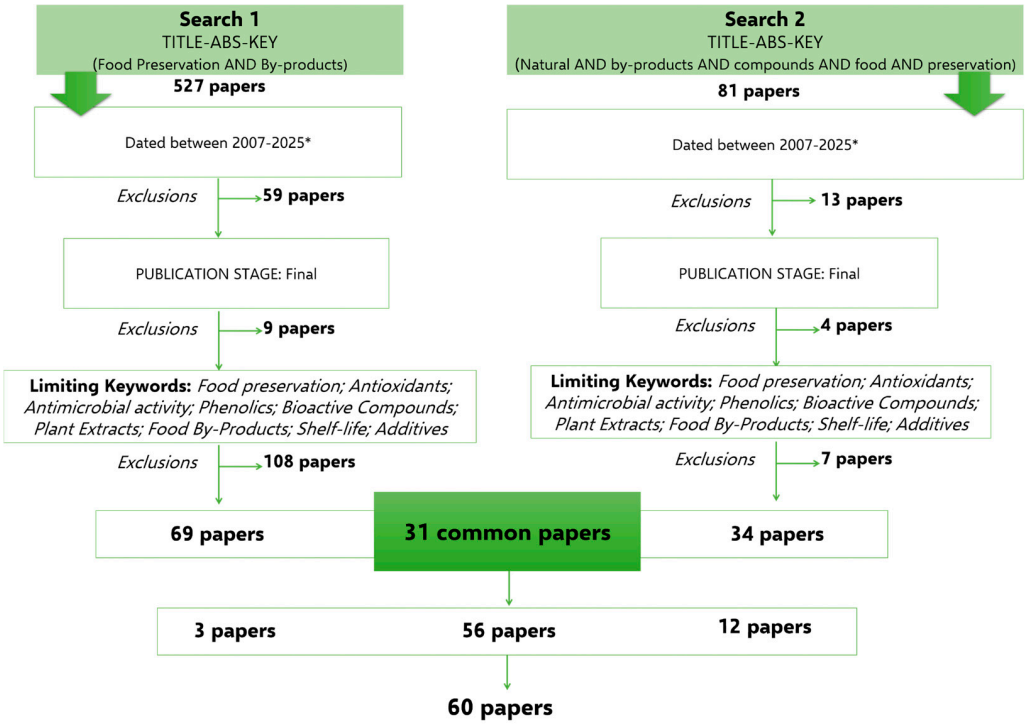

Figure 1. Article selection processes of the two keywords used (*Food preservation* AND *by-products*; *Natural* AND By-*Products* AND *food* AND *preservation* AND *Compounds*) (* Article issued in volume dated 2025).

3. Agro-Industrial By-Products

Agro-industrial by-products represent one of the main challenges and opportunities in the agro-food sector. Every year, high amounts of by-products are generated during the production and processing of food, such as husks, seeds, pomace, grains, whey, etc. Globally, an estimated 1.3 billion tonnes of food waste and by-products are produced yearly [19]. Figure 2 gives an overview of the global problem of food loss and agricultural waste. These losses represent wasted resources and contribute significantly to the production of agro-industrial by-products, which in turn offer opportunities for valorization in the context of food sustainability. The agri-food chain has a food loss that ranges from 2%, for the most virtuous supply chains, to around 45%. The most impactful food industries in terms of wasted amount are meat and animal products (0.17–50% of the total food production), followed by fruit and vegetables, which lose between 0.23% and 50%, and root, tuber, and oil-bearing crops (2.77–37.11% of the total food production) [19].

Furthermore, the highest losses (35%) in crop production occur at the early stages of the food chain: pre-harvest, harvest, and post-harvest. However, the processing and storage stages have losses of between 2% and 15%. In the later stages of the agri-food chain, involving packaging and distribution, losses are 5–18%. This phase also generates large amounts of waste, such as peels, leaves, or damaged parts of fruit and vegetables. Another important aspect concerns retail and sale, where losses range from 2% to 10%. In these stages, a large proportion of the by-products come from food discarded for aesthetic reasons or has passed its shelf life. In addition, household consumption and food services (such as restaurants, hotels, canteens, cafés, etc.) are some of the stages in the food chain where most food waste occurs, with a share of up to 40% [19]. Consequently, every stage of the agri-food chain produces or has the potential to produce food by-products.

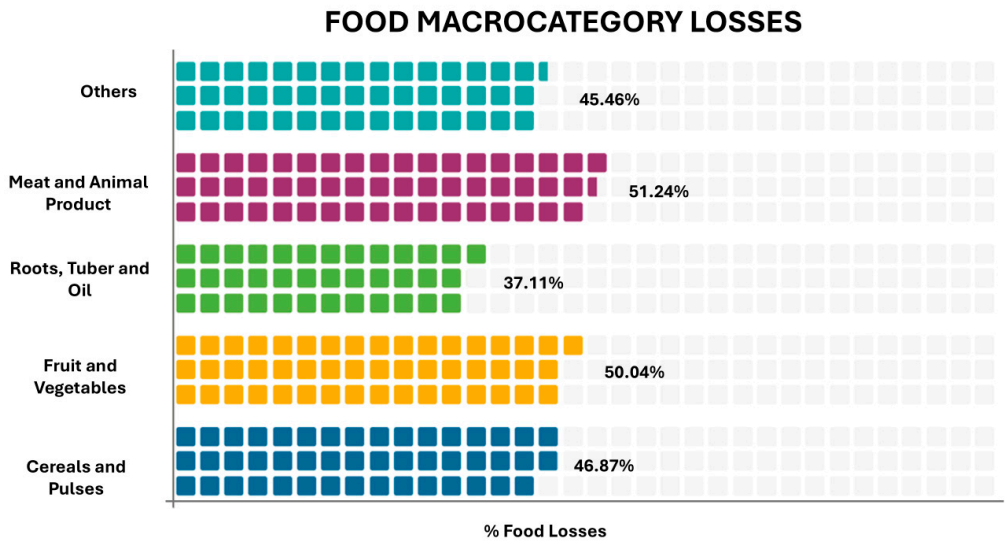

Figure 2. World loss percentage of agri-food macro categories [19].

Agro-industrial by-products are derived from the processing of agricultural produce and represent a significant source of material for secondary use. These by-products include a wide range of residues such as fruit peels, seeds, and pomace, which can be repurposed for various applications, reducing waste and adding value to the supply chain. Some examples of by-products:

- Fruit Peels: Citrus peels are rich in essential oils and pectin, making them valuable in food, cosmetic, and pharmaceutical industries. For example, orange peels are used to extract limonene, a natural solvent and fragrance component [19–23].
- Grape Marc: A commonly discussed by-product, grape marc consists of skins, seeds, and stems left after winemaking. It serves as a source of polyphenols and dietary fibers, used in animal feed, compost, or as raw material for extracting antioxidants [21–25].
- Seed Residues: Seeds from fruits like mangoes or avocados can be used to produce oils or as bioactive compound sources. For instance, mango seed butter is employed in cosmetics for its moisturizing properties [26–31].
- Cereal Bran and Husks: Derived from rice, wheat, or oats, these materials are utilized in producing dietary fiber supplements, biodegradable packaging, or as biofuel sources [32–35].
- Coffee and Cocoa Residues: Coffee husks and cocoa shells are by-products with applications in biochar production, natural fertilizers, or even in the food industry as flavor enhancers [36–39]

These by-products, often considered waste, pose significant environmental and economic challenges, as they require additional resources for disposal and contribute to 6% of total greenhouse gas emissions [40]. Meat production is among the most important: while it accounts for less than 5% of total food waste by volume, it contributes more than 20% to the carbon footprint of food waste. This is mainly due to methane emissions from livestock and emissions associated with the production and management of feed. In addition to meat, other agri-food chains that generate large volumes of waste and have a significant environmental impact include the dairy industry, which produces whey as a waste product representing about 85% of the total, and 90% of the milk volume used for cheese production, followed by the fish and seafood industry, and the fruit and vegetable industry [41].

Usually, some of these by-products are used for animal feed or biogas production, but a large proportion still ends up in landfills or is used inefficiently. However, due to the growing awareness of sustainability and scientific research, agro-industrial by-products are

now considered a valuable resource for extracting bioactive compounds (e.g., polyphenols, flavonoids, polypeptides, etc.), with potential applications in food preservation [14,42,43]. It is estimated that only a fraction of agro-industrial by-products are effectively reused. For example, the use of grape marc to produce distillates or polyphenols represents a limited fraction compared to the overall potential. These by-products could be valorized more through advanced extraction technologies to obtain natural ingredients that can improve food security, thus supporting a transition towards a circular bioeconomy [24]. In this context, converting by-products from waste to resources not only reduces environmental impacts but also creates new economic opportunities and promotes innovation in the food industry.

4. The Role of Additives in the Food Preservation Process

Increasing consumer awareness about food ingredients and the potential risks associated with synthetic additives has driven a growing demand for natural, minimally processed food products. Natural additives, obtained from organic sources (i.e., plants, animals, and microorganisms), are emerging as a viable alternative to meet both consumers' and food technicians' expectations. Besides extending the food shelf life, they offer significant safety and sustainability advantages. Being extracted from natural resources, natural additives are perceived as safer and more environmentally friendly than their synthetic equivalents [24]. Consumer studies show a preference for foods containing natural additives rather than those with synthetic substances, although this trend is disadvantaged by the lack of a clear and agreed definition of a "natural additive". Currently, only natural flavorings are specifically regulated in both the US and Europe [44]. Although useful, this regulation is partly extended to other additive categories, generating ambiguity and limiting consumers' ability to distinguish truly natural additives from those only partially derived from natural sources or chemically processed. Natural additives are generally considered healthier than synthetic ones, due to their bioactive and nutraceutical properties, thus performing multiple functions in food [8,26]. These include individual compounds, groups of substances and essential oils derived from plants, often traditionally used to improve the taste of food. Fungi, algae, and marine plants are also promising sources of natural additives. These compounds, which have been present for a long time, have recently attracted increasing interest in the food industry for their use directly or in combination with other additives, whether natural or synthetic. Their antimicrobial and antioxidant properties, among the most studied, contribute significantly to food safety and preservation [1].

