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Natural antioxidants recovered from food by-products as inhibitors of lipid oxidation

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KEY CONTRIBUTION
Lipid oxidation deteriorates food quality by reducing nutritional value, causing off-flavour, and shortening shelf life, posing a major challenge to the food industry. Natural antioxidants from food by-products, rich in polyphenols, flavonoids, carotenoids, and tocopherols, effectively inhibit lipid oxidation and improve food stability in oils, meats, and dairy products. Overcoming challenges like cost-effective extraction methods is crucial for utilizing natural antioxidants in sustainable food systems and industrial applications.

ABSTRACT

Lipid oxidation is a major factor in food quality deterioration, leading to reduced nutritional value, off-flavours, and shorter shelf life, and is one of the major challenges facing the food industry worldwide. The production and use of natural antioxidants recovered from food by-products that have a high ability to inhibit lipid oxidation could have profound effects on improving food quality. These by-products, which are rich in bioactive compounds such as polyphenols, flavonoids, carotenoids, and tocopherols, play an important role in scavenging free radicals, chelating metal ions, and delaying the formation of peroxides. This review explores the potential of natural antioxidants derived from fruit peels, vegetable pomace, cereal bran, dairy by-products, and seafood residues in enhancing oxidative stability in various food systems, including oils, meats, and dairy products, and provides a comprehensive understanding of the potential of antioxidants recovered from food by-products in preventing lipid oxidation. However, there are serious obstacles, such as improving budget-friendly extraction techniques for the production and use of natural antioxidants extracted from lipid oxidation inhibitor by-products. Future research tackling these difficulties could open up suitable ways to utilize the complete capacity of natural antioxidants in industrial utilizations and sustainable food systems.

Introduction

Background on lipid oxidation

Lipids, one of the primary components in food, are categorized in three groups: simple lipids (triglycerides, steryl esters, and wax esters), compound lipids (phospholipids, glycolipids, sphingolipids, and lipoproteins), and derived lipids (fatty acids, fat-soluble vitamins and provitamins, sterols, terpenoids, and ethers). In the process called lipid oxidation, lipids undergo chemical oxidation, reacting with oxygen, which subsequently leads to physicochemical alterations in the quality and safety of foods (Domínguez et al., 2019). Lipid oxidation is carried out in three major mechanisms: autoxidation, photooxidation, and enzymatic oxidation. In autoxidation, free radicals generated from lipid molecules react with oxygen to form peroxyl radicals (Rontani and Belt, 2020). Photooxidation occurs due to ultraviolet radiation and causes the production of free radicals, while oxidation is triggered by enzyme function (Abeyrathne et al., 2021). The impact of lipid oxidation on food is significant, resulting in rancidity and undesirable flavours, and reducing food quality by destroying essential fatty acids and vitamins (Medina-Vera et al., 2021).

Mechanisms of lipid oxidation

Lipid oxidation typically takes place in three phases: initiation, propagation, and termination. In the initiation stage, reactive species such as hydroxyl radicals attack fatty acids to remove hydrogen atoms and generate lipid radicals (Laguerre et al., 2020). In the propagation stage, lipid radicals react with molecular oxygen to form lipid peroxy radicals, which can remove hydrogen from adjacent lipid molecules and continue the chain reaction to form hydroperoxides. Finally, in the termination stage, antioxidants or additional stabilizing agents provide hydrogen atoms to lipid peroxy radicals, converting them into stable nonradical products, successfully terminating the oxidative chain reaction. Key reactive species involved in lipid oxidation include reactive oxygen species and various free radicals, which promote these reactions and ultimately cause lipid degradation and off-flavouring in food products (Amaral et al., 2018) (Figure 1).

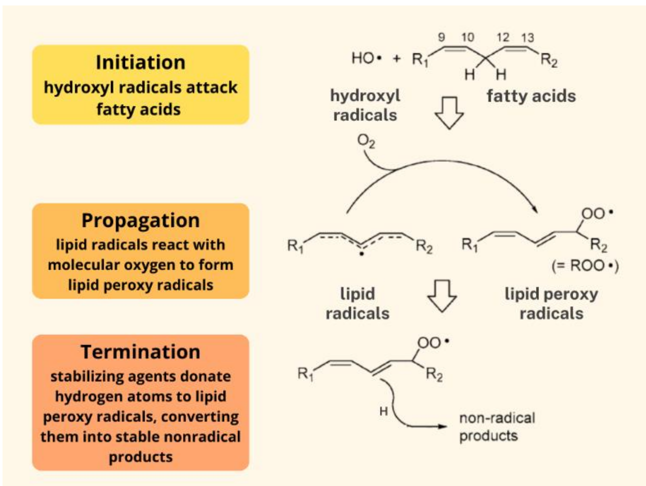

Figure 1. Mechanism of lipid oxidation.

Health and economic impacts of lipid oxidation in foods

The consumption of oxidized lipids due to the formation of advanced lipid oxidation end products poses serious risks to human health because it can cause serious complications at the cellular and molecular levels due to cytotoxic and genotoxic effects (Huang and Ahn, 2019). These compounds can lead to the stimulation of inflammatory responses and the development of cardiovascular diseases and cancer (Zeng et al., 2024). In addition, lipid oxidation has significant detrimental effects on the food industry and can lead to spoilage of food products and significant financial losses due to reduced shelf life and reduced food quality (Peña-Bautista et al., 2019). The presence of sourness or undesirable taste certainly has negative effects on consumer acceptance and marketability of food products. Therefore, today, controlling lipid oxidation to maintain food quality and safety standards and reducing food waste is one of the most important concerns of the food industry.

Food by-products as sources of natural antioxidants

Common food by-products rich in antioxidants

Food by-products, including fruit and vegetable peels, seeds, pulp, cereal bran, husks, dairy products, seafood by-products, and spice and herb residues, have gained attention as potential sources of natural antioxidants due to their rich bioactive compound content. Polyphenolic compounds and flavonoids are among the most important substances with high antioxidant properties and are present in the peels of many fruits, bran, and cereal husks (Tinello and Lante, 2018). In addition, spice and herbal residues such as turmeric and oregano have attracted attention because of the presence of bioactive compounds due to their high antioxidant capacity.

