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Microalgae-derived antioxidants and antimicrobials: a sustainable approach for natural food preservatives

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Artificial preservatives such as nitrates, benzoates, sulphites, sorbates, parabens, formaldehyde, butylated hydroxytoluene (BHT), and butylated hydroxyanisole (BHA) have been used for ages to extend the shelf life of food items. However, increasing scientific evidence links their excessive intake to severe health hazards like cancer, endocrine disruption, allergies, and neurotoxicity. As people become more aware and prefer natural clean-label foods, the demand for safer options from the industry is growing. In this situation microalgae can be a strong natural source of preservatives. They are rich in active compounds that show both antioxidant and antimicrobial effects. Microalgal extracts give a green way to improve food safety and shelf life. This review discusses major antioxidant constituents of microalgae, including carotenoids (e.g., astaxanthin, β-carotene), phenolics, and vitamins that reduce oxidative degradation of food matrices. Mechanisms of action, delivery modes, and incorporation into active packaging and food coatings are covered. Despite efficiency challenges associated with extraction, compound stability, and large-scale industrial production, breakthroughs in bioprocessing and biotechnology are rapidly expanding the boundaries of commercial application. In summary, microalgal bioactives offer a promising and sustainable approach to natural food preservation and safety, while also addressing consumer demand for cleaner and safer food products.

KEYWORDS

antioxidants, antimicrobials, food preservatives, microalgae, bioactive compound

1 Introduction

Throughout human evolution, civilizations have developed a wide array of food preservation techniques to ensure availability across seasons, prevent contamination, and reduce the risk of foodborne diseases. Today's food preservation techniques include a range of physical methods, including freezing, refrigeration, thermal processing, and air-drying, as well as chemical techniques that employ nitrates, benzoates, and BHT, along with other chemical agents, organic acids and salts (Mafe et al., 2024). Although they are useful for extending shelf life and inhibiting microbial spoilage, they may also have negative effects on the quality of food. This includes alterations in nutritional value, such as the loss of heat-sensitive vitamins and essential nutrients, as well as changes in

organoleptic properties, including texture, flavor, color, and aroma (Wong et al., 2023). Growing consumer awareness and the shift toward green consumerism are prompting a reassessment of the validity and continued use of some commercially available synthetic preservatives. Consequently, there is a need to develop preservation strategies using natural products that maintain bioactivity and enhance shelf life. Although the search for natural food preservatives is a hot topic, most studies are focused on plant extracts.

Microalgae are photosynthetic microorganisms that are found everywhere in nature, thriving in a wide variety of aquatic environments from freshwater lakes and rivers to saline oceans and even in terrestrial environments like soil. They are known to be a rich source of bioactive compounds, such as proteins, lipids, pigments, polysaccharides, vitamins, and antioxidants (Gauthier et al., 2020). Secondary metabolites produced by microalgae include polyunsaturated fatty acids (PUFAs), carotenoids like β-carotene, astaxanthin, and lutein, and certain stress-induced enzymes- all of which have strong antioxidant properties (Cezare-Gomes et al., 2019). Along with high antioxidant properties, these metabolites exhibited strong broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacterial strains. Chlorellin, which is a growth inhibitor of both Gram-positive and Gram-negative bacteria can be extracted from *Chlorella* sp. likewise, eicosapentaenoic acid (EPA), hexadecatrienoic acid, and palmitoleic acid from *Phaeodactylum tricornutum* have been found to exhibit antimicrobial activity against methicillin-resistant Gram-positive *Staphylococcus aureus* (Alsenani et al., 2020; Smith et al., 2010).

The incorporation of microalgae antioxidant and antimicrobial extracts in food preservation systems provides an attractive solution to address increasing consumer demand for natural and greener products (Figure 1). Microalgal extracts hold significant market potential given their functional diversity, sustainability, and capacity for year-round production. The global market for microalgal products is currently valued at approximately USD 4.96 billion and is projected to grow to between USD 8.9 and 9.1 billion by 2032, reflecting a robust compound annual growth rate (CAGR) in the coming years (Martínez-Ruiz et al., 2025).

This review highlights key antioxidant compounds from microalgae such as carotenoids, phenolics, and vitamins that help reduce oxidative degradation in foods as well as antimicrobial agents like fatty acids, peptides, and polysaccharides effective against various foodborne pathogens. It also covers their mechanisms of action, delivery systems, integration into active packaging and edible coatings, and addresses regulatory, safety, and consumer acceptance considerations for food industry applications.

2 Bioactive compounds in microalgae

Microalgae constitute a promising and sustainable source of bioactive compounds with significant potential for applications in the food industry (Bhardwaj et al., 2025). Bioactive compounds like carotenoids and PUFAs have multiple applications in food and pharmaceuticals (Sun et al., 2023). Microalgae such as *Chlorella vulgaris*, *Euglena gracilis*, and *Nannochloropsis* have gained recognition as edible algae across numerous countries, primarily due to their rich content of proteins, lipids, and various bioactive metabolites (Maurício et al., 2023; Xie et al., 2023; Ragini and Arumugam, 2023). This global approval has led to a surge in the development of edible products based on microalgal biomass. For instance, a German company has developed a natural product called Green Trio Tantellen, which utilizes the biomass of *Spirulina* sp. and *Chlorella* sp. (Maehle and Skjeret, 2022). Furthermore, microalgal species including *Haematococcus* sp., *Chlorella* sp., *Dunaliella* sp., *Scenedesmus* sp., *Chlamydomonas* sp., and *Phaeodactylum* sp. are widely employed in biotechnological processes owing to their ability to produce a variety of valuable compounds such as proteins, carbohydrates, pigments, phenolic compounds, and vitamins (Figure 2) (Katiyar et al., 2017). The structure of bioactive compounds such as astaxanthin, fucoxanthin, lutein, β-carotene, eicosapentaenoic acid, docosahexanoic acid, vitamin A, C, and E, and polysaccharides/beta-glucans is shown in Figure 3.

Metabolites, such as phenolics, flavonoids, and tocopherols, can effectively mitigate oxidative stress and lower the risk of chronic diseases (Torres-Tiji et al., 2020). S*pirulina* phenolic extract has shown a strong radical scavenging activity of 79.95% at a concentration of 449 mg/ml, making it a promising supplement for antiaging and heart health (Bellahcen et al., 2020). Under specific growth conditions, *Dunaliella salina* can produce lipids, carbohydrates, and proteins at levels reaching up to 70%, 60%, and 20%, respectively (Roy et al., 2021). Additionally, *Haematococcus pluvialis* is capable of synthesizing astaxanthin up to 5% of its dry weight (DW) (Mularczyk et al., 2020), while *Spirulina platensis* can produce phycocyanin at concentrations as high as 17.5% (Khandual et al., 2021). Microalgae-based food products start entering the market, but some challenges need to be addressed to make them functional, new-era food. Efforts like screening of nutrient-rich microalgae species, development of nutrient-rich food products, and their promotion and marketing (Chen et al., 2022). Table 1 provides some important microalgal extracts with antioxidant and antimicrobial activity that are used in food system.