A natural additive is identified as a substance extracted from biological sources such as plants, animals, or microorganisms, used to improve the quality, preservation, appearance, or taste of food [45]. Unlike synthetic additives, natural additives are not produced artificially through synthetic chemical processes but are obtained through natural methods such as extraction, fermentation, or purification [26]. The types of natural additives include several categories of compounds, each with specific functions and applications in the food industry (Figure 3). The most important are the following:

(a) *Natural plant-based additives:* extracts from various plant parts (leaves, roots, seeds, fruits) that provide bioactive compounds like essential oils (e.g., rosemary, thyme) and polyphenols, contributing to food quality and safety [26–28,46].
(b) *Natural microorganism additives:* Bacteriocins like nisin, produced by Lactococcus lactis, which inhibit harmful bacteria in, and extend the shelf life of, products like cheeses and meats [24,29].

(c) *Plant extracts:* This refers to active substances obtained from various parts of plants, such as leaves, roots, flowers, fruits, seeds, or bark, through extraction methods concentrating the active ingredients [30,31].

(d) *Natural animal-based additives:* Products like lysozyme, derived from egg whites, which inhibit bacterial growth in cheese production [47].

(e) *Natural algae additives:* Substances like agar-agar, carrageenan, and alginates, extracted from red and brown algae, used as thickeners, stabilizers, and texture enhancers in dairy and frozen products [48–50].

(f) *Natural fungi-derived additives*: Polysaccharides from mushrooms and yeast, used as emulsifiers and stabilizers to improve texture and structure in beverages, baked goods, and dairy desserts [51].

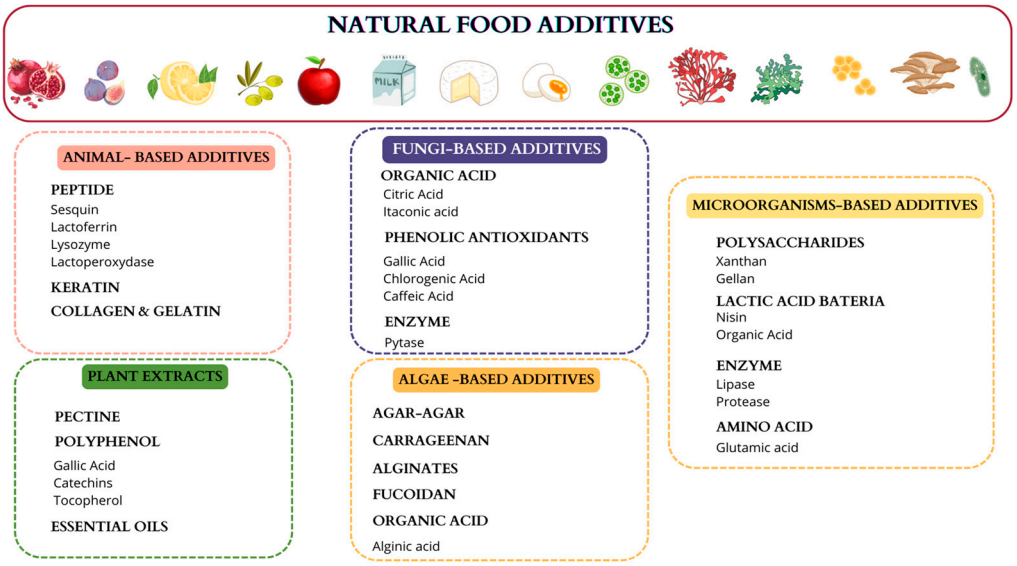

Figure 3. Natural food additive sources.

4.1. Natural Additives Function

Natural additives perform numerous functions in food, improving its quality, safety, and palatability, satisfying the growing demand for natural and minimally processed ingredients. Each class of natural additives offers specific benefits that contribute to food preservation, improved taste and appearance, and reduced risk of contamination [8,52]. Figure 4 shows the main natural additives compounds and their classification.

The main functions performed by natural additives can be classified as follows [8,45,52,53]:

(a) *Natural antioxidants*: Natural antioxidants are essential to prevent food spoilage, particularly in foods containing fats and oils, by protecting them from lipid oxidation. Oxidation can cause rancidity, altering the taste and reducing the nutritional quality of the product. Antioxidants inhibit these processes, extending shelf life and keeping the organoleptic properties of food intact. Among the most effective natural antioxidants is carnosic acid, extracted from rosemary, which is particularly valued for its powerful protective action on fats. Other antioxidants include beta-carotene, which protects baked goods and dairy products, and tocopherol (vitamin E), often used in oils and baked goods. Ascorbic acid, known as vitamin C, is also widely used for its ability to preserve food and prevent oxidation. These natural antioxidants are commonly added to meats, oils, dairy products, snacks, and baked goods, where they help preserve flavor and freshness over time.

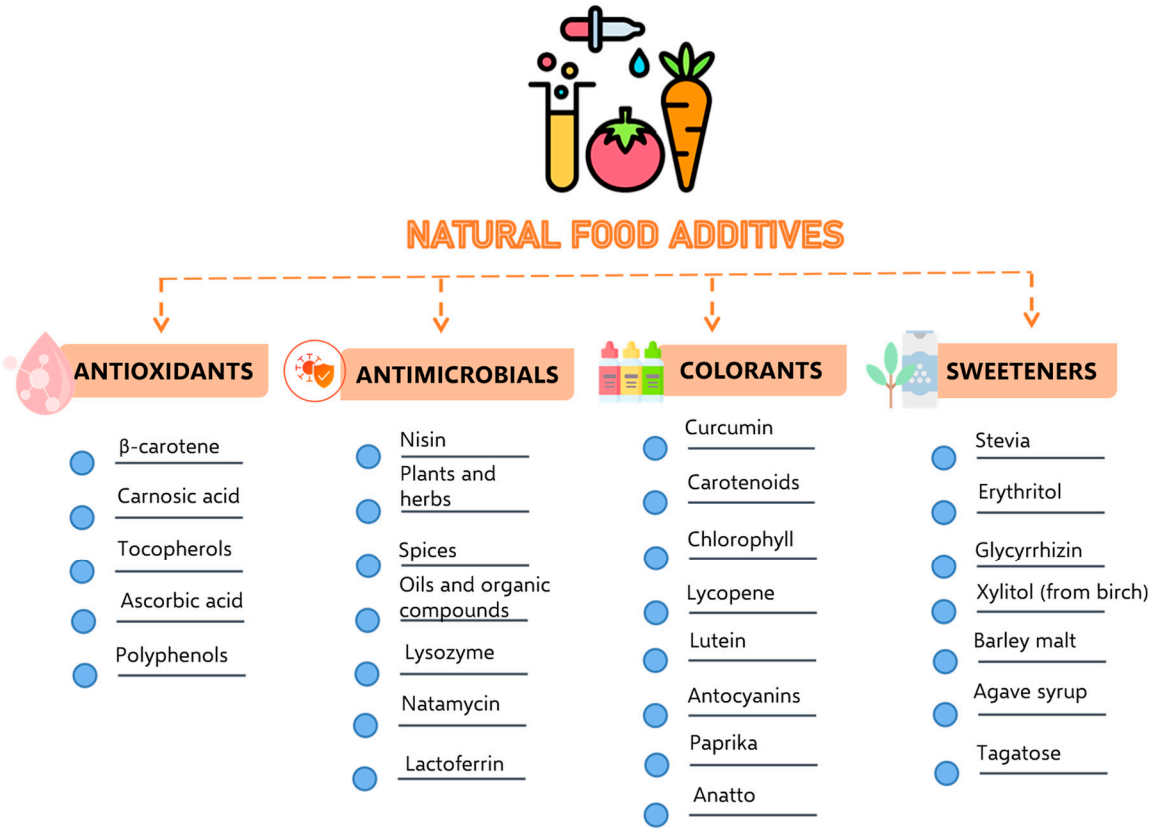

Figure 4. Natural food additives and classification.

(b) *Natural antimicrobials*: These play a key role in food safety, preventing the growth of bacteria, yeasts, and molds that can lead to spoilage or, worse, dangerous contamination. These additives ensure the preservation of food without the need for synthetic preservatives, something that is particularly appreciated by consumers. Nisin, a polypeptide produced by lactic bacteria, is one of the most widely used additives to protect dairy products from bacterial contamination. Another widely used natural additive with antifungal action is natamycin, an organic compound produced by *Streptomyces natalensis* and *Streptomyces chattanoogensis*, commonly used to prevent mold growth on cheese and beverages. Other natural additives with an antimicrobial function are essential oils, such as oregano and rosemary oil, which are widely used in meat, dairy products, vegetables, and fruits to reduce the risk of contamination and prolong freshness.