Fruit and vegetable peels, seeds, and pomace

The utilization of fruit and vegetable peels, seeds, and pomace as sources of natural antioxidants has gained significant attention in recent years. In a study, the antioxidant capacity of ethylacetate, butanol, and water fractions of peel, pulp, and seeds of *Canarium odontophyllum* Miq. were determined using various *in vitro* antioxidant models. The findings highlighted the potential of different parts of the fruit as rich sources of antioxidants (Prasad et al., 2010). In a subsequent study, the carotenoids and antioxidant capacities of the same fruit were investigated, and the results revealed the importance of these compounds in promoting health and preventing diseases (Prasad et al., 2011). The soluble and insoluble-bound phenolics and antioxidant activity of various industrial plant wastes including apple peel, apple pomace, pomegranate peel, pomegranate seed, and black carrot pomace were studied, and the findings showed that not only soluble but also insoluble-bound fraction of the industrial wastes has good potential for valorization as a source of natural antioxidants (Gulsunoglu et al., 2019). Although grape pomace, consisting of peel, seed, stem, and pulp, is discarded during grape processing, including juice extraction and winemaking, it has a substantial antioxidant content. Additionally, the potential health benefits of phenolic compounds in grape processing by-products have been reported due to their antioxidant capacity (Averilla et al., 2019). It has been shown that avocado by-products in the form of peel, seed coat, and seeds are currently of no commercial use, while they constitute a natural source of bioactive compounds. An investigation on neuroprotective effects of a methanolic extract of avocado peel demonstrates its antioxidant properties in protection against oxidative stress and movement impairment (Ortega-Arellano et al., 2019). Juçara fruit pomace is one of the most abundant byproducts of the pulp-making process, generally discarded despite its attractive nutritional content. Research focusing on the valorization of juçara fruit pomace and seeds highlights the potential of fruit pomace and seeds as alternative sources of valuable compounds with high antioxidant capacity (Carpiné et al., 2020). Pumpkin as a vegetable crop was reported to be abundant with carotenoid compounds, lutein, and zeaxanthin with high antioxidant capacity. Research has found that among all pumpkin fruit parts (peel, flesh and seed), pumpkin peel had the highest antioxidant activity (Wen and Ahmad, 2020). Furthermore, extracts of melon fruit, mainly from the peel, have been shown to possess phytochemical compounds that exhibit antioxidant effects in various in vitro and in vivo tests (Gomez-Garcia et al., 2020). In a recent review study, it has been highlighted that tomato pomace is a source of valuable functional ingredients with high antioxidant properties for improving physicochemical and sensory properties and extending the shelf life of foods (Chabi et al., 2024). Additionally, studies highlight 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 demonstrate strong antioxidant properties, prolonging the shelf life of food products and improving their safety and quality (Ebrahimi and Lante, 2021; Maddaloni et al., 2025). Overall, these studies collectively underscore the importance of fruit and vegetable peels, seeds, and pomace as valuable sources of natural antioxidants.

Cereal brans and husks

Studies concerned with measuring the cereal bran and husk antioxidant capacity reveal their potential as a valuable source of natural antioxidants. The findings of a study on optimizing the enzymatic extraction of ferulic acid from wheat bran highlight the potential of cereal brans as a rich and sustainable source of natural antioxidants (Barberousse et al., 2009). The antioxidant potential of soft wheat and oat bran was investigated emphasizing the importance of bioactive compounds with high potential antioxidant capacity in these cereal sources (Vijayalaxmi et al., 2015). Additionally, the results from the evaluation of phenolic compounds and the antioxidant capacity of oats further showcase the antioxidant properties of cereal bran (Meziani et al., 2020). It has been shown that agricultural residues like sugarcane bagasse, corn husk, peanut husk, coffee cherry husk, rice bran, and wheat bran are low-value byproducts of agriculture. The extraction of polyphenols from these agricultural residues highlights their potential as a valuable source of natural antioxidants suitable for the use in dietary supplements and food additives (Rao and Zheng, 2025). The antioxidant activity of an adlay extract was explored with different solvents, highlighting the importance of selecting the appropriate extraction method to maximize antioxidant potential (Tensiska et al., 2020). Furthermore, a study investigated the composition of total polyphenols, flavonoids and the evaluation of the antioxidant power present in whole prevision oats, whole black oats, and prevision oat bran and black oat bran. The findings revealed that black wheat bran is a promising source of food fibres with expanded functionalities and antioxidant capacity, indicating the diverse nutritional benefits of cereal brans (Meziani et al., 2021). Investigation on the use of rice bran oil to improve the stability of flaxseed oil emphasizes the potential of utilizing cereal by-products for enhancing the nutritional value of food products (Waseif et al., 2022). It has been highlighted that *Zea mays* is one of the main cereal crops in the world, and its by-products have exhibited medicinal properties to explore. Chemical compositions and pharmacological activities of by-products of *Z. mays* (corn silks, roots, bracts, stems, bran, and leaves) support their antioxidant potential (Zhang et al., 2023). A recent review study has highlighted that the green husk and shell, by-products of macadamia fruit generated during nut kernel processing, are rich in phenolic compounds, which exhibit significant antioxidant properties (Ahmed et al., 2024). Overall, the reviewed studies collectively demonstrate that cereal brans and husks, such as those from wheat, oats, rice, corn, and even macadamia, are valuable sources of natural antioxidants, largely due to their rich content of polyphenols, flavonoids, and ferulic acid. Various extraction methods, including enzymatic and solvent-based techniques, have been explored to maximize the yield of these compounds. Research also highlights the diverse applications of these by-products, from enhancing the nutritional profile of food products to serving as sustainable raw materials for dietary supplements.