3 Antioxidant activities of microalgal extracts

Reactive oxygen species (ROS) like singlet oxygen ($^1O_2$), superoxide radicals (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicals (OH) are reactive molecules with the potential to spoil food components (Scaglioni and Badiale-Furlong, 2017). ROS are responsible for lipid peroxidation, protein degradation, and vitamin losses, ultimately reducing food quality and accelerating spoilage. Figure 4 illustrates the steps of lipid and protein oxidation and the role of antioxidants in preventing it. Antioxidants are essential in neutralizing ROS, which thereby ensures the nutritional value, safety, and shelf life of food items. Microalgal extracts contain a variety of antioxidants, including vitamins A, C, and E, as well as polyphenols, carotenoids, and bioflavonoids (Vignaud et al., 2023).

Among the most widely used analytical techniques for determining antioxidant activity are the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay, ABTS (2,2′-azino-bis-3-ethylbenzothiazoline-6-sulfonic acid) assay, and the

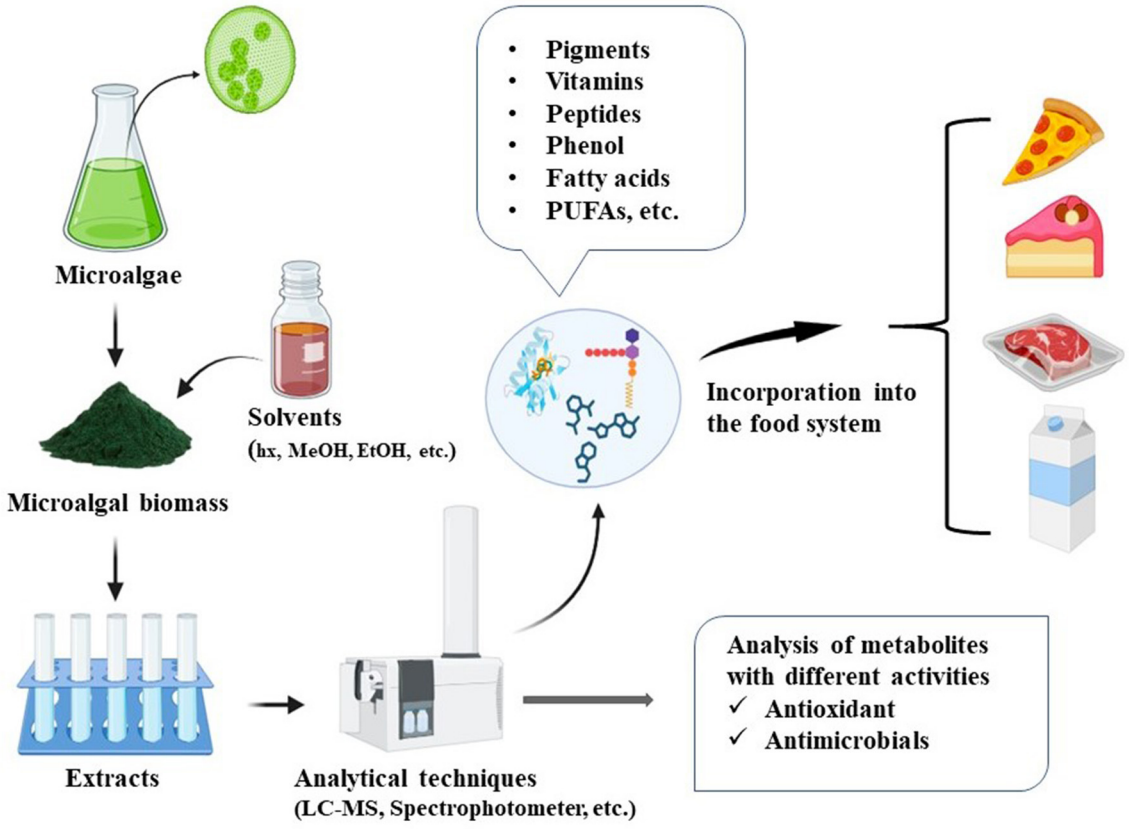

FIGURE 1
Diagram illustrating the incorporation of microalgal extracts into food matrices.

Folin–Ciocalteu antioxidant (FCA) assay. Each of these tests measures the ability of microalgal extracts to scavenge free radicals or reduce oxidative agents. For instance, in the DPPH assay, antioxidant activity can be quantified as the percentage of radical inhibition at specific extract concentrations, or expressed as IC50 values (the concentration needed to inhibit 50% of radicals), Trolox equivalents, or ascorbic acid equivalents per unit extract or dry weight (Martinez-Morales et al., 2020). Similarly, ABTS and FCA assays offer complementary insights by measuring total antioxidant capacity and phenolic content, respectively (Danet, 2021). Table 2 provides a summary of the most commonly used and recent antioxidant assays employed in microalgae-based studies, highlighting their relevance and application in evaluating natural antioxidant sources for potential use in food preservation and nutraceuticals.

3.1 Food oxidation processes and the role of antioxidants in preventing food oxidation

Reactive oxygen species (ROS) such as hydroxyl radicals ($^{\bullet}OH$) and superoxide anions ($O_2^{\bullet-}$), react with molecules like PUFAs in food lipids. The removal of a hydrogen atom from a PUFA generates a lipid radical ($R^{\bullet}$), which reacts with oxygen to form unstable lipid peroxyl radicals ($ROO^{\bullet}$). These unstable lipid peroxyl radicals react with adjacent lipids, creating lipid hydroperoxides (ROOH). They are decomposed into aldehydes, ketones, and malondialdehyde which are responsible for rancidity, off-flavors, and cytotoxicity (Prisacaru, 2016; Martemucci et al., 2022). Similarly, proteins undergo oxidative modifications at specific amino acid residues (e.g., cysteine, methionine, tryptophan), leading to carbonylation, fragmentation, and aggregation. These molecular events disrupt food structure, color, taste, and nutritional integrity (Hellwig, 2019).

Antioxidants act at distinct molecular targets to prevent or delay these oxidative processes. Radical scavengers such as phenolic compounds, carotenoids, and tocopherols donate a hydrogen atom or an electron to lipid peroxyl radicals ($ROO^{\bullet}$). This converts the $ROO^{\bullet}$ into stable, non-propagating molecules and terminates the chain reaction (Chaudhary et al., 2023). For instance, tocopherol reacts with $ROO^{\bullet}$ to yield a stable, less reactive tocopheroxyl radical (Gulcin, 2025). Carotenoids and phycobiliproteins quench singlet oxygen ($^1O_2$) through physical energy transfer, dissipating its energy as heat instead of initiating oxidation (Ramel et al., 2012). By targeting radicals and excited oxygen species at the molecular level, natural antioxidants maintain food quality, slow nutrient degradation, and extend shelf life (Figure 4).