(c) *Natural dyes or colorants*: These are used to improve the visual appearance of food, which often loses color intensity during processing and storage. One example is annatto, extracted from the seeds of the plant *Bixa orellana*, which gives yellow to orange hues and is used in baked goods and beverages. Anthocyanins, natural plant pigments found in fruits and flowers, are also widely used as natural coloring agents, as they provide red and purple tones and are especially added to desserts and fruit preparations. Another natural coloring agent is curcumin, extracted from turmeric, which gives an intense yellow color and is often used in sauces, yogurt, and dairy products.

(d) *Natural sweeteners:* These are used to reduce the caloric content of foods, offering a sweetness similar to sucrose but with fewer calories, making them ideal for products intended for those wishing to reduce their caloric intake. One of the best-known of these is stevia, a high-potency sweetener extracted from the leaves of the *Stevia rebaudiana* plant. It is highly valued for its intense sweetness and low caloric con-

tent. Other natural sweeteners are erythritol, a polyol found naturally in fruit and fermented foods, and glycyrrhizin, extracted from licorice root. Stevia is widely used in beverages, dairy products, and baked goods, while erythritol is used in candies, chewing gum, and low-calorie chocolate. Glycyrrhizin is found in sweets, frozen dairy products, and baked goods, offering an alternative sweetness without excessively increasing the caloric value.

4.2. Regulated Amount of Food Additives for Preservation

Synthetic and natural additives find widespread application in the food industry due to their antioxidant properties, which help delay lipid oxidation and extend the shelf life of food products.

The use of these compounds in food is regulated to ensure their safety for human consumption and effectiveness in preserving food quality. The amounts of food additives used in different food processes can vary depending on their specific function, the food category, and current legislation (Table 1). Table 1 lists the primary food additives, including natural and synthetic polyphenols and antioxidants, permitted under EU regulations. It specifies the additive names, E-codes, functions, food categories for application, and maximum allowable quantities.

Table 1. Chemical and natural additives in the food industry: classification and function.

Additive Name	E-Code	Function						Food Categories Allowed for Addition	Maximum Allowed Amount
		Colorant	Preservative	Acidity Regulator	Antioxidant	Acidifier	Stabilizing Agent		
Curcumin	E100	×						Dairy products, snacks, sweets	*Quantum satis* *
Carotenes	E160a	×						Beverages, margarine, baked goods	*Quantum satis*
Sodium Benzoate	E211		×		×			Soft drinks, fruit juices	
Sorbic Acid	E200		×					Bakery products, cheeses, beverages	Within 300 and 1000 mg/kg
Benzoic acid	E210		×					Soft drinks, canned goods	Within 150 and 1000 mg/kg
Vitamin C (ascorbic acid)	E300				×			Baked goods, fruit juices, snacks	Up to 2000 mg/kg
Citric Acid	E330			×				Beverages, jams, sweets	*Quantum satis*
Calcium Ascorbate	E302		×				×	Baked goods, beverages, meat	Up to 1000 mg/kg
Malic acid	E296			×	×	×	×	Beverages, candies, fruit products	*Quantum satis*
Tocopherols	E306				×			Oils and fats, baked goods	Up to 300 mg/kg
BHT (Butylated Hydroxy-toluene)	E321				×			Snacks, oils, margarines, ground meat	Up to 200 mg/kg
BHA (Butylated Hydroxyanisole	E320				×			Snacks, oils, margarines	Up to 200 mg/kg
Ferulic acid	E322				×			Oils, cereals, bakery products	Up to 200 mg/kg
Rosemary extract	E392				×			Oils, meats, bakery products	Up to 500 mg/kg
Resveratrol	E-XX				×			Wine, grape products	Up to 100 mg/Kg
Gallic acid	E310				×			Oils, beverages, bakery products	Up to 500 mg/Kg

Table 1. *Cont.*

Additive Name	E-Code	Function					Food Categories Allowed for Addition	Maximum Allowed Amount
		Colorant	Preservative	Acidity Regulator	Antioxidant	Acidifier	Stabilizing Agent	
Betaine	E162	×			×			Beverages, fruit products, yogurt	Up to 200 mg/kg
Lactic Acid	E270		×			×		Dairy products, meats, bakery products	Up to 1000 mg/kg
Sodium Ascorbate	E301		×				×	Bakery products, beverages, meat	Up to 1000 mg/kg
Calcium Ascorbate	E302		×				×	Bakery products, beverages, meat	Up to 1000 mg/kg
Tertiary Butyl-hydroquinone (TBHQ)	E319		×					Snacks, oils, margarines	Up to 200 mg/kg
Propyl Gallate	E310		×					Oils, meats, baked goods	Up to 1000 mg/kg

* *Quantum satis*: as much as needed.

European Union legislation, such as Regulation (EC) No. 1333/2008, sets clear limits on the use of food additives, including natural ones, based on the principle of "quantum satis" (q.s.) to achieve the required effect without exceeding safe levels. For natural additives such as ascorbic acid (E300) and its derivatives, the maximum amount usually ranges from 50 to 300 mg/kg, depending on the food product. For example, in fruit juices, ascorbic acid may be used up to 300 mg/kg, while in other foods it may be lower. This regulation specifies the types of additives that can be used in food and their maximum allowable quantities, and regulates their application only when justified to prevent toxicity risks.

For example, the maximum concentration limits for natural antimicrobial additives such as sorbates (E200-E203) and benzoates (E210-E213) are between 100 and 2000 mg/kg, depending on the food category. These values are defined to ensure that the additive does not exceed the acceptable daily intake (ADI) set by EFSA and European Food Law (Reg. EC 178/2002; Regulation (EC) No. 1333/2008) [10].

These limits reflect a balance between the efficacy of the additives and consumer safety, highlighting the need for science-based evaluation for each new natural additive placed on the market.

4.3. Changes in Natural Additives During Food Preservation Processes

Changes in natural additives during food storage are of great importance in ensuring the quality and safety of food. Indeed, during food storage, natural additives can undergo a series of chemical, physical, and biochemical changes, which not only reduce the effectiveness of natural additives but can also alter the organoleptic quality and shelf life of the food. Given the importance of polyphenols and antioxidant compounds as the main natural additives extracted from agri-food waste [9,12,13], this section explores their structural stability and the main chemical changes during the food preservation process.

The changes that affect natural additives, in particular, polyphenols and ascorbic acid (vitamin C), during food preservation are distinct and influenced by various factors. In particular, polyphenols, organic compounds found in many foods of plant origin, play an essential role in preservation due to their antioxidant properties; however, they can undergo various chemical changes that affect their stability, efficacy, and bioavailability [31]. Furthermore, these transformations in natural additives lead to organoleptic changes (e.g., changes in taste, appearance, and texture) and nutritional changes in the food [54,55].

The main causes of chemical changes in polyphenols during food preservation mainly depend on physico-chemical factors related to food preservation, such as temperature, pH, light, and oxygen, as well as the presence of endogenous enzymes in the food matrix. The

main reaction affecting polyphenols during storage is oxidation. This takes place in the presence of oxygen, high temperature, and light, and can be accelerated by enzymes (e.g., polyphenol oxidase or *PPO*), or by catalysts such as metals (e.g., iron and copper), which are often present in traces in food [56]. Therefore, two types of polyphenol oxidation can take place within the food: enzymatic and non-enzymatic. The first reaction involves PPO, which catalyzes the oxidation of the hydroxyl groups (-OH) of polyphenols, transforming them into quinones. These compounds are highly unstable and can further react with each other or with other molecules, leading to the formation of polymeric compounds or dark pigments (such as melanoidins) (quinone polymerization) (Figure 5) [57]. Another reaction that can occur with polyphenols during food preservation is the hydrolysis of glucose into glycosylated polyphenols. This reaction is accelerated during the food preservation process by low pH and the presence of enzymes. Another reaction involving these compounds is the Maillard reaction, favored by high temperatures and neutral or slightly basic pH [58]. A further reaction involving these compounds is photochemical degradation (photooxidation); this reaction occurs in the presence of light as polyphenols absorb UV radiation, causing chemical breaks within the molecule or changes in structure, with a significant reduction in antioxidant capacity [59].

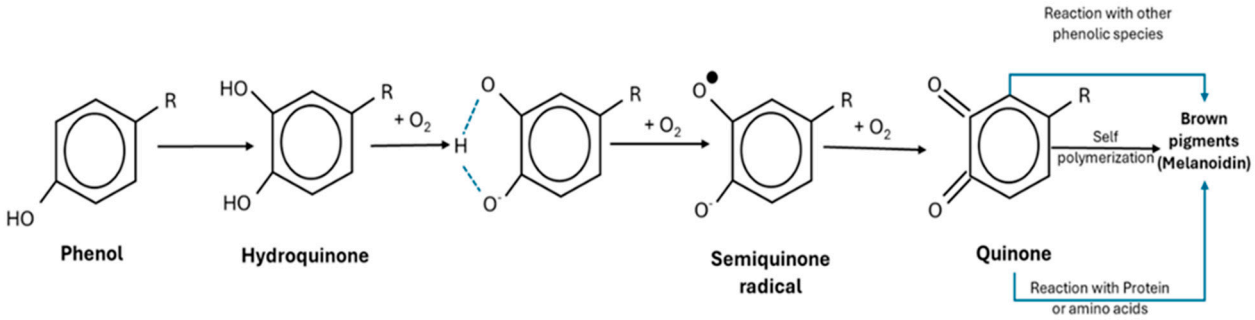

Figure 5. General oxidation reaction of polyphenol and brown pigment formation.