Dairy and seafood by-products

The utilization of dairy by-products, such as skim milk, buttermilk, whey, and ghee residues, is crucial in the food industry. Various studies have explored the antioxidant properties of different dairy by-products and their potential applications in food products. Research findings indicate that whey, a dairy by-product of cheese or casein production, holds significant importance in the dairy industry due to the large volumes which are produced and its rich nutritional composition. Moreover, it has demonstrated the potential to function as an antioxidant (Anand et al., 2013). Seafood by-products, particularly peptides derived from processing waste, have been shown to possess significant antioxidant activity, helping to prevent lipid oxidation in seafood systems. These natural additives offer a safe and effective alternative to synthetic antioxidants, addressing concerns about their toxicity and carcinogenic effects (Nikoo and Benjakul, 2015). Studies show that marine by-products serve as a valuable source of antioxidant peptides, which can be generated through enzymatic hydrolysis and utilized as functional foods and nutraceuticals (Sila and Bougatef, 2016). Additionally, seafood by-products, such as tuna protein hydrolysates, exhibit antioxidant capacity. The presence of antioxidant peptides and high levels of polyunsaturated fatty acids highlights their potential for adding value to fishing industry waste through their antioxidant properties (Oliveira et al., 2017). The dairy by-products, such as scotta, have been reported to have antioxidant capacity. Protein-enriched fractions of scotta, digested with enzymes like Papain and Pancreatin, demonstrated enhanced antioxidant activity. In addition, sub-fractionation of digested proteins identified peptides with strong bioactivity, highlighting their potential as valuable sources of natural antioxidants (Monari et al., 2019). In a review study, the authors explored the use of bacterial exopolysaccharides for improving the technological and functional properties of yoghurt, indicating the potential of microbial by-products in enhancing the nutritional value of dairy products (Tiwari et al., 2021). The antioxidant activity of yoghurt acid whey from different milk origins before and after *in vitro* gastrointestinal digestion was investigated, highlighting the antioxidant potential of this by-product, particularly from ovine origin, in human and animal nutrition (Dalaka et al., 2023). In summary, dairy and seafood by-products may serve as unique sources of natural antioxidants with potential applications in enhancing the nutritional value and health benefits of food products.

Spices and herb residues

Spices and herb residues have become recognized as significant sources of natural antioxidants in recent years. It has been found that the herb of fennel, which is often considered both an herb and a spice, is a potential source of natural antioxidants (Ghanem et al., 2012). Similarly, antioxidant properties of *Zingiber officinale* (ginger), a commonly used spice, have been characterized for their medicinal purposes (Ghasemzadeh et al., 2016). In a study, thyme extract was identified as a natural antioxidant source suitable for bakery products, while rosemary extract was recommended to be used cautiously in fat-rich products exposed to high temperatures (Zawada et al., 2015). The antioxidant mechanism, chemistry, and food applications of rosemary (a woody, aromatic herb) extract were investigated, emphasizing its bioactive compounds with antioxidant capacity (Senanayake, 2018). Furthermore, the sustainable processing of floral bio-residues of saffron was studied, demonstrating the potential for obtaining valuable antioxidant phytochemicals through green extraction methods (Stelluti et al., 2021). In a study, piper chaba, a traditional Southeast Asian medicinal herb and well-known curry spice, was studied to evaluate its suitability as a source of natural preservatives for beef products. The findings revealed significant antioxidant activities and potential antibacterial activity of *P. chaba* extracts (Rahman et al., 2023). Recently, the bioactivity and antioxidant capacity of 34 edible herbs were evaluated. The findings showed that *Smilax glabra Roxb*, *Coreopsis tinctoria Nutt*. and *Smilax china* L. had the best bioactivity and antioxidant capacity (Xiong et al., 2025). In conclusion, spices and herb residues can serve as valuable sources of natural antioxidants with various health benefits, making them attractive options for food and medicinal applications.

Extraction and recovery techniques

Solvent-based extraction

Solvent-based extraction techniques are commonly used to isolate antioxidant compounds from food by-products, and they can be broadly categorized into solid-liquid extraction (SLE) and liquid-liquid extraction (LLE). Solid-liquid extraction (SLE) involves using of solvents to extract bioactive compounds from solid plant materials such as cereal brans, fruit pomace, or husks. Common solvents used in SLE include methanol, ethanol, and water. Ethanol iseffective in extracting phenolic compounds with strong antioxidant properties. Methanol is widely used due to its cost-effectiveness and its ability to extract a broader range of bioactive compounds. Water, as a green and environmentally friendly solvent, is primarily effective for extracting polar compounds (Carpentieri et al., 2021; Panzella et al., 2020). Liquid-liquid extraction (LLE), on the other hand, involves the separation of compounds based on their differential solubility in two immiscible liquids—typically an aqueous phase and an organic solvent. This method is particularly useful for refining or concentrating specific antioxidant compounds after initial extraction. For example, polyphenols from apple pomace and grape pomace have been successfully extracted and further purified using LLE techniques (Hammad et al., 2022). To reduce extraction time, increase extraction yield, and improve the quality of extracts, a number of novel techniques have been recently developed, including accelerated solvent extraction, supercritical fluid extraction, ultrasound-assisted extraction, and microwave-assisted extraction (Sawant et al., 2024) (Figure 2).

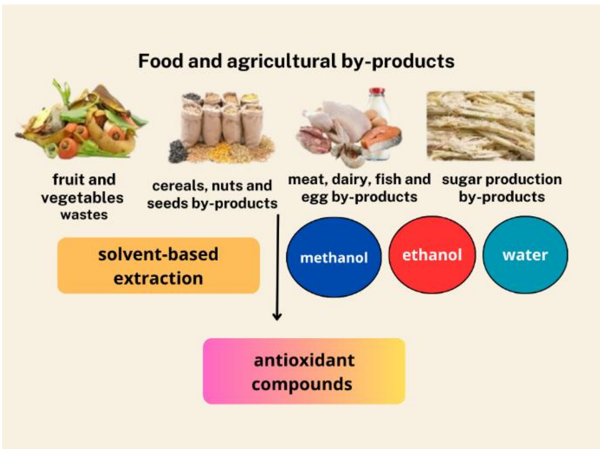

Figure 2. Solvent-based extraction techniques using solvents such as methanol, ethanol, and water are used to isolate antioxidant compounds.