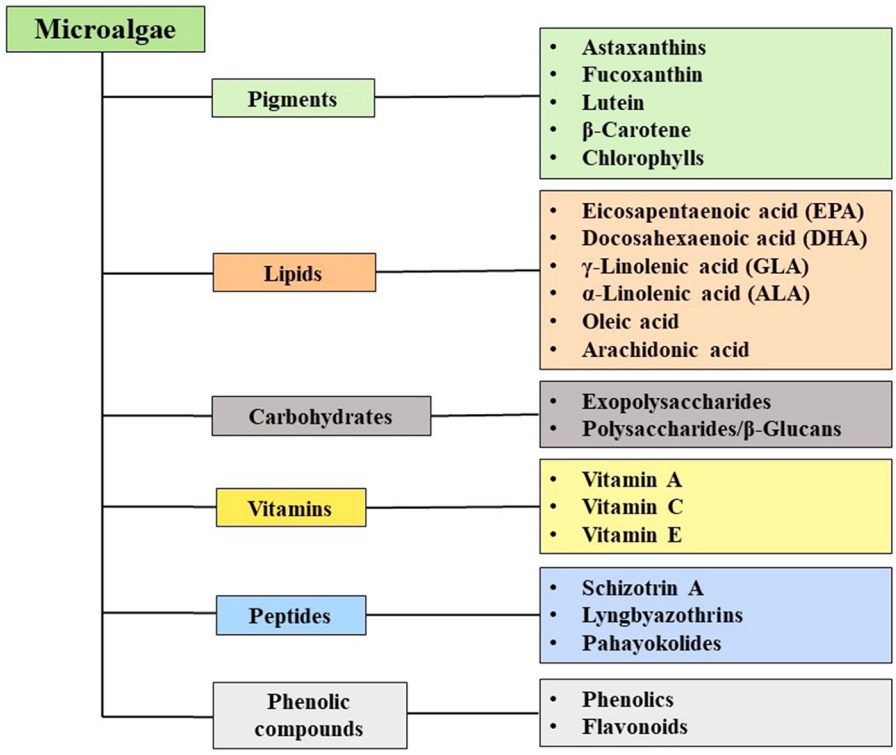

FIGURE 2
Bioactive molecules of microalgae.

3.2 Pigments

Carotenoids like β-carotene, astaxanthin, lutein, and fucoxanthin derived from microalgae hold significant potential as natural food preservatives due to their strong antioxidant and health-promoting properties (Sathasivam and Ki, 2018; Aditi et al., 2025). β-Carotene, primarily produced by *Dunaliella salina* and *Tetradesmus almeriensis* and is widely used as a natural antioxidant and food colorant (Molino et al., 2018; Khaw et al., 2022; Seth et al., 2021). Astaxanthin, especially from *Haematococcus pluvialis* (up to 5% of its dry weight, DW) (Mularczyk et al., 2020) and *Chlorella zofingiensis*, exhibits antioxidant activity up to ten times stronger than other carotenoids, making it highly potential (Zhang et al., 2021). Lutein, sourced from *Spirulina platensis* and *Chlorella* species, enhances antioxidant content in food products, such as fish burgers, improving their shelf life and nutritional quality (Saeed et al., 2025). Fucoxanthin, abundant in marine algae can contribute to food preservation through its anti-inflammatory and antioxidant effects, offering a natural alternative to synthetic additives (Khaw et al., 2022).

The total carotenoid content in microalgae can vary depending on growth conditions, with stress conditions often leading to higher carotenoid production. For example, high light intensity exposure (240 $\mu E\ m^{-2}\ s^{-1}$ for 20 days) in *Chlamydomonas acidophila* raised carotenoid content from <40 to >50 mg L^{-1} culture. At 40 °C for 20 days, the levels went up from <40 to >40 mg L^{-1} culture, whereas UV-A radiation (10 $\mu E\ m^{-2}\ s^{-1}$ for 15 days) raised it from <50 to >50 mg L^{-1} culture (Garbayo et al., 2008). Exposure to UV-B radiation (15 W m^{-2} for 1 h), *Chlorella vulgaris* increased from 0.98 to 1.18 mg g^{-1} FW, and *Chlorococcum humicola* from 1.02 to 1.36 mg g^{-1} FW (Singh et al., 2019). These findings indicate that light, temperature, and UV stress enhance carotenoid accumulation in microalgae. Applying such stresses can markedly boost metabolite production, which can subsequently be utilized in microalgae-based food systems.

3.3 Vitamin C, E, and glutathione

Microalgae are a rich natural source of vitamins such as vitamin C (ascorbic acid) and vitamin E (tocopherols and tocotrienols). These bioactive compounds are highly valued for their capacity to counteract oxidative stress, rendering them great prospects as natural food preservatives. Vitamin C is a water-soluble antioxidant primarily located in the cytosol and chloroplasts of microalgal cells. Scavenging ROS and regenerating other antioxidants like vitamin E and glutathione are some of its main functions (Rezayian et al., 2019). Vitamin E has the function of preventing lipid peroxidation by donating a hydrogen atom to lipid radicals and thereby halting oxidative chain reactions (Gulcin, 2020).

Vitamin C concentration differs greatly among microalgal species. Genus *Skeletonema* has been found to contain as low as 0.06 mg/g DW, while the genus *Chaetoceros* has a range of 0.12–18.79 mg/g DW (Del Mondo et al., 2020). Microalgae under stress conditions are often found to synthesize more ascorbic acid. *Chlorella vulgaris* under phosphorus limitation (0.01 mM, 5

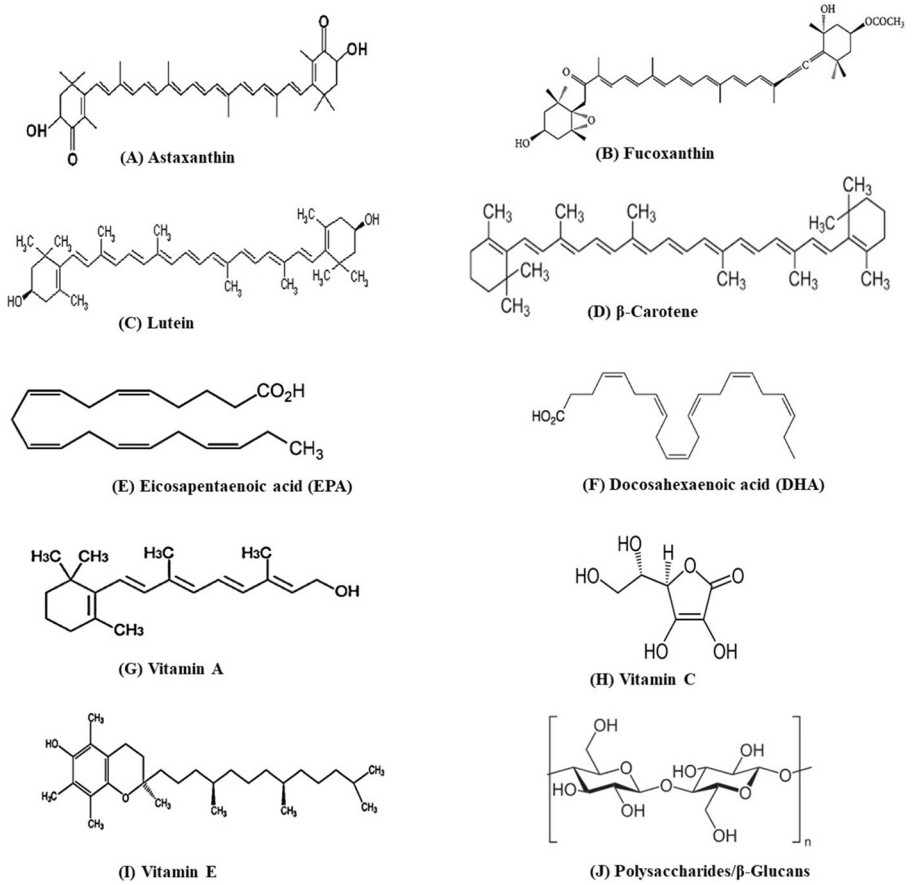

FIGURE 3
Structure of some important bioactive molecules of microalgae.

days) increased from <1.0 to >1.0 mg g^{-1} DW. *Phaeodactylum tricornutum* showed increases from <1.0 to >1.5 mg g^{-1} DW under phosphorus limitation and from <1.0 to >1.0 mg g^{-1} DW under nitrogen limitation (0.2 mM, 5 days). *Tetraselmis suecica* exhibited a stronger response, rising from <2.0 to >5.0 mg g^{-1} DW under phosphorus limitation and from <2.0 to >3.0 mg g^{-1} DW under nitrogen limitation (Goiris et al., 2015). This highlight species-specific enhancements in ascorbic acid production under nutrient stress. After oxidation, tocopherols and tocotrienols can be restored by ascorbate and glutathione or coenzyme Q, supplementing the antioxidant system in microalgal extracts (Coulombier et al., 2021).