Polyphenols and other natural additives, when added to foods, interact with numerous components, such as proteins, lipids, sugars, vitamins, and minerals, giving rise to effects that can positively or negatively affect the quality, stability, and safety of the food. Their antioxidant properties make them particularly effective in protecting lipids from oxidation, thus slowing down the rancidifying process of fats and oils. This slows food spoilage and prolongs its shelf life, contributing to freshness and product integrity. However, under certain conditions, polyphenols themselves may oxidize or degrade, losing their antioxidant capacity and, in some cases, even contributing to lipid oxidation, with detrimental effects on food stability [60]. The preservation of vitamins can also be affected by the presence of polyphenols and other natural antioxidants. For example, vitamin C can be protected from oxidation by these interactions, thus maintaining its nutritional properties. However, light or oxygen can induce processes that reduce the bioavailability of vitamins, compromising their nutritional value. Concerning minerals, polyphenols can bind to elements such as iron and form complexes that reduce their bioavailability, hindering their absorption. This may limit the intake of essential minerals through consumption of foods, affecting the overall nutritional value. Finally, interactions with other food compounds may also alter certain organoleptic properties, such as taste, color, and texture. To preserve the beneficial effects of these natural additives and reduce any undesirable effects, it is essential to carefully control storage conditions, such as temperature, humidity, and exposure to light. These measures help to maintain the positive qualities of the natural additives while ensuring that no undesirable alterations to the organoleptic characteristics of the product occur [60,61].

5. Natural By-Products Compounds for Food Shelf Life

The increasing demand for sustainable solutions in the food industry has highlighted the potential of natural additives derived from food by-products to extend shelf life. These by-products, which include fruit peels, vegetable scraps, seeds, and other plant residues, are often discarded as waste despite being rich in valuable bioactive compounds [62,63]. Extracting antioxidants, antimicrobials, and other functional substances from these by-products can offer an eco-friendly alternative to synthetic additives. Such natural additives not only help preserve food quality and safety but also contribute to a circular economy by turning waste from the food industry into valuable resources and reducing environmental impact. By integrating these bioactive compounds into food preservation processes, food producers can align with consumer preferences for "clean-label" and *"natural"* products while supporting sustainability initiatives [64]. The development and application of these natural additives represents a promising approach to enhance food shelf life, reducing waste and promoting a more resource-efficient food supply chain. Furthermore, natural extraction methods have evolved to include "green technologies" using environmentally safe solvents and processes, while ensuring that the production of natural additives is both safe and sustainable [36,65]. This integration of sustainable technologies reinforces the overall environmental benefits, making natural additives a strategic choice for food preservation that prioritizes both consumer well-being and ecological responsibility.

5.1. Natural Additive Extraction from Food By-Products

Figure 6 includes the main natural compounds extracted from food by-products and applied as natural additives, thus distinguishing among eight main bioactive components: tannins, stilbenes, lignans, flavonoids, antioxidants, polypeptides, carotenoids, and tocopherols [66].

Figure 6. Main natural by-product compounds extracted.

Literature studies have focused on the recovery of compounds with natural additive functions (e.g., antioxidants, antimicrobials, and preservatives in food), especially polyphenols, from food waste from different industrial processes (i.e., the elaio-technical sector, the fruit and vegetable sector, etc.) [37,67]. This approach not only meets the growing demand for natural alternatives for synthetic food additives but also promotes environmental sus-

tainability by valorizing waste materials. The main by-products used come from a variety of plant and agricultural sources, all rich in phenolic compounds and antioxidants [68]. Among the most widely used are by-products of seeds and shells (i.e., sesame seed husks, peanut husks, rice, and wheat bran) [32–35]; olive leaves and residues (i.e., olive leaves and olive vegetation water) [67,69–72]; and fruit and vegetable waste (i.e., orange, lemon and grapefruit peels, grape marc and grape skins, potato skins, pomegranate skins, mangoes and avocados) [20–23,25,73,74].

Polyphenols are extracted using different methods and solvents, which influence the yield and quality of the final extract. When choosing solvents for the extraction of natural additives from by-products, the selection is mainly based on choosing solvents that are non-toxic to human health and environmentally friendly [75,76]. In particular, the most commonly used solvents are water and ethanol, or hydroalcoholic solutions of these components at different concentrations. However, some studies have used methanol or hydroalcoholic solutions of methanol for the extraction of bioactive compounds that constitute natural additives, although these solvents, despite having a high extraction yield [77,78], are toxic for human consumption [79]. Instead, Siripattanakulkajorn et al. (2025) applied innovative and natural solvents (Natural Deep Eutectic Solvent; NADES) for the extraction of bioactive compounds from black and red rice bran [80]. Among the extraction techniques most commonly used in the studies are Soxhlet or ultrasound-assisted extraction (UAE). Other methods are the application of overnight food waste maceration or agitation and subsequent centrifugation [20,81–83]. The studies also examined the characterization of the extract to identify the main components present; in particular, the presence of polyphenols including gallic acid, quercetin, epicatechin and rutin was highlighted [32,81,84–86].

5.2. Natural Additives from Food By-Products to Extend Shelf Life

Table 2 provides a detailed overview of the application of natural extracts, obtained from agri-food by-products, as natural additives to improve the quality and shelf life of different foods. These extracts are known to contain bioactive compounds, such as polyphenols, flavonoids, terpenes, and tannins, which have shown potent antioxidant and antimicrobial effects. Shahidi and Ambigaipalan (2015) have shown that the polyphenols present in by-products can reduce oxidation and inhibit microbial proliferation, making them promising natural additives [87]. The total of added extract varies significantly among treated foods, with amounts ranging from 100 mg/kg [23,70] up to 10% by weight [88,89], a variability that reflects the need to adapt the treatment to the characteristics of the food. For example, sesame seed extract was used at 100 mg/mL in sterilized milk [32], while pomegranate peel extract was used at concentrations between 1% and 10% in beef burgers [23], and olive vegetation water between 50 and 100 mL in extra virgin olive oil [67,71,72,90]. These differences reflect the need to adapt the concentrations of the extracts to the food matrix under investigation. In products with a high lipid content, such as oils and meats, higher concentrations are often required to reduce lipid oxidation [31,59,70,84]. Enciso-Martínez et al. (2024) highlight how this phenomenon degrades the taste, aroma, and appearance of foods, as well as reducing the content of essential nutrients [91]. To limit these effects, adding high concentrations of natural extracts rich in polyphenols is a widely adopted strategy, as polyphenols act as powerful antioxidants that reduce lipid oxidation and prolong the shelf life of food. Regulation (EC) 1333/2008, about the use of additives in food, restricts the use of certain plant extracts and natural antioxidants to avoid overdosing, which could alter the sensory quality of the food by imparting a bitter or astringent taste, and could mask natural flavors [10]. Furthermore, excessive polyphenol

content may interact negatively with nutrients, forming insoluble complexes with minerals such as iron and calcium, thus reducing their bioavailability [92].

Table 2. Natural additives from food by-products and extraction methods.

Reference	By-Product Sample	Extraction Methods	Extraction Solvent Used	Natural Compound Extract
[32]	Sesame seed coat	Thermostatic bath	Methanol solution 70%	Catechin, gallic acid, quercitin, p-cumaric acid, caffeic acid
[93]	Rice bran	Thermostatic bath	Ethanol, water	Trans-ferulic acid, p-cumaric acid, oryzanol
[69]	Olive Leaf	Soxhlet system	Water	Phenolic acid (gallic acid, neochlorogenic acid, p-coumaroylquinic acid), flavanol (epicatechin), flavonols (quercetin-3-O-rutinoside, quercetin-3-O-galactoside, kaempferol)
[33]	Brewer's spent grain	nd *	NaOH 0.75%, 50% MeOH, 50% acetone	nd
[84]	Euryale ferox seed	Centrifuge and rotary evaporator under low pressure	Ethyl acetate, ethanol, and 50% v/v ethanol	Gallic acid, epicatechin, rutin, catechin, epicatechin gallate, ferulic acid, chlorogenic acid
[94]	*Pituranthos scoparius* (stems and leaves)	Hydrodistillation	nd	Monoterpenes, diterpenes, oxygenates
[95]	Defatted soybean flour	Orbital shaker	Ethanol/water/hydrochloric acid (89:19:1 v/v)	Isoflavones (daidzein, genistein, glycitein, daidzin, genistin, and glycitin) and 21 phenolic compounds (gallic acid, homogentisic acid, protocatechuic acid, chlorogenic acid, catechin, p-hydroxybenzoic acid, vanillic acid, caffeic acid, syringic acid, p-coumaric acid, rutin, ferulic acid, veratric acid, naringin, myricetin, quercetin, trans-cinnamic acid, kaempferol, hesperetin, hesperidin, and sinapic acid)
[96]	Commercial grape seed extract	nd	nd	nd
[88]	Grape pomace extracts	Soxhlet apparatus	Ethanol/water (95:5 v/v)	nd
[67]	Olive vegetation water	nd	nd	nd
[63]	Pomegranate peels	nd	nd	nd
[85]	Devidson's plum powder	Ultrasonication bath	Water and methanol (80 mL/dl)	Cynidin 3-O(6 malonyl-3-glucosyl-glucoside), cyanidin 3-O-glucoside, delphinidin, delphinidin 3-glucoside, delphinidin 3-O-sambubioside, peonidin derivative, peonidin derivative, pelargonidin 3-O-glucoside, 6_trialloyl-glucose, ascorbic acid, casuarinin, chebulagic acid, chebulinic acid, corilagin, elaeocarpusin, ellagic acid, gallic acid, punicafolin, rutin
[97]	Grape pomace extracts	nd	nd	nd