Advanced methods

The use of advanced extraction methods significantly enhances the efficiency, selectivity, and yield of natural antioxidants from food by-products. Supercritical fluid extraction (SFE) is one method, which uses supercritical carbon dioxide as a solvent to extract antioxidant compounds while minimizing thermal degradation. This technique is especially effective for non-polar antioxidants such as carotenoids and tocopherols. When a co-solvent like ethanol is added, SFE also becomes effective for extracting polar compounds, such as phenolics, due to improved solubility and extraction efficiency (Herzyk et al., 2024). Ultrasound-assisted extraction (UAE) employs ultrasonic waves to disrupt plant cell walls, enhancing solvent penetration and mass transfer. This leads to higher extraction rates and yields in shorter durations. Studies have demonstrated that UAE significantly increases the flavonoid content extracted from citrus and other fruit by-products (Ferdosh et al., 2025; Gadi et al., 2024). Enzyme-assisted extraction utilizes specific enzymes such as cellulases, hemicellulases, and pectinases to hydrolyze plant cell wall components and release bound bioactive compounds. This method has shown high efficacy in extracting phenolic compounds and other antioxidants from complex plant matrices such as fruit pulps and cereal brans (Haase et al., 2024). Microwave-assisted extraction (MAE) is another innovative technique that uses microwave energy to heat the solvent and plant matrix rapidly, causing cell rupture and improved compound release. MAE is particularly beneficial for heat-stable antioxidants like polyphenols and flavonoids, and offers reduced solvent use and extraction time. Extraction under high pressure and temperature, such as pressurized liquid extraction or subcritical water extraction, involves using high-pressure conditions to maintain solvents in liquid form at elevated temperatures. These methods improve the extraction of both polar and non-polar antioxidants while maintaining compound stability. Collectively, these advanced methods offer eco-friendly and efficient alternatives to conventional extraction, with specific techniques that are selected based on the target antioxidant compounds and desired applications (Figure 3).

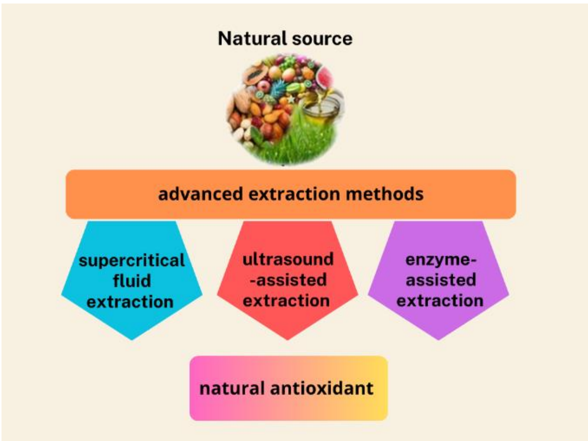

Figure 3. Advanced extraction methods used to increase the efficiency and yield of natural antioxidants.

Green extraction technologies

Green extraction technologies utilize environmentally friendly solvents, such as deep eutectic solvents and ionic liquids, to maximize antioxidant recovery while minimizing environmental impact. These solvents are often derived from renewable resources and can be specifically designed for targeted extractions. Advanced methods also tend to produce minimal hazardous waste, making them suitable for sustainable food and pharmaceutical applications. The shift from traditional solvent-based techniques to advanced and green technologies reflects a growing demand for more efficient, selective, and eco-conscious extraction processes (Lante et al., 2022; Morón-Ortiz et al., 2024; Shrivastav et al., 2024). In addition, fermentation-assisted extraction and the integration of multiple extraction technologies have been explored, demonstrating variable yields and antioxidant characteristics depending on the raw materials and processing parameters (Vilas-Franquesa et al., 2024).

Overview of the application of extraction and recovery techniques

The extraction and recovery of antioxidants from food by-products have gained significant attention in recent years. Various studies have focused on different agro-food by-products for the recovery of antioxidants and other bioactive compounds. In a study conducted under the European Project SusFoFlex, different agro-food by-products for the recovery of antioxidants and cellulose were screened. The study applied a common process for the production of antioxidant extracts and cellulose fractionation to select an ideal by-product for both applications. The results demonstrated that extraction and recovery techniques play a pivotal role in increasing the antioxidant activity of products (Vellingiri et al., 2014). To optimize a two-step enzymatic plus solvent-based process for the recovery of bioactive compounds from white grape pomace, the winemaking primary by-product, the antioxidant, anti-tyrosinase, and anti-inflammatory activities of white grape pomace extracts were obtained through a sequential enzymatic plus ethanol-based extraction method. The findings indicate a significant association between the recovery method and the antioxidant property of the by-product (Ferri et al., 2017). A study focused on the recovery of bioactive molecules from chestnut by-products using different solvents and assessed their potential antioxidant activity. It has been found that boiling water was the best extraction solvent for polyphenols from chestnut shells and burs (Vella et al., 2018). Furthermore, in a study conducted to optimize extraction parameters for maximum recovery of antioxidant properties from the banana peel, ultrasound-assisted extraction conditions were optimized for the recovery of phenolic compounds and antioxidant capacity from banana peel using response surface methodology (Vu et al., 2017). Enhanced recovery of antioxidant compounds from hazelnut involucre based on extraction optimization revealed that hazelnut involucre extracts have high antioxidant capacity (Rusu et al., 2019). Findings of a study on agro-food industries aiming to achieve more diversified and sustainable solutions towards their main by-products and a proper recovery method suggested acidified hot water extraction as a sustainable approach for the recovery of polyphenols from apple pomace (Fernandes et al., 2019). In a study, response surface methodology was used to optimize the heat-assisted aqueous extraction of phenolic compounds from coffee parchment. The findings provided valuable insights into the potential application of a useful, clean, environmentally friendly, and cost-effective method to recover phenolic compounds from coffee parchment and, thus, to revalorize the by-product by converting it into high-added value new products to be used in the food and cosmetic industries (Aguilera et al., 2019). Additionally, the most relevant extraction techniques used for the recovery of phenolic compounds from Brewers' spent grain (BSG), the main by-product derived from the brewing industry, were reviewed discussing their advantages and shortcomings and the potential applications from BSG bioactive extracts in the cosmetic industry and their reported beneficial effects (Macias-Garbett et al., 2021). In addition, it has been shown that microwave-assisted extraction is a useful method to recover and enhance the antioxidant compounds from Turkish hazelnut by-products using natural deep eutectic solvents (Bener et al., 2022). A review on the feasibility of cloud-point extraction (CPE), a method employed for the extraction and preconcentration of various chemical compounds, for bioactive compound recovery from food byproducts highlights the advantages of CPE, including effectiveness, simplicity, safety, and rapidity of the method (Chatzimitakos et al., 2023). Recent advances in bio-based extraction processes for the recovery of bound phenolic compounds (BPC) from agro-industrial by-products and their biological activity indicate the recent advances in green techniques for the recovery of BPC, focusing on enzymatic-assisted and fermentation-assisted extraction as well as in the combination of technologies, showing variable yield and features (Vilas-Franquesa et al., 2024). These studies collectively highlight the importance of extracting methods and recovery techniques for antioxidants from food by-products for various applications, including waste management.