Another critical antioxidant found in microalgae is glutathione, which is an aqueous-soluble tripeptide made up of glutamate, cysteine, and glycine. Glutathione is found in all cell compartments and is pivotal in the detoxification of ROS (Swapnil et al., 2017, 2021). Glutathione is a cofactor for glutathione peroxidase, facilitating the reduction of hydrogen peroxide to water, and also assists in the recycling of ascorbate and tocopherol to their active reduced forms (Sharma et al., 2012). In addition, glutathione can directly scavenge harmful species like superoxide radicals, hydroxyl radicals, and singlet oxygen (Cassier-Chauvat et al., 2023), all of which are responsible for food spoilage. Together, the antioxidant systems found in microalgae, glutathione and vitamins C and E act synergistically to counteract oxidative damage in food matrices (Pruteanu et al., 2023). Their ability to inhibit lipid peroxidation and stabilize sensitive food components makes microalgal extracts promising natural alternatives to synthetic antioxidants used in food preservation. The utilization of microalgae in this regard parallels the increasing interest in clean-label, sustainable, and health-benefiting food ingredients.

3.4 Phenols

Phenolic compounds are a diverse group of natural antioxidants widely distributed in higher plants, macroalgae, and increasingly recognized in microalgae. They can inhibit oxidative deterioration of lipids and proteins, thereby increasing shelf life and preserving food quality. A recent study by Almendinger et al. (2021) tested 13 microalgal species and revealed that *Neochloris oleoabundans* and *Wilmottia murrayi* had very high concentrations of phenolics, higher than 20 mg gallic acid equivalents per gram. León-Vaz et al. (2023) investigated 19 Nordic microalgal species under control and stress conditions (high light and cold exposure). They indicated that species such as *Chlorococcum* sp. and *Scenedesmus* sp. accumulated more polyphenols under stress, demonstrating the possibility of induced antioxidant accumulation through environmental control. *Chlamydomonas reinhardtii* was

TABLE 1 Common microalgal antimicrobial/antioxidant metabolites and their uses in food systems.

Metabolites	Common algae/cyanobacteria sources	Antibacterial and antioxidant activity	Advantages	Typical mode(s) of application in food systems	References
Fatty acids	*Chlorella* spp., *Nannochloropsis*, *Tetraselmis*, *Scenedesmus*	Broad antibacterial activity against Gram-positive and Gram-negative foodborne bacteria (*S. aureus*, *E. coli*, *Salmonella*). Antioxidant indirectly via PUFAs' nutritional role.	Natural preservatives, functional ingredient (omega-3 enrichment), reduce pathogenic load	Direct extract addition, encapsulated lipid fractions in emulsions or coatings, and active packaging	(Biris-Dorhoi et al., 2020; El Shafay et al., 2016; Cakmak et al., 2014)
Phenolics/ Phlorotannins (polyphenols)	Brown macroalgae (*Fucus*, *Laminaria*), some green microalgae	Strong antioxidant and antibacterial effects against *Listeria*, *Salmonella*, *S. aureus*; antifungal.	Natural antioxidants and antimicrobials, extend shelf life, preserve sensory quality	Coatings/edible films, direct extract addition	(Gómez-Guzmán et al., 2018; Maadane et al., 2017)
Glycolipids	Green/red/brown seaweeds, some microalgae	Antibacterial and antiviral activity against *S. aureus* and biofilm-forming bacteria.	Natural antimicrobial, potential anti-biofilm agents	Polar lipid fractions, emulsions, and sanitizing formulations	(Vishwakarma and Vavilala, 2019)
Terpenes and Carotenoids	*Dunaliella salina*, *Haematococcus pluvialis*	Antibacterial against *Listeria*, *S. aureus*, *Salmonella*. Strong antioxidants.	Natural antioxidant and antimicrobial, natural colorant additives	Coatings, carotenoids in emulsions/packaging	(Cakmak et al., 2014; Ambrico et al., 2020)
Antimicrobial peptides (AMPs)	*Fischerella*, *Chlorella* sp.	Broad-spectrum bactericidal activity, antioxidant properties.	Natural preservatives in proteinaceous foods	Purified peptide additives, hydrolysates in formulations, and edible films	(Sedighi et al., 2019)
Polysaccharides	Brown macroalgae (*Laminaria*, *Fucus*), green macroalgae *(Ulva)*	Direct antibacterial effects (some sulfated polysaccharides), antioxidant, chelating properties.	Thickening/stabilizing agents and antimicrobial, antioxidant activity	Edible coatings/films, hydrocolloid matrices, microencapsulation matrices	(Guidara et al., 2020; Kocira et al., 2021)
Indole alkaloids	Marine bacteria (*Acinetobacter* sp.), fungi (*Scedosporium apiospermum*) and algae (*Caulerpa racemose*)	Potent antibacterial compounds; some cytotoxic (dose-dependent).	Source of novel antimicrobials, potential in food contact surfaces	Extracts in surface sanitizers, semi-synthetic derivatives	(Güven et al., 2010; Li et al., 2020)