Table 2. *Cont.*

Reference	By-Product Sample	Extraction Methods	Extraction Solvent Used	Natural Compound Extract
[34]	Pistachio green hull	Stirring	Water	Gallic acid, 4-hydroxybenzoic acid, protocatechuic acid, naringin, eriodictyol-7-O-glucoside, isorhamnetin-7-O-glucoside, quercetin-3-O-rutinoside, isorhamnetin-3-O-glucoside, catechin
[80]	Red and black rice bran	Stirring	NADES (i: Betaine/Citric acid/water in molar ratios of 1.5:1:5; ii: Betaine/sucrose/water in molar ratios of 2:1:8.5) at 20% *w*/*w*	nd
[98]	Commercial grape seed extract	nd	Ethanol/water (1:1 *v*/*v*)	nd
[81]	Kakadu plum	Ultrasonication bath	Methanol/water (80:20 *v*/*v*)	3,4,6-trialloy-glucose, ascorbic acid, casuarinin, chebulagic acid, corilagin, elaeocarpus, ellagic acid, gallic acid, punicafolin, rutin
[89]	Citrus by-products (peeled lemon, peeled oranges, peeled grapefruits)	nd	Orange freeze-dried	Antioxidant and fiber
[95]	Defatted soybean meal	Rotavapor	Ethanol 80% and aqueous solution	nd
[70]	Olive waste extract	nd	nd	Antioxidant activities
[99]	Orange peels	nd	ethanol/water (52.9%)	nd
[62]	Passion fruit by-products	Maceration	Water and ethanol (99.3%)	Cinnamic derivative, flavonoid class, vitexin, ellagic acid, 6-isomer C-fucosylueteoin, luteolin-rhamnosyl-glycoside, (iso)orientin, lucenin
[100]	Peanut skin extract	Thermostatic bath	Ethanol (80%)	Antioxidant activities
[43]	Peanut skin extract	Subctitichal fluid extraction (SPE)	Ethanol (95%)	Antioxidant activities
[101]	Colombian berry (*Vaccinium meridionale sw.*) extracts	Rotavapor	Ethanol/water (50:50 *v*/*v*)	Cyanidin derivatives, quercetin-3-glucuronide, quercetin-3-glucoside, syringic acid, p-coumaric acid, kaempferol derivatives, 3-glucoside + rutinoside
[82]	Sesame seed coat	Ultrasonication bath	Ethanol (90%)	Gallic acid, caffeic acid, syringic acid, coumaric acid, ferulic acid, naringenin, propyl gallate, p-hydroxybenzoic, quercitin, cinnamic acid, sesamol, sesamin, sesamolin
[71]	Olive mill wastewater (OMWW)		Hydrophilic solution	Oleacein, hydroxytyrosol, tyrosol, verbascoside, oleocanthal
[102]	Wheat bran	Solid-phase extraction (SPE)	n-Hexane/chloroform (1:1, *v*/*v*)	Alkylresorcinols

Table 2. *Cont.*

Reference	By-Product Sample	Extraction Methods	Extraction Solvent Used	Natural Compound Extract
[103]	Potato peels	Cryomaceration	Distilled water or ethanol/water (90:10 *v*/*v*)	Antioxidant activities
[72]	Olive mill wastewater (OMWW)	Rotavapor	acetate (1:4 *v*:*v*)	Hydroxytyrosol, protocatechuic acid, tyrosol, chlorogenic acid, caffeic acid, p-coumaric acid, quercetin, oleuropein, luteolin, apigenin, rutin, rosmarinic acid
[83]	Pomace powder of musky squash	Wltrasound-assisted method	Ethanol (70:30 *v*/*v*)	nd
[104]	Lingonberry extract	Microwave electromagnetic field	Water/alcohol	nd
[105]	Pomegranate peel extract	Water bath shaker	Ethanol	nd
[25]	Bergamot pomace	Heater and continuous stirring	ethanol/water; 1:1, *v*/*v*	nd
[35]	Sugarcane bagasse aqueous extract	Maceration	Water, methanol (95%), ethanol (95%), water/ethanol (1:2), water/methanol (1:2)	nd
[38]	Spent coffee ground	Maceration	Ethanol	nd
[106]	Pistachio hull extract	Maceration and stirring	Distilled water	nd
[107]	Olive leaf extract	Maceration and stirring	Ethanol/water	nd
[108]	Olive leaf extract	Maceration and stirring	Ethanol 50%	nd
[90]	Olive mill wastewater (OMWW)	Maceration and stirring	Ethyl acetate	nd
[109]	Pomegranate peel extract	nd	nd	nd
[73]	Broccoli by-products	Supercritical fluid extraction	nd	nd
[105]	Date pit powder	nd	nd	nd
[110]	Olive leaf extract	nd	nd	nd
[74]	Saffron tepal extract	Stirring	Water, ethanol/water 80:20 *v*/*v* and methanol/water 80:20 *v*/*v*	nd
[20]	Avocado by-products	Ultrasonic bath	Ethanol	Syringic acid, caffeic acid, 4-hydroxybenzoic acid, catechin, and 3,4-hydroxybenzoic acid
[21]	Mango by-products	Stirring	Ethanol (80%)	nd
[76]	Peanut skin extracts	Sonication and ultrasonication bath	Ethanol (95%)	nd
[22]	Potato peel	Maceration overnight	Ethanol (96%); ethanol (80%); water	nd

Table 2. *Cont.*

Reference	By-Product Sample	Extraction Methods	Extraction Solvent Used	Natural Compound Extract
[86]	Chestnut shell extract	SLE–Soxhlet apparatus	ethanol	Catechin, gallic Acid, resveratrol, rosmarinic acid
[111]	Pomegranate peels and seed	Vertical shaker	Distilled water	nd
[112]	Pomegranate peel powder	nd	nd	nd
[88]	Grape pomace (seeds, skins and stems)	Soxhlet	Ethanol/water (95:5)	nd
[113]	Fruit (citrus, orange, apple, pear, peach, banana, kiwifruit), vegetables (tomato, potato, carrot), and oilseed (cottonseed, sunflower, soybean) by-products	nd	nd	nd
[75]	Pomegranate peel extract	Stirring at 70 °C	Distilled water	Gallic acid, chlorogenic acid, cathin, methyl gallate, caffeic acid, syringic acid, pyrocatechol, rutin, ellagic acid, coumaric acid, vanilin, ferulic acid, naringernin, daidzein, quercetin, cinnamic acid, apigenin, kaempferol, hesperetin
[114]	Kinnow rind, Pomegranate rind, and seed powders	Boiling and macerated 1 h	Distilled water	
[23]	Pomegranate peel extract	Supercritical fluid–CO_2	nd	Gallic acid, cathechin, gallocatechin, ellagic acid, Monogalloyl-hexoside, ellagic acid-pentoside, ellagic acid-deoxyhexoside, ellagic acid-hexoside, digalloyl-hexoside, galloyl hexoside, punicalin, punicalagin a, punicalagin b

* nd = not defined.

5.3. Food Storage Conditions After the Addition of Natural By-Product Extract

Table 3 gives a broad overview of the use of natural extracts obtained from food by-products to improve the shelf life of different food products. The use of these extracts for food preservation varies significantly depending on the type of food and the concentration of the extract applied. Different studies highlight shelf-life elongation of a few days (3 to 9 days) [70,88], while others showed positive effects of up to 120 days [72,75,115]. These differences mainly depend on three factors: the type of food, and the type of extract and its concentration. Fresh and highly perishable foods, such as dairy and meat products, generally have a shorter shelf life, as they are more vulnerable to microbial contamination [20,62,81,85,88]. For dairy products, such as sterilized milk or milk-based emulsions, sesame seed extracts and *Pituranthos scoparius* were used to keep the food stored for between 3 and 7 days [94]. These results, reported by Khazaal et al. (2024) and Chikhoune et al. (2017), show that for easily perishable foodstuffs such as milk, even the most effective natural extracts offer a relatively short shelf life, while providing greater safety [32,94]. Other studies, such as those of Martillanes et al. (2020) and Codina-Torrella et al. (2021), have used rice bran and pomegranate peel extracts to preserve mayonnaise for up to

7 days at both 4 °C and 20 °C, suggesting that these extracts can preserve the stability of mayonnaise even at room temperature for short periods [33,93].

Extracts of grape seeds, pomegranate peels, and olive vegetative water allow, depending on temperature and concentration, to extend the shelf life of meat from 9 to 120 days [75,88,96,109,112]. These compounds show strong antimicrobial and antioxidant activity, making them particularly effective in preventing bacterial growth and lipid oxidation in meat products [71,84,97,98]. Oils, such as extra virgin olive oil and other vegetable oils, were treated with olive leaf extracts, pomegranate peel, and *Euryale ferox* extracts [84]. These extracts keep the oil stable for up to 70 days, reducing oxidation and significantly extending shelf life, especially when stored at a controlled temperature [35,69,102].

For baked products and biscuits, such as those enriched with pomegranate and bergamot peels, the shelf life can be up to 10 weeks [66,116]. Giri et al. (2021) and Gattuso et al. (2024) point out that these natural extracts, used in suitable concentrations, not only prolong product shelf life but also help maintain sensory quality and color stability [25,112]. Sauces and seasonings, such as pesto and mayonnaise, are also well preserved with the addition of olive mill wastewater (OMWW) and pomegranate peels, which guarantee a shelf life of between 20 and 40 days [72,90]. Studies such as those of Sordini et al. (2022) and De Bruno et al. (2024) show that, even at moderate temperatures, these natural extracts can prolong the shelf life of sauces, keeping flavor and freshness unaltered [71,72].