Antioxidant activity of recovered compounds

Methods for evaluating antioxidant activity

Various *in vitro* assays are commonly used to assess the antioxidant activity of recovered compounds, including DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)), which measure the ability of antioxidants to neutralize free radicals (Kotha et al., 2022; Ebrahimi et al., 2024). Other methods for assessing antioxidant activity include the ferric reducing antioxidant power (FRAP) assay and the oxygen radical absorbance capacity assay, which assess the capacity of antioxidants to reduce ferric ions and inhibit peroxyl radical-induced oxidation, respectively (Figueroa et al., 2023). Various techniques have been developed to evaluate the effects of natural extracts and antioxidants in inhibiting lipid peroxidation. Studies show that natural products have a significant capacity to inhibit lipid peroxidation through various mechanisms, including direct neutralization of lipid peroxyl radicals (Ahmad et al., 2024). In addition, muscle-based food-simulating model systems, such as emulsions and liposomes, have been used to study lipid oxidation pathways and antioxidant efficacy (Wu et al., 2024). On the other hand, studies suggest that it is important to select appropriate measurement techniques for assessing lipid oxidation in foods, including spectroscopic and chromatographic methods, which help in the quantification of primary and secondary oxidation products (Mahrous et al., 2024). These advances will not only increase our understanding of lipid stability in food systems but also pave the way for the development of more effective natural preservatives (Figure 4).

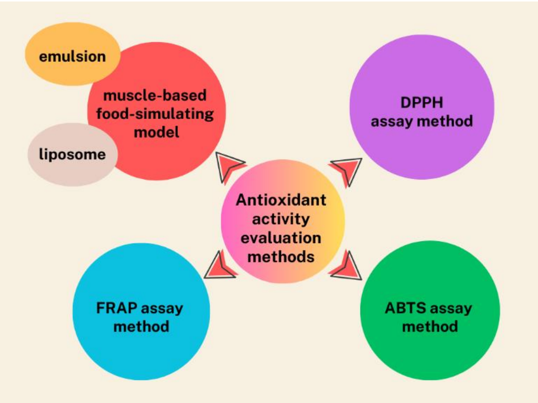

Figure 4. Methods for evaluating antioxidant activity. DPPH (2,2-diphenyl-1-picrylhydrazyl), ABTS (2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid), the ferric reducing antioxidant power (FRAP) assay methods, and muscle-based food-simulating model systems, such as emulsions and liposomes, are common methods used for evaluating antioxidant activity.

Efficacy of antioxidants in inhibiting lipid oxidation

Many studies have shown that antioxidants play a very effective role in inhibiting lipid oxidation. Researchers have discussed the potential therapeutic antioxidants that combine the radical scavenging ability of myricetin with the lipophilic chain of vitamin E to effectively inhibit microsomal lipid peroxidation (Bennett et al., 2004). In a study, active antioxidant peptides in potato protein hydrolysate were identified to inhibit autoxidation of soybean oil-in-water emulsions (Cheng et al., 2010). It was also shown that phenolic compounds such as tert-butylhydroquinone that act as antioxidants, and synthetic antioxidants such as butylhydroxy anisole and butylhydroxy toluene exhibit effective inhibitory effects against lipid oxidation (Seppanen et al., 2010). The potential anticancer properties of grape antioxidants were explored, emphasizing their ability to scavenge free radicals and inhibit lipid oxidation in various food and cell models (Zhou and Raffoul, 2012). The investigation on the antioxidant efficacy of unripe banana peel extracts in stabilizing sunflower oil has revealed that unripe banana peel extract may be used as a potential source of natural antioxidants in the application of the food industry to suppress lipid oxidation (Ling et al., 2015). Additionally, the *in vitro* and *in vivo* antioxidant capacity of chia protein hydrolysates and peptides was investigated, highlighting the importance of antioxidants in preventing lipid oxidation (Coelho et al., 2019). In research the efficacy of four natural antioxidants, quercetin, curcumin, rutin hydrate. And ascorbic acid, and their ability to combat lipid oxidation within different oil-in-water (O/W) emulsion environments was investigated, indicating the efficacy of four natural antioxidants against lipid oxidation (Noon et al., 2020). A comparative survey on the antioxidant potential of carotenoids extracted from Iranian shrimp waste and synthetic antioxidants butylated hydroxyanisole and butylated hydroxytoluene suggested that the natural antioxidants from shrimp waste could effectively inhibit oxidation, potentially replacing synthetic antioxidants (Saatloo et al., 2021). This aligns with the findings of a comparative study on natural chain-breaking antioxidants and their synthetic analogues, emphasizing the importance of understanding the structure-activity relationship in antioxidant activity against lipid oxidation (Kancheva et al., 2021). Lastly, a study on the anti-oxidative potential of ginger extract and its constituents on meat protein isolate under induced Fenton oxidation was carried out, demonstrating the effectiveness of ginger extract as an antioxidant in inhibiting lipid oxidation (Ivane et al., 2022). Acid-hydrolyzed phenolic extracts of sugar beet leaves in oil-in-water emulsions have been reported to exhibit significant antioxidant and prooxidant activity (Ebrahimi et al., 2024). Overall, the literature indicates a shift towards exploring natural antioxidants as effective inhibitors of lipid oxidation compared to synthetic counterparts. Understanding the interactions and structure-activity relationship of antioxidants is crucial in determining their efficacy in inhibiting oxidation in various lipid systems.