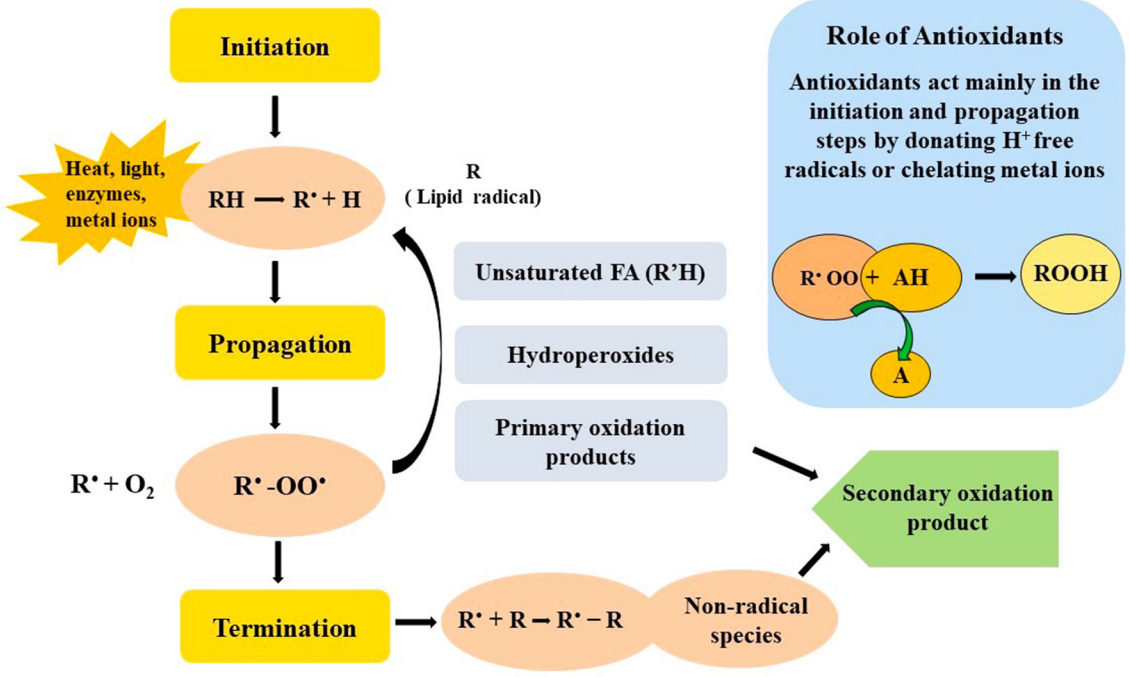

FIGURE 4
Steps involved in the oxidation of food matrices and the role of antioxidant in preventing it.

TABLE 2 Common assays for antioxidant activity.

Name of the method	Principle	Advantages	Limitations	References
DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging capacity assay	The DPPH assay measures antioxidant activity based on the reduction of the purple DPPH radical to a pale-yellow compound, with absorbance decrease recorded at 515 nm.	■ Simple, fast, sensitive, and highly reproducible ■ Widely used for evaluating antioxidant capacity in foods, beverages, and herbal extracts ■ Requires minimal labor, inexpensive reagents, and no sophisticated equipment ■ High-throughput potential—multiple samples can be analyzed quickly ■ Color change allows easy monitoring ■ Suitable for rapid screening of radical scavenging activity ■ Applicable to various antioxidants using common solvents like methanol or ethanol	■ Does not measure reaction rates, missing kinetic details ■ Limited antioxidant access to DPPH slows reactions ■ Methanol inhibits hydrogen atom transfer (HAT) ■ Reaction efficiency affected by steric hindrance at high concentrations ■ Electron transfer is pH-dependent; HAT is pH-independent	(Natrah et al., 2007; Amorati and Valgimigli, 2015)
β-Carotene bleaching assay	Evaluated by monitoring the discoloration of β-carotene at 434 nm using a photocolorimeter.	■ Measures antioxidant activity based on inhibition of β-carotene bleaching ■ Simulates lipid peroxidation in a biologically relevant emulsion system ■ Simple and visually trackable colorimetric method ■ Useful for evaluating antioxidant effects in food and lipid-based systems ■ Expresses results as % inhibition, offering clear comparison with controls	■ Poor reproducibility of radical initiation ■ Complex reaction behavior of carotenes under varying oxygen levels ■ Carotenes can switch roles—antioxidants at low O_2, pro-oxidants at high O_2 ■ Crude kinetic analysis may affect accuracy and interpretation	(Aremu et al., 2014; Gorbachev et al., 2021)
TEAC (trolox equivalent antioxidant capacity) assay	Evaluates antioxidant activity by measuring the reduction of the blue chromophore ABTS [2,20-azino-bis(3-éthylbenzothiazoline-6-sulphonique)] radical cation to a colorless form, with absorbance monitored at 734 nm.	■ Simple, fast, and widely used assay for assessing antioxidant capacity ■ Uses a stable and water-soluble radical cation ($ABTS^+$) with strong absorbance at 734 nm ■ Suitable for both hydrophilic and lipophilic antioxidants ■ Quantitative results can be directly compared to Trolox standard ■ Can be modified to assess both reaction kinetics and stoichiometry ■ Applicable to a broad range of antioxidant compounds	■ Does not distinguish between antioxidant reaction kinetics and stoichiometry in short-term assays ■ Final results depend heavily on the time point chosen for absorbance reading ■ $ABTS^+$ is a charged radical cation, not physiologically representative of neutral peroxyl radicals ■ Reactions occur mainly via electron transfer, unlike peroxyl radicals that undergo hydrogen atom transfer (HAT) ■ Potential overestimation of antioxidant capacity for compounds that react rapidly with $ABTS^+$	(Litescu et al., 2014)
FRAP (ferric-reducing antioxidant power) assay	The FRAP assay measures the antioxidant capacity based on the reduction of ferric-TPTZ to ferrous-TPTZ, forming a blue complex detected at 593 nm.	■ Simple, fast, and cost-effective spectrophotometric method ■ Provides quantitative estimation of antioxidant reducing power ■ High reproducibility and suitable for routine antioxidant screening ■ Results are expressed as Fe^{2+} equivalents, allowing direct comparison among antioxidants ■ Effective for antioxidants with fast redox reactions (e.g., ascorbic acid, uric acid) ■ No requirement for free radical generation, avoiding complications from radical instability	■ Measures only reducing capacity, not actual radical scavenging activity ■ Non-specific: any compound with appropriate redox potential can reduce Fe^{3+} ■ Time-dependent: incomplete reactions for some antioxidants within 4 min can lead to underestimation ■ Does not account for antioxidant reaction kinetics or bioavailability	(Benzie and Devaki, 2018; Henderson et al., 2015)
ORAC (oxygen radical absorbance capacity) assay	The chain-breaking antioxidant capacity is measured by monitoring the fluorescence decay of fluorescein (FL) caused by peroxyl radicals generated from the thermal decomposition of AAPH [2,2′-azobis(2-amidinopropane) dihydrochloride]	■ Measures antioxidant capacity against biologically relevant peroxyl radicals ■ High-throughput, suitable for microplate format ■ Provides quantitative data (area under the curve, AUC) ■ Widely used for evaluating antioxidant content in foods	■ AUC method can mask antioxidant differences ■ Fluorescein has low reactivity with peroxyl radicals ■ May underestimate strong antioxidants ■ Nutritional relevance of ORAC values is debated ■ Requires careful selection of fluorescent probes for accurate results	(Ou et al., 2013; Figueroa et al., 2023)

(Continued)

TABLE 2 (Continued)