Regarding white meats (such as chicken and lamb), the use of grape seeds and pomegranate extracts allows a shelf life of about 9 days, with checks carried out every three days to monitor microbial growth and oxidation [117]. Muíño et al. (2017) and Al-Baidhani et al. (2024) confirm that these extracts help stabilize fresh meat products, even for short storage periods at refrigeration temperature (4 ± 1 °C) [70,111]. Cheese and other fresh dairy products treated with chestnut and olive leaf extracts can be stored for up to 15 days [108]. Ferreira and Shalaby found that these extracts protect against rancidity and microbial growth, making them particularly useful in delicate products such as fresh cheese [86,108]. For seafood products, such as fillets and smoked sardines, the addition of pomegranate extracts and squid ink allows a shelf life of about 14 days [20,23,54]. De O. Silva et al. (2021) show how these extracts can maintain the freshness of fish, reducing the perishability of fish products [23].

The concentration of the extract also has a significant influence: higher concentrations tend to increase the preservative efficacy, but risk altering the taste and smell of the food. It is therefore necessary to balance the efficacy of the extract and its compatibility with the organoleptic characteristics of the product [70,118].

Another crucial factor is the storage temperature. Most studies monitor the effectiveness of extracts at low temperatures, around 4 °C, ideal conditions for slowing microbial growth. At these temperatures, natural extracts show their maximum effectiveness, combining antimicrobial and antioxidant properties with the natural effect of refrigeration. However, in some studies, shelf life is also tested at higher temperatures, such as ambient temperature (25 ± 1 °C), to simulate non-refrigerated transport and storage conditions. In these cases, the shelf life is significantly reduced, revealing the limitations of natural extracts at high temperatures. However, some compounds, such as citrus extracts, retain some efficacy even at room temperature, suggesting that they may be useful under less controlled conditions [25].

Table 3. Shelf life, storage conditions, and natural by-product compound amounts in food.

Reference	By-Product Sample	Natural Additive Amount	Enriched Food	Shelf Life Time	Shelf Life Temperature	Analysis Timing
[32]	Sesame seed coat waste	100 mg/mL sesam extract emulsion	Sterilized milk	7 days	nd *	0, 1, 3, and 7 days
[93]	Rice bran	0.5 and 2% extract	Mayonnaise	7 days	4 °C and 20 °C	0 and 7 days
[69]	Olive leaf	50 to 100 mL in 50 mL Oil	Extra virgin oil	nd	nd	nd
[33]	Brewer's spent grain	nd	Sunflower oil	14 days	34 °C	
[84]	Euryale ferox seed	200 to 500 mg/Kg	Pork sausages	10 week	nd	1 week
[94]	*Pituranthos scoparius* (stems and leaves)	2%	Milk emulsion	nd	nd	nd
[95]	Defatted soybean flour	0.15 to 1.5 g/L	Fruit	6 days	25 °C	0, 3, 4, 5, and 6 days
[96]	Commercial grape seed extract	0.1% extract and 0.1% extract combined with NaCl	Chicken thigh meat	12 days	4 °C	0, 4, 8, and 12 days
[88]	Grape pomace extracts	1%, 2%, 5%, and 10%	Beef patty	48 h	4 °C	2, 12, 24, and 48 h
[67]	Olive mill wastewater (OMWW)	75 and 100 mg of phenol extract/100 g of meat	Pork sausages	14 days	c	0, 7, and 14 days
[63]	Pomegranate peels	15 g/100 g of powder in filling and 2.5 and 5 mg/100 g kneaded	Fresh filled pasta (Ravioli)	nd	nd	nd
[85]	Devidson's plum powder	0.2, 0.4, 0.6, and 0.8 g/hg	Beef patty	20 days	4 °C	0, 4, 8, 12, 16, and 20 days
[97]	Grape pomace extracts	2%	Beef patty in modified atmosphere	15 days	4 °C	0, 4, 8, 12, and 15 days
[34]	Pistachio green hull	0.05 to 0.8 w/v	Button mushroom	10 days	4 °C	1 and 10 days
[80]	Red and black rice bran	0.3% Nades1 and 1.9% Nades2	Mayonnaise	69 days	20 °C	nd
[98]	Commercial grape seed extract	1 g/kg	Pork patties under modified atmosphere (80% O_2 and 0% CO_2)	20 days	2 °C	1, 6, 13, and 20 days
[81]	Kakadu plum	0.2, 0.4, 0.6 and 0.8%	Raw beef patties under modified atmosphere	20 days	4 °C	0, 4, 8, 12, 16, and 20 days
[89]	Citrus by-products (peeled lemon, peeled oranges, peeled grapefruits)	2.5; 5 and 7.5%	Sausages	28 days	4 °C	
[95]	Defatted soybean meal	Immersion in the extraction solution	Figs	21 days	0 °C	0, 7, 14, 17, and 21 days
[70]	Olive waste extract	100, 200, and 400 mg/kg	Lamb meat patties	9 days	4 °C	0, 3, 6, and 9 days

Table 3. *Cont.*

Reference	By-Product Sample	Natural Additive Amount	Enriched Food	Shelf Life Time	Shelf Life Temperature	Analysis Timing
[99]	Orange peels		Fruit (peach)	nd	nd	nd
[62]	Passion fruit by-products	1000 mg/kg for aqueous extract and 500 mg/kg for ethanolic extract	Beef burger	12 days	4 °C	0, 3, 6, 9, and 12 days
[100]	Peanut skin extract	1000 mg/Kg	Sheep patties under modified atmosphere (80% O_2 and 20% CO_2)	20 days	2 °C	0, 5, 10, 15, and 20 days
[43]	Peanut skin extract	1 and 2 mg/g	Mayonnaise sauce	6 months	25 °C	nd
[101]	Colombian berry (*Vaccinium meridionale sw.*) extracts	250, 500, and 750 mg/Kg	Pork patties	9 days	2 °C	nd
[82]	Sesame seed coat waste	200, 400, and 600 mg/kg	Refined olive oil	48 days	40 or 60 °C	0, 6, 12, 18, 24, 30, 36, 42, and 48 days
[71]	Olive mill wastewater (OMWW)	250 and 500 mg/kg	Pesto sauce	7 days after opening	4 °C	0, 1, 2, 3, 6, and 7 days
[102]	Wheat bran	0.01% and 0.02% (oil-in-water emulsion)	Minced-meat models	9 days	4 °C	nd
[103]	Potato peels	nd	Apple	3 days	4 °C	nd
[72]	Olive mill wastewater (OMWW)	3%	Pesto sauce	90 days	4 °C	nd
[83]	Pomace powder of musky squash	10, 15, 20, 25, and 30%	Foamy confectionery products	40 days	5 °C	0, 10, 20, 30, and 40 days
[104]	Lingonberry extract	0.1, 0.2, 0.3, and 0.4% dissolved in water (1:5 *v*/*v*)	Meat paste	14 days	nd	nd
[119]	Pomgranate peel extract	1.25, 2.5, and 3.75 mg/g	Home-made butter	15 days	nd	0, 3, 6, 9, 12, and 15 days
[25]	Bergamot pomace	2 and 4% added in vegetables oil of biscuits ingredients	Biscuits	nd	nd	nd
[35]	Sugarcane bagasse aqueous extract	125, 250, 500 ppm	Refrigerated fresh meat	10 days	4 °C	nd
[38]	Spent coffee ground	0.01%, 0.02%, and 0.03%	Refined sunflower oil	120 days	nd	2 or 3 weeks for 16 weeks.
[106]	Pistachio hull extract	0.156, 0.312, and 0.625%	Raw minced beef	14 days	4 °C	0, 3, 7, 10, and 14 days
[107]	Olive leaf extract	500 ppm	Frankfurter sausage	45 days	4 °C	1, 15, 30, and 45 days
[108]	Olive leaf extract	1-, 2-, and 3-mL extract	Minced beef	4 weeks	5 °C	0, 1, 2, 3, and 4 weeks

Table 3. *Cont.*

Reference	By-Product Sample	Natural Additive Amount	Enriched Food	Shelf Life Time	Shelf Life Temperature	Analysis Timing
[90]	Olive mill wastewater	100 ppm	Sunflowers and rapeseed oil	nd	60 °C	each week
[109]	Pomegranate peel extract	5%	Thornback ray sausage	15 days	4 °C	nd
[73]	Broccoli by-products	10%, 15%, and 20% *v*/*w*	Filled pasta	2 months	4 °C	nd
[105]	Date pits powder	1.5%, 3%, and 6%	Beef burgers	10 days	4 °C	0, 3, 6, and 10 days
[110]	Olive leaf extract	1000 mg/kg	Stracciatella cheese	8 days	4 °C	1 and every 4 days
[74]	Saffron tepal extracts	1%	Pacific white shrimp	9 days	4 °C	0, 3, 6, and 9 days
[20]	Avocado by-products	2000 ppm	Tambaqui fishburger	14 days	4 °C	
				90 days	18 °C	0, 3, 7, 14, 30, 60, and 90 days
[21]	Mango by-products	1% and 2%	Beef sausage	12 days	4 °C	every 4 days
[76]	Peanut skin extracts	0.01, 0.05, 0.1, 0.5, and 1%	Button mushrooms	nd	4 °C	nd
[22]	Potato peels	200 and 500 ppm	Rapeseed oil	21 days	nd	0, 9, 15, and 21 days
			Sunflower oil	9 days	nd	0, 3, 6, and, 9 days
[86]	Chestnut shell extract	1 and 2 g/L	Fresh cheese	2 weeks	4 °C	0, 1, 2, and 14 days
[111]	Pomegranate peels and seed	1%	Chicken patties	12 days	4 °C	nd
[112]	Pomegranate peel powder	2%, 4%, 6%, 8%, and 10% powder ingredients	Muffins	14 days	27–30 °C	nd
[88]	Grape pomace (seeds, skins, and stems)	0, 1, 2, 5, and 10% added extract	Beef patty	48 h	4 °C	2, 12, 24, and 48 h
[113]	Fruit (citrus, orange, apple, pear, peach, banana, kiwifruit), vegetables (tomato, potato, carrot) and oilseed (cottonseed, sunflower, soybean) by-products	nd	Protein flour and concentrate, fruit jelly	nd	nd	nd
[75]	Pomegranate peel extract	0.1%; pomegranate extract 0.1% + lactic acid 0.1%	Khalal barhi date fruits	6 weeks	4 °C	0, 1, 2, 3, 4, 5, and 6 weeks
[112]	Pomegranate peel powder	8%	Muffins	14 days	27–30 °C	nd
[114]	Kinnow rind, pomegranate rind, and seed powders	0.1 g/mL	Cooked goat meat patties	12 days	4 °C	0, 3, 6, 9, and 12 days