Applications of antioxidants in food systems

Effectiveness in preventing lipid oxidation in oils

Various studies have been conducted to evaluate the effectiveness of different antioxidants in inhibiting lipid oxidation in oils. An investigation of the antioxidant activity of α- and γ-tocopherols in bulk oils and oil-in-water emulsions reveals the effectiveness of α-tocopherol as an antioxidant or prooxidant depending on various factors such as concentration, oxidation time, and test system. This highlights the importance of understanding the specific conditions under which antioxidants can effectively prevent lipid oxidation (Huang et al., 1994). The antioxidative effect of thyme ethanol extract on sunflower oil during storage was evaluated to demonstrate the inhibitory effects of antioxidants on lipid oxidation in food products. The findings emphasize the practical application of antioxidants in food processing and storage to maintain product quality (Zaborowska et al., 2012). It has also been shown that an antioxidant active packaging effectively prevents lipid oxidation in oils, a major cause of spoilage that compromises both sensory and nutritional quality and can produce toxic aldehydes (Gómez-Estaca et al., 2014). Additionally, the findings of a study showed that natural antioxidants in Jussara berry oil-in-water emulsions prevent or delay the oxidation of oil. The study highlighted the potential of minor compounds in Jussara berry oil to enhance the oxidative stability of oil-in-water emulsions. This suggests that natural antioxidants derived from fruits can be effective in preventing lipid oxidation in oils (Carvalho et al., 2019). A study highlighted the use of synthetic and natural antioxidants in the edible oils industry to enhance oxidative stability. It reviewed the effectiveness of widely studied antioxidants like tocopherols, carotenoids, ascorbic acid, lignans, flavonoids, and polyphenols, emphasizing their synergistic and antagonistic combinations in preventing lipid oxidation (Mishra et al., 2021). A review study highlights that lipid oxidation is a critical factor in the edible oils production chain, however, antioxidants from natural sources are preferable for use in frying as well as cooking in general, as an efficient option to inhibit lipid oxidation (Viana da Silva et al., 2022). Efforts to minimize lipid oxidation in edible oils have emphasized the effectiveness of antioxidants, particularly in oil-in-water emulsions, where the interfacial region adds complexity. Kinetic approaches, including pseudophase models, have been used to study antioxidant partitioning and inhibition reactions, offering insights into their efficiency. These methods help design novel antioxidants with tailored properties and optimize environmental conditions to enhance their effectiveness in preventing lipid oxidation (Bravo-Díaz, 2023). In addition, research findings show that natural antioxidants derived from fruits and vegetable waste effectively prevent lipid oxidation in edible oils by scavenging free radicals, chelating metal ions, and delaying the formation of peroxides. These natural alternatives enhance oxidative stability, offering a safer and more sustainable solution compared to synthetic antioxidants (Zahid et al., 2024). Table 1 provides an overview of studies on antioxidants and their role in preventing lipid oxidation in oils.

Table 1. Overview of studies on antioxidants in lipid oxidation prevention.

Study/Research	Key Findings	Reference
Antioxidant activity of α- and γ-tocopherols in bulk oils and oil-in-water emulsions	The effectiveness of α-tocopherol as an antioxidant or prooxidant depends on factors like concentration, oxidation time, and test system. Highlights the importance of understanding specific conditions for effective prevention of lipid oxidation.	Huang et al. (1994)
Thyme ethanol extract on sunflower oil during storage	Demonstrates the inhibitory effects of antioxidants on lipid oxidation in food products. Emphasizes practical applications in food processing and storage to maintain product quality.	Zaborowska et al. (2012)
Antioxidant active packaging in oils	Effectively prevents lipid oxidation in oils, reducing spoilage and preserving sensory and nutritional quality while preventing toxic aldehyde formation.	Gómez-Estaca et al. (2014)
Natural antioxidants in Jussara berry oil-in-water emulsions	Prevents or delays the oxidation of oil and highlights the potential of minor compounds in Jussara berry oil to enhance oxidative stability. Suggests that natural antioxidants from fruits are effective in preventing lipid oxidation in oils.	Carvalho et al. (2019)
Synthetic and natural antioxidants in edible oils	Reviews the effectiveness of antioxidants like tocopherols, carotenoids, ascorbic acid, lignans, flavonoids, and polyphenols. Highlights synergistic and antagonistic combinations to prevent lipid oxidation.	Viana da Silva et al. (2022)
Use of natural antioxidants in edible oils production	Highlights that lipid oxidation is a critical factor in edible oils production. Prefers antioxidants from natural sources for frying and cooking, offering an efficient option to inhibit lipid oxidation.	Mishra et al. (2021)
Kinetic approaches to study antioxidant partitioning and inhibition reactions	Pseudophase models and other kinetic approaches are used to study antioxidant efficiency, offering insights for designing novel antioxidants with tailored properties and optimizing environmental conditions to prevent lipid oxidation.	Bravo-Díaz (2023)
Natural antioxidants derived from fruit and vegetable waste	Effectively prevent lipid oxidation by scavenging free radicals, chelating metal ions, and delaying peroxide formation. Provides a safer and sustainable alternative to synthetic antioxidants while enhancing oxidative stability.	Zahid et al. (2024)