Name of the method	Principle	Advantages	Limitations	References
TBARS (thiobarbituric acid reactive substances) assay	Lipid peroxidation is assessed by measuring the pink complex formed between thiobarbituric acid (TBA) and end-products at 100 °C in acidic conditions, with absorbance read at 534 nm using photocolorimetry	■ Simple and widely used for assessing lipid peroxidation ■ Detects malondialdehyde (MDA), a key lipid peroxidation product ■ Commercial kits available for ease of use	■ Non-specific; TBA reacts with non-lipid compounds ■ Cannot separate reaction kinetics from stoichiometry ■ High temperature and acidic conditions may affect sample integrity	(De Leon and Borges, 2020; Ghani et al., 2017)
Superoxide radical scavenging activity assay	Superoxide radical scavenging activity is measured by the inhibition of blue-colored formazan formation from nitroblue tetrazolium (NBT), generated via NADH–PMS or xanthine–xanthine oxidase systems, with absorbance recorded at 560 nm using photocolorimetry.	■ Simple and widely used method ■ Provides IC50 value for comparing antioxidant potency ■ Useful for evaluating SOD-mimicking antioxidants ■ Can be adapted for cell-based assays (e.g., SOD-deficient yeast survival)	■ Does not measure the actual catalytic rate of superoxide dismutation ■ Prone to artifacts (e.g., antioxidants reducing NBT or inhibiting xanthine oxidase) ■ May misestimate antioxidant activity ■ More accurate kinetic methods (e.g., pulse radiolysis) require advanced instrumentation	(Tao et al., 2014; Jayshree et al., 2016)
CAA (cellular antioxidant activity) assay	Measure the inhibition of intracellular oxidation of nonfluorescent DCFH (2′,7′-dichlorodihydrofluorescein) to fluorescent DCF by peroxyl radicals generated from ABAP [2,2′-azobis(2-amidopropane)] or AAPH [2,2′-azobis(2-amidinopropane) dihydrochloride], with antioxidants reducing fluorescence intensity (excitation at 485 nm, emission at 520 nm) using fluorimetry.	■ More biologically relevant than chemical *in vitro* assays ■ Measures intracellular antioxidant activity, not just radical quenching ■ Considers cellular uptake, metabolism, and bioavailability ■ Uses DCFH-DA probe to monitor real-time ROS activity inside cells ■ Adaptable to high-throughput screening using microplates ■ Applicable to various food extracts and pure compounds	■ No standardization yet; results may vary across labs ■ Fluorescence can be affected by probe stability and cell conditions ■ Cannot isolate specific antioxidant mechanisms (e.g., gene regulation) ■ Limited by cell type and conditions used (e.g., plating density, radical generator)	(Kellett et al., 2018; Lauritano et al., 2016)

also found to accumulate more polyphenols when grown at high light, further indicating that stress conditions may be leveraged to maximize antioxidant production in microalgal cultures (Vignaud et al., 2023). The phenolic compounds extracted from *Spirulina* sp., *Dunaliella salina*, *Fischerella ambigua*, *Oocystis pusilla*, and *Scenedesmus rubescens* (Anwer et al., 2022; Faraloni et al., 2021) have significant antioxidant activity.

4 Antimicrobial activities of microalgal extracts

Multidrug-resistant (MDR) bacteria have been recognized by the World Health Organization (WHO) as a major public health threat (Salam et al., 2023). This has motivated the search for new antimicrobial agents, especially from natural sources. Microalgae have been of particular interest because they contain a rich variety of bioactive compounds with antibacterial activity. Microalgal natural products are also a few steps ahead of synthetic antibiotics. Microalgal derived antimicrobial compounds are safer, more biocompatible, and ecologically sustainable compared to traditional synthetic antimicrobial compounds (Pratap et al., 2020; Kumawat et al., 2024). They have fewer side effects, such as allergic reactions, immunosuppression, and hypersensitivity. These antimicrobials are also less likely to cause resistance in microbes and are suitable for long-term use, such as in food preservation. Recent research has indicated that extracts of microalgal species including *Chlorella vulgaris*, *Dunaliella salina*, *Fischerella ambigua*, *Nostoc muscorum*, *Oocystis pusilla*, and *Scenedesmus rubescens* exhibit strong antibacterial activity (Amaro et al., 2011; Jena and Subudhi, 2019; Dantas et al., 2019). The bioactive peptide extracts have been found to inhibit some of the most common foodborne bacteria, such as *Staphylococcus aureus* and *Escherichia coli* (Corrêa et al., 2023). Extracts from seaweed algae *Enteromorpha intestinalis* and *Ulva reticulata* were discovered to show potent inhibition against *S. aureus* and even Methicillin-resistant *S. aureus* (MRSA) (Uddin et al., 2020). Seaweed-derived laminarin and essential oils have been discovered to be active against *Listeria monocytogenes*, a severe food safety issue in milk and meat foods (Patra and Baek, 2016). Likewise, various extracts of *Ulva lactuca*, *Chaetomorpha linum*, and *Turbinaria triquatra* have been discovered to show potent bactericidal activity against *Bacillus cereus*, a common food spoilage microorganism (Silva et al., 2020; Shannon and Abu-Ghannam, 2016). Against Gram-negative bacteria, *Cystoseira barbata*, *Padina gymnospora*, and microalgae *Tetraselmis spp.* (Zerrifi et al., 2018) and *Nannochloropsis oculata* extracts showed significant inhibition zones against *Salmonella* spp. and *E. coli* (Wali et al., 2020). Furthermore, recent evidence on the activity of brown algal phlorotannins showed not only highly significant anti-*Salmonella* activity but also longer food shelf life when added to alginate-based nanofiber packaging (Surendhiran et al., 2019).

Methanolic and acetone extracts have shown strong antibacterial activity against foodborne and human pathogens (Ibrahim and Kebede, 2020; Ullah et al., 2020). Techniques such as supercritical CO_2 extraction, pressurized liquid extraction (PLE), and subcritical water extraction (SWE) are gaining attention as these methods minimize solvent use, are faster, and offer better selectivity for target compounds. For example, supercritical CO_2 successfully extracted lipid fractions from *Chaetoceros muelleri* with antibacterial effects against *Staphylococcus aureus* and *Escherichia coli* (Mendiola et al., 2007; Jena and Subudhi, 2019), even when conventional solvents showed no such activity. Likewise, PLE and SWE have been effective in extracting antimicrobial agents from *Haematococcus pluvialis*, especially during its red phase (Bueno et al., 2020). The antimicrobial efficacy of the extracts can be analyzed by techniques such as agar diffusion method, Time kill kinetics, Flow Cytometry, Agar dilution and broth dilution methods, etc. (Table 3).

4.1 Fatty acids and polyunsaturated fatty acids (PUFAs)

Microalgae-derived fatty acids (FAs) are of interest as naturally occurring antimicrobial compounds with possible applications in food preservation. Fatty acids such as 10-undecylenic acid are employed clinically for the treatment of fungal infections, thus demonstrating their effectiveness (Day et al., 2022). Microalgae synthesize Free fatty acids (FFAs) as a protection against environmental stress or microbial infection (Lauritano et al., 2020). Such naturally occurring FFAs are chemical deterrents that provide ecological security and are of potential application for biotechnological uses.

Microalgae are a rich source of PUFAs like eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), γ-linolenic acid (GLA), α-linolenic acid (ALA), oleic acid, and arachidonic acid (Maltsev and Maltseva, 2021). The PUFAs have shown wide-spectrum antimicrobial activity against foodborne pathogens like *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Bacillus species* (Biris-Dorhoi et al., 2020; Marrez et al., 2019; Falaise et al., 2016). Apart from their antibacterial activity, PUFAs, more so ω-3 fatty acids such as EPA, DHA, and ALA, have demonstrated potent antibiofilm, antifungal, and antiparasitic activities (Table 4). Studies in animal models have revealed that oral or intraperitoneal supplementation with ω-3 PUFAs prevents infection with *Plasmodium*, *Toxoplasma*, and *Trypanosoma* species (Choi et al., 2019; Ilieva et al., 2024a,b). EPA and DHA-supplemented transgenic zebrafish survived by 70% following infection with *Vibrio vulnificus*, whereas wild-type fish survived by only 20% (Cheng et al., 2015). Similar advantages were demonstrated in mouse and caterpillar models. Such effects are not replicated by oral antimicrobial activity *per se* but also by improved immune modulation by increased production of anti-inflammatory cytokines.