Table 3. *Cont.*

Reference	By-Product Sample	Natural Additive Amount	Enriched Food	Shelf Life Time	Shelf Life Temperature	Analysis Timing
[23]	Pomegranate peel extract	100 ppm	Bluefish fillet	9 days	4 °C	0, 3, 6, and 9 days

* nd = not defined.

5.4. Analytical Techniques for Food Shelf Life Monitoring

To effectively monitor the shelf life of foods treated with natural extracts, different analytical methods are employed to evaluate how these compounds impact quality, safety, and sensory properties over time. Table 4 summarizes the key parameters and properties assessed, including chemical, physical, and microbiological aspects, to provide a comprehensive view of natural extracts' influence on food preservation. These analyses are aimed at determining the potential of natural extracts to extend shelf life while maintaining the sensory and nutritional qualities of treated foods, a primary objective in the search for natural alternatives to synthetic additives [1,8,26]. This is particularly relevant as consumer demand continues to shift towards more natural, sustainable food options. Shelf-life studies focus on parameters essential for understanding food quality and safety, such as lipid oxidation, chemical and nutritional stability, and microbiological safety, all of which are critical for perishable foods that tend to deteriorate quickly during storage and distribution. Foods like meat, dairy products, sauces, fruits, vegetables, and baked goods are especially susceptible to rapid spoilage and benefit significantly from treatments with natural extracts [13,100,120,121].

One of the most important analyses in shelf-life studies for foods rich in fats, such as meat and dairy, is *lipid oxidation measurement*. Lipid oxidation is a major cause of food spoilage, resulting in rancidity, off-flavors, and nutritional degradation, which can significantly reduce the product's appeal. Analytical techniques for monitoring lipid oxidation include peroxide value measurements and conjugated diene and triene (K_{232} and K_{270}) tests, which monitor the formation of primary and secondary oxidation products. These measurements are crucial to determine whether natural antioxidants in extracts can effectively prevent rancidity and preserve freshness. For example, studies by Sagdic et (2011) al. and Balzan et al. (2017) utilized these tests to highlight that pomegranate peel extract significantly reduced lipid oxidation in meat products, which helped maintain quality and freshness over extended storage periods [67,88].

In addition to oxidation monitoring, *chemical and nutritional stability analyses* are useful for evaluating how natural extracts affect the fundamental composition of treated foods. By analyzing key nutrients such as protein, fat, fiber, and micronutrients, researchers can determine whether the food's nutritional profile is maintained throughout storage. For instance, studies involving sesame seed and rice bran extracts, used, respectively, in dairy products and emulsified foods, indicate that these extracts help stabilize lipids without negatively impacting the nutrient content. This stability is important for foods where nutrient degradation would otherwise be accelerated, allowing these products to retain their quality and value during extended storage [32,63,72].

Table 4. Analysis of food shelf life after adding natural by-products compound.

Ref.	Lipid Oxidation									Physical Parameters						Chemical and Nutritional Composition								Antioxidant			SA	MA
	OR	PI	FFAs	K_{232}	K_{270}	CO	TA	V	M	pH	C	T	TSS	F	A_w	MCA	Fi	P	Fa	CHO	S	PP	AA	TPC	TFC		
[32]																											×
[93]		×																									×
[69]	×																										
[33]	×																										
[84]	×									×	×												×				
[94]	×																									×	
[95]							×				×		×	×													×
[96]	×								×	×					×												
[88]																											×
[67]		×				×			×	×								×	×		×	×				×	
[63]										×													×	×		×	×
[85]	×	×								×	×																×
[97]									×	×					×	×	×	×	×					×			×
[34]											×	×											×	×		×	×
[80]	×	×					×			×	×				×												
[98]		×								×	×																×
[81]	×									×	×																×
[89]	×										×																
[95]							×			×			×	×												×	×
[70]	×										×												×			×	
[99]																											×
[62]	×									×	×	×															×
[100]	×		×							×	×																×
[43]								×	×	×	×				×											×	
[101]	×									×	×															×	
[82]	×	×	×	×																			×				
[71]		×	×							×	×											×	×			×	
[102]	×	×									×																
[103]											×			×													
[72]									×	×	×				×							×	×	×		×	
[83]										×	×	×			×											×	×
[104]																										×	×

Table 4. *Cont.*

Ref.	Lipid Oxidation								Physical Parameters							Chemical and Nutritional Composition							Antioxidant			SA	MA
	OR	PI	FFAs	K_{232}	K_{270}	CO	TA	V	M	pH	C	T	TSS	F	A_w	MCA	Fi	P	Fa	CHO	S	PP	AA	TPC	TFC		
[105]																										×	×
[25]	×	×					×		×	×	×	×			×								×	×	×		
[35]																										×	×
[38]		×	×	×	×																					×	
[106]	×	×	×																							×	×
[107]	×									×	×	×			×		×							×		×	×
[90]	×									×	×																×
[109]		×	×		×		×																				
[73]	×	×							×	×	×				×	×			×	×	×						×
[105]																								×		×	×
[110]	×									×	×													×		×	×
[74]							×			×	×												×			×	×
[20]	×																										
[21]																×		×	×	×							×
[76]	×									×	×															×	×
[22]																											
[86]		×	×																								
[111]										×														×		×	
[112]	×									×																	
[88]								×			×	×					×	×	×							×	
[113]																											×
[75]																											
[114]																											
[23]								×																			
[32]	×									×	×												×	×		×	
[69]	×		×								×																

OR: Oxidative Rancidity by TBARS method; PI: Peroxidatio Index; FFAs: Free Fatty Acids; CO: Cholesterol Oxidation; TA: Total Acidity; V: Viscosity; M: Moisture; C: Color; T: Texture; TSS: Total Soluble Solid; F: Firmness; A_w: Activity of Water; MCA: Mineral Contents and ashes; Fi: Fibers; P: protein; Fa: Fat; CHO: Carbohydrates; S: Salt; AA: Antioxidant Activity by ABTS, DPPH, FRAP, ORAC or TEAC; SA: Sensory Analysis; MA: Microbiological Analysis. "×" referred to the selected analysis investigated in the paper.

Another crucial area of shelf-life analysis is *color and texture assessment*, especially for products like fresh fruits, vegetables, and meat, where appearance plays a significant role in consumer acceptance. Colorimetric analyses help track changes in pigmentation, which are often associated with oxidation or enzymatic browning, particularly in fresh-cut fruits like apples and bananas. A study by de O Silva et al. (2020) demonstrated that pomegranate extract effectively preserved the color of sliced apples by preventing browning, thus maintaining the fruit's visual appeal. Texture assessments, which include measurements of firmness and consistency, are also important for products such as sauces, dairy, and fresh produce [23]. These analyses confirm whether the structural integrity and desirable physical properties of treated foods are retained over time, even under extended storage conditions. Monitoring pH and acidity is also crucial, particularly for dairy products, sauces, and fruit-based foods. pH stability is essential as it can influence both microbial growth and enzymatic reactions, affecting the overall shelf life and safety of the food. Natural extracts with acidic properties, such as those derived from citrus peels, help maintain a lower pH level, which is known to inhibit microbial growth. Gattuso et al. (2004) showed that lemon peel extracts effectively stabilized the pH in strawberries, reducing microbial growth and spoilage. Thus, pH analysis serves as a valuable indicator of the effectiveness of natural extracts in managing spoilage in fruit and vegetable products [25].

Microbiological analysis is fundamental in assessing the safety of perishable foods such as fresh produce, meat, and dairy, which are prone to contamination by bacteria and fungi. Microbial load tests are conducted to evaluate the antimicrobial efficacy of natural extracts by measuring the counts of bacteria, yeasts, and molds over time. For example, extracts from sesame seeds and citrus peels have been shown to limit microbial growth in milk and strawberries, respectively, helping to extend the safety and shelf life of these products. Such microbiological assessments are essential for verifying that natural extracts can effectively reduce pathogen levels and spoilage organisms, contributing to safer food products for consumers [95,102].