Effectiveness in preventing lipid oxidation in meats

Lipid oxidation is a major deteriorative factor in meats. The use of natural antioxidants in different meat products to enhance their shelf life and quality has been explored in a number of studies. In a study, the antioxidant content of different varieties of honey was investigated spectrophotometrically, and the honey's effectiveness in reducing the oxidation of ground poultry was determined. The results revealed that honey has great potential as an antioxidant source and may result in greater acceptability of meat products and prevent negative health implications of oxidized meats (McKibben and Engeseth, 2002). Grape seed extract was investigated as an antioxidant in cooked, cold-stored turkey meat, indicating the efficiency of different concentrations of grape seed extract in retarding oxidative rancidity. The research demonstrated the effectiveness of grape seed extract in preventing lipid oxidation in meat (Mielnik et al., 2006). In addition, the antioxidative properties of holy basil and galangal were studied in cooked ground pork. The findings suggested that these natural antioxidants could be beneficial in reducing lipid oxidation in meat products (Juntachote et al., 2006). The effectiveness of mint leaves, a common herb used in Indian cuisine, as a natural antioxidant for radiation-processed lamb meat was investigated, indicating that mint could be used as a natural antioxidant to prevent lipid oxidation in meat (Kanatt et al., 2007). In an *in vitro* study, the efficiency of different concentrations of grape antioxidant dietary fibre on the susceptibility of raw and cooked chicken breast hamburgers to lipid oxidation was investigated. The results highlighted the potential of grape antioxidant dietary fibre in reducing lipid oxidation in meat products (Sáyago-Ayerdi et al., 2009). Additionally, the antioxidant and antimicrobial effectiveness of different forms of garlic was evaluated in emulsion-type sausages during refrigerated storage. The study emphasized the importance of antioxidants in preventing lipid oxidation and microbial growth in meat products (Kim et al., 2010). Natural antioxidants such as bee pollen extract have also been studied for their ability to prevent lipid oxidation in refrigerated sausages. The results revealed that lyophilized bee pollen was effective in retarding lipid oxidation in sausage (de Florio Almeida et al., 2017). Essential oils, as natural antioxidants, have also been explored as additives to prevent oxidation reactions in meat and meat products. The findings highlighted that the essential oils protect meat and meat products from several deteriorative reactions, and phenolic compounds are responsible for the strong antioxidant activity of essential oils (Pateiro et al., 2018). Recent trends have also focused on nano-encapsulated essential oils as a preservation strategy for meat and meat product storage, aiming to prevent meat spoilage by controlling oxidation reactions and microbial growth. The studies are critically analyzed considering their effectiveness in the nanostructuring of essential oils as natural antioxidants and improvements in the quality of meat and meat products by focusing on the control of oxidation reactions and microbial growth to increase food safety and ensure innocuity (Ojeda-Piedra et al., 2022). It has been shown that the extracts from sources like grains, oilseeds, spices, fruits, and vegetables enhance the quality and shelf life of chicken meat during processing, storage, and distribution, offering a health-promoting and safer alternative to synthetic antioxidants (Barbosa et al., 2023). Furthermore, natural antioxidants derived from plant by-products effectively prevent lipid oxidation in meats by scavenging free radicals and protecting against oxidative stress. Rich in bioactive compounds like phenolics, tocopherols, and carotenoids, these antioxidants preserve meat quality by mitigating detrimental changes in colour, texture, flavour, and nutritional value. Encapsulation technologies further enhance their stability and controlled release, making them a safer, cost-effective, and environmentally friendly alternative to synthetic additives while extending shelf life and meeting consumer demand for clean-label products (Kumar et al., 2024). Overall, the studies suggest that natural antioxidants such as honey, grape seed extract, holy basil, galangal, mint, and grape antioxidant dietary fibre can be effective in preventing lipid oxidation in meats. These antioxidants offer a potential eco-friendly approach to enhancing the quality and shelf life of meat products. Table 2 shows the types of antioxidants, their corresponding meat types, their effectiveness in preventing lipid oxidation, and the relevant references for each study.

Table 2. Effectiveness of natural antioxidants in preventing lipid oxidation in meats.

Antioxidant	Meat Type	Effectiveness	Reference
Honey	Ground poultry	Effective in reducing oxidation, enhances acceptability, and prevents negative health implications.	McKibben and Engeseth (2002)
Grape seed extract	Cooked, cold-stored turkey	Retards oxidative rancidity, effective in preventing lipid oxidation.	Mielnik et al. (2006)
Holy basil and Galangal	Cooked ground pork	Beneficial in reducing lipid oxidation.	Juntachote et al. (2006)
Mint leaves	Radiation-processed lamb meat	Prevents lipid oxidation, effective as a natural antioxidant.	Kanatt et al. (2007)
Grape antioxidant dietary fiber	Raw and cooked chicken breast hamburger	Reduces lipid oxidation, effective in both raw and cooked forms.	Sáyago-Ayerdi et al. (2009)
Garlic (various forms)	Emulsion-type sausages	Prevents lipid oxidation and microbial growth during refrigerated storage.	Kim et al. (2010)
Bee pollen extract	Refrigerated sausages	Lyophilized bee pollen retards lipid oxidation.	de Florio Almeida et al. (2017)
Essential oils	Various meat products	Protects from oxidation reactions, phenolic compounds provide strong antioxidant activity.	Pateiro et al. (2018)
Nano-encapsulated essential oils	Meat and meat products	Controls oxidation reactions and microbial growth, enhances shelf life.	Ojeda-Piedra et al. (2022)
Plant by-products (grains, oilseeds, spices, fruits, vegetables)	Chicken meat	Enhance quality and shelf life, an eco-friendly alternative to synthetic antioxidants.	Barbosa et al. (2023)
Plant by-products (e.g., phenolics, tocopherols, carotenoids)	Meat products	Scavenge free radicals, preserve colour, texture, flavour, and nutritional value.	Kumar et al. (2024)

Effectiveness in preventing lipid oxidation in dairy

The effectiveness of natural antioxidants in preventing lipid oxidation in dairy products such as milk, cheese, butter, and cream has been a topic of interest in the food industry. Studies have shown that the antioxidant components of milk play a crucial role in increasing the oxidative stability of dairy products (Lante et al., 2006; Khan et al., 2019). Additionally, research has focused on the benefits of natural antioxidants, such as rosemary, in retarding lipid oxidation, increasing shelf life, and promoting the overall quality of dairy products (Gad and Sayd, 2015). Furthermore, the addition of antioxidants has been identified as an effective method for delaying lipid oxidation in dairy products, thereby improving their overall quality and shelf life (Kumbhare et al., 2021). Additionally, dairy foods naturally contain carnitine, which has been linked to various health benefits (Alhasaniah, 2023). Incorporating plant extracts and essential oils as natural antioxidants in dairy products, particularly cheese, effectively delays lipid oxidation and extends shelf life. Delivery systems for these bioactives enhance their stability and efficacy, offering the potential to create cheese products with improved preservative properties and enhanced quality. This approach aligns with the growing demand for clean-label, natural, and commercially viable cheese products, leveraging plant-based antioxidants to ensure freshness and sustainability (Christaki et al., 2021). It has been shown recently that supplementing dairy cows with red clover isoflavones effectively enhances the antioxidant capacity of milk, reducing lipid oxidation. This natural antioxidant improves milk quality by increasing the activity of antioxidant enzymes, reducing oxidative products, and boosting vitamin E and C concentrations. Additionally, it positively influences the milk fatty acid profile by lowering saturated and increasing unsaturated fatty acids. Studies in mice further demonstrated that milk from cows fed red clover isoflavone alleviates inflammation and tissue damage while modulating metabolic pathways, showcasing its potential as a natural strategy to prevent lipid oxidation and develop functional dairy products (Zhang et al., 2024). In conclusion, the use of natural antioxidants in dairy products has shown promise in preventing lipid oxidation and improving the overall quality and shelf life of these products. Table 3 summarizes the various antioxidants and their effects on lipid oxidation in dairy products, with additional notes on their benefits to product quality, shelf life, and overall health properties.