Fatty acid structure–activity relation indicates that highly unsaturated and long-chain fatty acids are most effective against microbes. This makes microalgal PUFAs potential candidates for application as food, especially to substitute chemical preservatives with safer, chemical-free, and eco-friendly options. Their application as edible coatings, biodegradable packaging, or as natural food additives can prevent microbial contamination, improve shelf life, and comply with clean-label regulations.

4.1.1 Mechanism of action of antibacterial FAs and PUFAs

The amphipathic nature of FAs and PUFAs allows them to insert into bacterial cell destabilizing the membrane bilayers. This leads to increased permeability, pore formation, and eventual cell lysis. This membrane disruption can lead to either bacteriostatic effects (growth inhibition) or bactericidal effects (cell death). By compromising membrane integrity, FAs and PUFAs interfere with essential bacterial processes such as nutrient transport and osmotic balance, ultimately impairing cell survival (Obukhova and Murzina, 2024; Douglas et al., 2025).

FAs and PUFAs disrupt vital metabolic functions linked to the bacterial cell membrane, including the electron transport chain and oxidative phosphorylation. They may bind to electron carriers, alter membrane potential, and collapse the proton gradient, thereby reducing energy generation (Yoon et al., 2018). Moreover, they can inhibit key membrane-associated enzymes, such as glucosyltransferases, and impair nutrient uptake systems.

4.2 Antimicrobial peptides (AMPs)

Microalgae were found to be an effective source of AMPs which are gaining attention as natural alternatives to synthetic preservatives and conventional antibiotics (Vasquez-Moscoso et al., 2025). The peptides show strong activity against MDR bacteria. The increasing demand for clean-label, green food preservation also supports the investigation of AMPs of microalgal origin. AMPs are typically produced via enzymatic hydrolysis of algal proteins with proteolytic enzymes. Some of the most widely used species to produce peptide-rich protein hydrolysates are *Chlorella vulgaris*, *Chlorella ellipsoidea*, *Tetradesmus obliquus*, *Navicula incerta*, and *Nannochloropsis oculata* (Sathya et al., 2021; Yang et al., 2024). These bioactive peptides provide a range of desirable characteristics, including antioxidant, anticancer, antihypertensive, and strong antimicrobial effects. Notably, their antibacterial activity might be enhanced by structural modification, e.g., by the addition of essential amino acids such as lysine or alanine analogs, without increasing cytotoxicity (Ayswaria et al., 2023).

Peptides isolated from microalgae were shown to have direct antibacterial activity. An example is a 62 kDa peptide isolated from *Chlorella vulgaris* that inhibits *Escherichia coli* by interfering with bacterial cell wall formation (Sedighi et al., 2019). Similarly, peptides from *Chlorella sorokiniana* have been shown to inhibit *E. coli* and *Staphylococcus aureus*, as indicated by agar diffusion assays (Tejano et al., 2019). A heptapeptide (LWFYTMWH) known as AQ-1766, isolated from *Tetraselmis suecica*, exhibited broad-spectrum activity toward major foodborne and clinical pathogens such as *Salmonella typhimurium*, *Bacillus cereus*, *Pseudomonas aeruginosa*, and *methicillin-resistant S. aureus* (MRSA) (Sivakumar and Santhanam, 2011). Some of the antimicrobial peptides derived from microalgae and cyanobacteria along with their target microorganism are given in Table 5.

TABLE 3 Common assays for antimicrobial activity.

Name of the method	Principle	Advantages	Limitations	References
Agar diffusion-based assays	Agar diffusion assays work by allowing antimicrobial agents to diffuse from disks, wells, plugs, or spots into an inoculated agar medium. The resulting clear zone of inhibition indicates the compound's effectiveness, with larger zones reflecting greater antimicrobial activity.	• Simple, low-cost, and easy to perform • Allows testing of multiple samples at once • Indicates relative antimicrobial potency via inhibition zones • Standardized and reproducible • Fast results (18–48 hours) • Offers flexible formats (disc, well, plug, spot)	• Provides only qualitative, not quantitative results • Zone size is affected by temperature, pH, and diffusion properties • Uneven diffusion of extract components may skew results • Less sensitive to weak or low-concentration agents • Not suitable for volatile or heat-labile compounds	(Tarannum et al., 2023; Hossain, 2024)
Co-culture assay	The co-culture assay grows two microbes together to assess if the test organism inhibits the indicator strain. Reduced growth on selective media indicates antimicrobial activity.	• Mimics natural microbial interactions for realistic antimicrobial assessment • Enables real-time observation of test–indicator interactions • Distinguishes between bactericidal vs. bacteriostatic effects • Identifies synergistic or antagonistic relationships • Tracks time-dependent antimicrobial changes • Simple, low-cost, and easy to perform	• Limited for quantitative antimicrobial assessment • Less suitable for non-microbial agents like plant extracts • Mixed media may hinder optimal growth and accuracy • Cross-feeding can complicate result interpretation • Variable interactions may affect reliability and reproducibility	(Maglangit et al., 2020; Jia et al., 2020; Hossain, 2024)
Time kill kinetics	The time-kill kinetics assay evaluates antimicrobial effectiveness by exposing microbes to varying concentrations of the agent over time and measuring the viable cell counts. It reveals the rate and extent of microbial killing or inhibition, distinguishing bactericidal from bacteriostatic effects.	• Tracks microbial killing over time • Reveals the rate and extent of antimicrobial action • Aids in optimizing dose and exposure time • Differentiates bactericidal vs. bacteriostatic effects • Evaluates synergy or antagonism in combinations • More informative than single-time-point assays	• Time- and resource-intensive due to frequent sampling • Lacks insight into killing mechanisms • *In vitro* setup may not reflect *in vivo* complexity • Static concentrations may not mimic real drug dynamics	(Adusei et al., 2019; Hossain, 2024)
Agar dilution and broth dilution methods	Agar and broth dilution methods determine the minimum inhibitory concentration (MIC) by exposing microbes to varying antimicrobial concentrations in solid or liquid media. The MIC is the lowest concentration that completely inhibits visible growth, providing quantitative data for treatment and resistance monitoring.	• Standardized and reliable for MIC determination (CLSI, EUCAST approved) • Agar dilution offers high accuracy and visual clarity • Agar tests multiple strains per plate; broth tests multiple agents per strain • Both provide precise MIC values, unlike disk diffusion • Broth microdilution is fast, cost-effective, and convenient • Semi-automation enhances agar dilution efficiency and consistency	• Time- and labor-intensive due to multiple dilutions • Agar plates have a limited shelf life • Agar tests one agent; broth tests one microorganism at a time • Not ideal for fastidious or slow-growing microbes • Some agents (e.g., oils, extracts) may not mix well or interfere with results • MICs don't reveal mode of action or predict *in vivo* efficacy	(Wu et al., 2015; Golus et al., 2016)
Antimicrobial gradient diffusion test	The antimicrobial gradient diffusion test uses a strip with a concentration gradient placed on an inoculated agar plate. As the agent diffuses, it forms an inhibition ellipse. The MIC is read where bacterial growth meets the zone, providing a precise, quantitative measure of antimicrobial susceptibility.	• Rapid, convenient, and quantitative MIC determination • Highly reproducible with clear, direct MIC reading • Tests multiple agents on one plate • Works for diverse microbes, including fastidious and slow-growing types • Suitable for yeasts, molds, and mycobacteria • Overcomes diffusion issues of disk tests (e.g., vancomycin) • CDC-recommended for detecting resistant strains (e.g., VISA)	• Best suited for antibiotics; less reliable for novel compounds • E-test strips are costly for large-scale use • Visual reading may introduce observer variability • Irregular growth can hinder clear MIC interpretation • Potential MIC bias with certain microbe-drug pairs • Inconsistent results reported for some antibiotics	(Chiu et al., 2021; Hossain, 2024)
Flow cytometry	Flow cytometry uses lasers to analyze cells in fluid flow based on size, granularity, and fluorescence. In antimicrobial studies, fluorescent dyes like SYTO 9 and propidium iodide distinguish live and dead cells, allowing rapid, precise assessment of cell viability and antimicrobial effects.	• Rapid, high-throughput single-cell analysis • Sensitive detection of viability and membrane changes • Differentiates live/dead cells with fluorescent dyes • Provides accurate, quantitative data • Applicable to diverse microbes (bacteria, fungi, parasites) • Ideal for antimicrobial screening and mechanism studies	• Expensive equipment and reagents limit accessibility • Requires skilled personnel and complex protocols • Sensitive to experimental variability, affecting reproducibility • Dyes may alter cell behavior • Less suited for biofilms without modifications	(Adan et al., 2017; McKinnon, 2018)