Lastly, *sensory analysis* is an important component, although it is not always highlighted in tabular summaries of shelf-life studies. Sensory evaluations assess attributes such as taste, aroma, and overall consumer acceptability. This is particularly important because certain natural extracts, especially those rich in polyphenols, can introduce flavors that are bitter or astringent if used in high concentrations. Studies by Martínez et al. (2019) indicate that sensory analysis is necessary to determine optimal dosages that achieve preservation goals without compromising the flavor or appeal of the food. Balancing preservation with sensory quality ensures that foods treated with natural extracts remain desirable to consumers [53]. Together, these analytical methods allow researchers to gain a comprehensive understanding of how natural extracts function as preservatives in different types of foods. Each type of food presents unique challenges; for instance, meat products are particularly susceptible to lipid oxidation and microbial growth, while fresh fruits and vegetables are more prone to enzymatic browning and texture changes. By monitoring parameters such as oxidation, nutrient stability, color, texture, pH, and microbial activity, shelf-life studies validate the preservative effects of natural extracts. These studies also contribute to the development of natural, safe alternatives to synthetic preservatives, aligning with consumer demands for minimally processed, and sustainable foods [71].

6. Discussions

The use of natural chemical compounds and extracts from food by-products represents a possible strategy for by-product recovery and valorization that could contribute to mitigating potential environmental, economic, and social impacts associated with the food production chain. In these regards, this literature review highlighted some critical issues,

limitations, and gaps. In particular, the absence of regulations regarding extracts used as natural food additives and their quantities is a crucial factor to be given importance. The lack of consistency in measuring units and concentrations limits the possibility of direct comparisons between results and complex the conversion of data into practical applications. Dos Santos et al. (2021) suggest that standardization of measurement units and treatment conditions could facilitate comparison between studies and industry-wide implementation of the results [39].

Furthermore, regarding the chemical composition of natural extracts used for food preservation, the absence or incomplete chemical characterization of bioactive components is emphasized. This represents a major gap to be filled since, in some cases, such as the addition of olive mill wastewater, the addition of these chemical compounds for food preservation is not regulated and/or not admitted. In this regard, there is, for some food classes such as vegetable fats, olive oil, and butter, Regulation (EU) No. 1129/2011 (amending Annex II to Regulation (EC) No 1333/2008) establishing a Union list of food additives, prevents the addition of substances for its preservation; in this regard, it highlights the need to strengthen the regulations as well as controls for monitoring food quality and safety along the entire food production chains [10].

Concerning the additives' concentration addition, a dose defined as *"Quantum Satis"* (i.e., up to *"just enough"*) is often considered, but there is effectively a lack of regulation for the actual amounts to be added about the use of natural extracts for food preservation. In the literature, relevant studies have predominantly involved the addition of polyphenols [70]. In this regard, it is noteworthy to mention that an excessive amount of these compounds in foods can exert negative activity due to the presence of chelating compounds for some micronutrients, but at the same time induce accelerated organoleptic alteration of taste, aroma, and flavor of foods [122]. The mechanism of action for antioxidants, whether natural or synthetic, remains consistent and includes processes such as free radical scavenging, metal chelation, and singlet oxygen quenching. Some antioxidants, known as secondary antioxidants, do not directly neutralize free radicals but instead act indirectly by slowing the oxidation process. They achieve this by chelating prooxidant metals, returning hydrogen to primary antioxidants, absorbing ultraviolet light, or acting as singlet oxygen quenchers. Notable examples of secondary antioxidants that function as chelating agents in foods include ascorbic acid (vitamin C), ascorbyl palmitate, erythorbic acid (a stereoisomer of vitamin C), and sulfites [56].

Furthermore, the absence of regulated amounts may have negative effects on consumer health, concerning the bioaccumulation effect or sum effect of these compounds, which does not exclude undesirable effects of the extracts [123], even though they resulted from natural synthesis. From this perspective, the non-homogeneity in the concentration of bioactive molecules added to food is highlighted, as well as a need to strengthen the regulations concerning the amount of bioactive compounds (e.g., polyphenols) added to food. Depending on this, however, it should be pointed out that *Reg. (EU) 2017/2470 on novel foods* sets maximum limits for the addition of different compounds, also defining a limit of maximum daily consumption of polyphenolic substances between 300 and 600 mg/day [124].

An additional issue that emerged from the review is the lack of studies on the detailed mechanisms of action of the extracts used (e.g., microbial inhibition and prevention of oxidation), as well as their interaction. Understanding these mechanisms, which are closely related to the chemical composition of the extracts, is essential to understanding the way the extracts act in food matrix. Naterra et al. (2018) described how the molecular structure of polyphenols can influence antimicrobial efficacy by interacting with pathogenic cell membranes. Including this information would enrich the evaluation of the efficacy

of extracts for specific food applications and food matrices [83]. For example, phenolic extracts have been shown to extend the shelf life of meats by reducing microbial growth and slowing lipid oxidation, phenomena that are particularly relevant in animal proteins, as highlighted in [98]. The use of agri-food by-products as food preservatives also represents a significant environmental opportunity, contributing to waste reduction and fostering a circular economy model. The use of extracts obtained from plant and fruit wastes responds to the growing consumer demand for natural additives and can reduce dependence on synthetic additives, as highlighted in [30].

Moreover, the comparison between natural additives and synthetic additives or traditional processing techniques is crucial to fully assess their viability in large-scale food production. Natural additives often offer advantages in terms of consumer acceptance and alignment with trends favoring health and sustainability. However, challenges such as cost, scalability, and efficacy compared to synthetic counterparts must be addressed to facilitate broader industry adoption. One of the primary challenges in adopting natural additives is their higher production cost compared to synthetic counterparts. This is largely due to the complex processes involved in their extraction, purification, and stabilization. For example, advanced techniques like supercritical fluid extraction, often required for polyphenolic extracts, are resource-intensive and contribute to their higher price. This financial barrier contrasts sharply with the cost-efficiency of synthetic additive manufacturing, which benefits from mature and streamlined industrial processes. Additionally, natural extracts often exhibit variability in composition due to factors like plant species, growing conditions, and extraction methods, further complicating standardization and increasing production costs. Conversely, synthetic additives benefit from well-established manufacturing processes and regulatory frameworks, allowing for more consistent quality and lower production costs. However, they face increasing consumer scrutiny regarding potential health risks and environmental impacts. This has driven interest in integrating natural additives despite their challenges.

Taking into account the large-scale production, natural additives must demonstrate not only effectiveness in food preservation but also compatibility with industrial food processing technologies. For example, phenolic compounds from agri-food by-products have shown promise in extending the shelf life of meat products through microbial inhibition and lipid oxidation-reduction. Nevertheless, ensuring their quality and maintaining stability under processing conditions, such as high temperatures or pH fluctuations, remain critical hurdles.

Otherwise, to verify the functionality and efficacy of natural extracts used as food adjuvants, shelf-life analyses often consider only a few parameters and do not examine microbiological or sensory aspects, which are key aspects in defining the food quality. Therefore, further studies should be carried out to better investigate this aspect.

7. Conclusions and Future Perspectives

This literature review highlights the significant potential of natural compounds derived from agro-industrial by-products in enhancing food preservation processes, to promote the valorization of by-products in a circular economy perspective. These bioactive components, mostly polyphenols, flavonoids, and essential oils, offer promising antioxidant and antimicrobial properties that can effectively extend the shelf life of food while maintaining safety and quality. In these regards, the possibility of using natural extracts from food by-products also aligns with sustainable and circular economy principles, reducing waste and reinforcing the overall environmental benefits, for food preservation that prioritizes both consumer well-being and ecological responsibility.

Despite its advantages, the use of natural extracts has some gaps and limitations. Some extracts are not compatible with all types of food: grape seed extract, for example, can be bitter at high doses, limiting its applicability to stronger-flavored products. Furthermore, although some extracts extend shelf life up to 120 days, long-term stability is not guaranteed; in some cases, the natural compound itself may degrade over time, especially under high-temperature conditions. Compared with synthetic additives, natural extracts tend to be less effective under extreme conditions, limiting their application in some industrial settings. Finally, there is also an economic aspect to consider: high-quality extracts may be expensive, and their availability may vary depending on seasonality and the source of the by-products.

However, for practical application and wider industry adoption, some challenges need to be addressed. The variability of extraction methods, regulatory gaps in dosing and standardization, and potential sensory impacts should be thoroughly investigated. Further research should focus on optimizing extraction techniques, understanding the mechanisms of action within different food matrices, and developing comprehensive guidelines to ensure consistent and effective use of these natural compounds. In detail, future research should prioritize the following:

- Advanced Extraction Technologies, through the development and optimization of green extraction methods, such as supercritical fluid extraction and natural deep eutectic solvents (NADES), can enhance the yield and purity of bioactive compounds from food by-products.
- Standardization and Regulation, by establishing clear regulatory frameworks that define acceptable limits and standardized testing protocols is critical. This would facilitate the consistent use of natural additives across different food products while ensuring safety and efficacy. Harmonized guidelines at both national and international levels would aid in their widespread adoption.
- Biochemical interaction studies: Focusing on the interaction of these compounds within various food matrices, can help identify the most effective combinations and concentrations for specific applications.
- Consumer Acceptance: By promoting natural additives aligned with the growing consumer preference for clean-label products, public education campaigns can bolster confidence in their safety and effectiveness. Engaging consumers through transparent communication about the benefits of these additives can strengthen their acceptance and preference for naturally preserved foods.
- Economic and Environmental Impact, by expanding research into the economic viability of large-scale production of natural additives from by-products, is essential. This includes assessing the cost–benefit balance and environmental impact to reinforce the value of these practices in supporting a circular economy. Such studies could also explore the potential for partnerships between the food industry and agricultural sectors to establish a sustainable supply chain for by-products.
- Multifunctional Applications to explore the multifunctional roles of natural additives, such as their potential health benefits and role as nutraceuticals. This would open new avenues for developing value-added food products that cater to health-conscious consumers.

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