Table 3. Effectiveness of natural antioxidants in preventing lipid oxidation in dairy products.

Antioxidant Source	Effect on Lipid Oxidation	Impact on Dairy Products	Additional Benefits	Reference
Milk's Natural Antioxidants	Enhances the oxidative stability of dairy products	Improves shelf life and quality of milk, cheese, butter, and cream	Promotes overall quality and freshness	Khan et al. (2019)
Rosemary (Natural Extract)	Retards lipid oxidation	Increases shelf life and quality of dairy products, particularly cheese	Acts as a natural preservative, aligning with clean-label demands	Gad and Sayd (2015)
Plant Extracts and Essential Oils	Delays lipid oxidation and extends shelf life	Enhances the shelf life and quality of cheese, and contributes to natural preservation	Supports sustainability in dairy product manufacturing	Christaki et al. (2021)
Carnitine (Naturally in Dairy)	Linked to antioxidant properties	Improves oxidative stability	Associated with various health benefits	Alhasaniah (2023)
Red Clover Isoflavone (Supplement in Cow's Diet)	Increases the antioxidant capacity of milk	Reduces lipid oxidation, improves milk quality, enhances fatty acid profile (lowering saturated fats, increasing unsaturated fats)	Increases antioxidant enzymes, boosts vitamin E and C, reduces inflammation and tissue damage	Zhang et al. (2024)

Mechanisms underlying the effectiveness of natural antioxidants in preventing lipid oxidation

Antioxidants play a key role in preventing lipid oxidation in oils, meats, and dairy products through various mechanisms. During lipid oxidation, unsaturated fatty acids react with oxygen to form free radicals and lipid peroxides. Antioxidants can prevent this process in several ways. Radical scavenging is a process by which antioxidants such as α-tocopherol (vitamin E) donate hydrogen atoms to free radicals, effectively neutralizing them and terminating the chain reaction of lipid peroxidation. This reaction reduces the concentration of reactive species that can propagate oxidation (Mittal et al., 2022; Zheng YZ et al., 2022; Zheng et al., 2024).

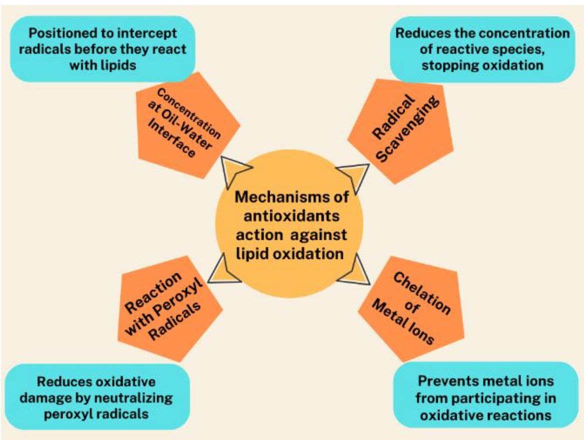

Figure 5. Mechanisms underlying the effectiveness of natural antioxidants in preventing lipid oxidation.

Some antioxidants can chelate transition metal ions (like iron and copper), which catalyze the formation of free radicals. By binding these metals, antioxidants prevent them from participating in oxidative reactions that lead to lipid degradation (Timoshnikov et al., 2022; Gulcin and Alwasel, 2022). In emulsions, antioxidants can concentrate at the oil-water interface, where lipid oxidation is most prevalent. This concentration enhances their effectiveness, as they are strategically positioned to intercept radicals before they can react with lipids (Farooq et al., 2021; Bayram and Decker, 2023). Certain antioxidants can react with peroxyl radicals to form stable products instead of allowing them to react with lipids, thereby reducing overall oxidative damage (Musakhanian et al., 2022; Helberg and Pratt, 2021). Finally, the effectiveness of an antioxidant can depend on its hydrophilic-lipophilic balance. Inoil-in-water emulsions, hydrophilic antioxidants may be more effective due to their ability to migrate to the interface where oxidation occurs (Costa et al., 2021; Wang et al., 2024). The combined action of these mechanisms enables antioxidants to significantly enhance the oxidative stability and shelf life of oils and fats, making them essential in food preservation and formulation. Figure 5 summarizes the mechanisms underlying the effectiveness of natural antioxidants in preventing lipid oxidation.

Conclusions

Overall, it is clear the high potential of natural antioxidants recovered from food by-products, such as fruit peels, vegetable pulp, cereal bran, dairy products, and seafood residues, in preventing and inhibiting lipid oxidation and increasing the shelf life and quality of food products. These by-products, which are rich in bioactive compounds such as polyphenols, flavonoids, and carotenoids, can be a sustainable alternative to synthetic antioxidants in the food industry. Furthermore, by investing in research related to advanced extraction methods, improving these methods, and increasing the stability and efficiency of antioxidants, a dramatic transformation in food production and preservation can be achieved. However, challenges remain, such as optimizing cost-effective extraction processes, ensuring scalability, and understanding the interactions of these compounds in complex food matrices and a molecular level. Future research should address these challenges to unlock the full potential of natural antioxidants in industrial applications and sustainable food systems.

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