(Continued)

TABLE 3 (Continued)

Name of the method	Principle	Advantages	Limitations	References
Bioluminiscence assay	The bioluminescence assay uses luciferase-expressing microbes to produce light in proportion to cellular ATP. Antimicrobial agents reduce metabolic activity and ATP levels, leading to decreased light, which reflects microbial viability and antimicrobial effectiveness.	• Versatile and applicable to various microbes and agents • Highly sensitive to changes in viability and metabolism • Enables real-time, non-invasive monitoring • Provides precise, quantitative antimicrobial data • Tracks dynamic microbial responses during treatment	• Requires time-consuming genetic modification • Light output may not directly reflect viability • Compounds can quench or enhance signals, affecting accuracy • Luciferase stability and activity depend on cell state and substrate • External factors may cause false readings	(Chen and Godwin, 2006; Lomakina et al., 2015; Hossain, 2024)

4.2.1 Mechanism of action of antimicrobial peptides

The mechanism of action for most of the microalgal AMPs, while not yet completely understood, is believed to be analogous to that of eukaryotic AMPs. It has been suggested that microalgal AMPs are induced or expressed due to environmental stress or pathogen-induced stress (Zehra et al., 2021; Meena et al., 2022; Tsintzou and Madesis, 2024). The peptides can be disruptive to microbial metabolism or cell integrity. Microalgal fatty acids have also been reported to lyse bacterial membranes, inhibit nutrient uptake, and inhibit respiration, providing a secondary mode of antibacterial action. Cationic peptides target the anionic bacterial membranes and induce disruption and cell lysis (Benfield and Henriques, 2020). Certain peptides exert non-membranous mechanisms such as inhibition of intracellular enzymes essential for bacterial survival. Brunsvicamides of *Tychonema* sp. inhibit phosphatase B of *Mycobacterium tuberculosis* and scyptolin A of *Scytonema hofmanni* inhibits bacterial transpeptidases for cell wall biosynthesis (Rojas et al., 2020).

4.3 Polysaccharides

Polysaccharides are natural polymers of 10 or more monosaccharide units in branched and linear chains. Polysaccharides occur in plants, animals, and microorganisms like microalgae. Polysaccharides in microalgae are of three general types: structural polysaccharides like cellulose in the cell wall, storage polysaccharides like starch and glycogen in the chloroplast, and extracellular polysaccharides secreted outside the cell to facilitate intercellular communication.

Microalgal polysaccharides have attracted significant attention due to their multi-functional uses in the food industry. Microalgal polysaccharides possess superior gelling, stabilizing, and emulsifying properties, and therefore are highly sought after as natural food additives (de Jesus Raposo et al., 2015). Apart from their functional applications, microalgal polysaccharides also possess potential antibacterial activity. Their antibacterial activities against a broad spectrum of Gram-positive and Gram-negative bacteria, including *Escherichia coli*, *Staphylococcus aureus*, *Listeria monocytogenes*, and *Salmonella Typhimurium* have been reported. For instance, sulfated polysaccharides including alginates, fucoidans, and laminarin, isolated from algae like *Chaetomorpha aerea*, *Ascophyllum nodosum*, and *Laminaria hyperborea*, exhibit high antibacterial activities against these bacteria with MICs of about 50 mg/mL (Ilieva et al., 2024a,b; Parsaeimehr and Lutzu, 2016; Moreira J. B. et al., 2023; Mohan and Thirupathi, 2022; McGurrin et al., 2025).

4.3.1 Mechanism of action of antibacterial polysaccharides

The antibacterial effect of polysaccharides is multifaceted and intricate. They primarily disrupt the integrity of bacterial cell walls and membranes, causing leakage of cellular material and resultant cell death. Polysaccharides disrupt the formation of bacterial biofilms, which are involved in chronic food surface contamination (Singh et al., 2021). They disrupt bacterial metabolism and protein synthesis, thus preventing cell growth and reproduction. A second vital mode of action is direct interaction with bacterial DNA and plasmids. Some polysaccharides can interact with genetic material, inhibiting essential processes such as replication, transcription, and translation. Furthermore, most polysaccharides possess an anionic nature, which allows them to chelate metal ions such as iron. Since iron plays a vital role in bacterial metabolism and multiplication, the removal of iron from the environment may trigger a cut-off effect on bacterial viability (Zhao et al., 2023; Shankar and Akhter, 2024). The hydroxyl and carboxyl functional groups of the polysaccharides enhance the metal-binding ability, further inhibiting bacterial growth. Figure 5 illustrates the antibacterial mechanisms of action of polysaccharides.

For food preservation, these bioactive polysaccharides are of immense promise. Microalgal polysaccharide-fortified edible films and coatings, as physical barriers and also with antimicrobial protection, enhance shelf life and food safety (Fan et al., 2025). Due to their natural origin, biodegradability, and wide-spectrum activity, they are the most suitable alternatives to substitute synthetic preservatives in the food system. More studies on their extraction, modification, and uses will result in more applications in food packaging and food safety technology.

5 Other applications of microalgal extracts in the food system

5.1 Microalgae-based films and coatings in food packaging

Microalgae-based films and coatings have emerged as eco-friendly and multifunctional materials with significant potential in the food industry. These biopolymer coatings contribute to

TABLE 4 Antibacterial fatty acids derived from microalgae and cyanobacteria, sources, and mechanisms of action.

FA/PUFA	Source organism	Target microorganisms	Mechanism(s) of action	Reference
EPA (20:5 n-3)	*Phaeodactylum tricornutum*	*S. aureus*, Gram-negative spp.	Membrane destabilization, increases permeability, lysis, disrupts ETC/potentially ATP synthesis	(Desbois et al., 2009)
Hexadecenoic acid (C16:1, palmitoleic)	*P. tricornutum*	*S. aureus*, Gram-positive spp.	Rapid bactericidal via membrane disruption at micromolar levels	(Desbois et al., 2009)
Hexadecatrienoic acid (C16:3 n-4)	*P. tricornutum*	*Listonella anguillarum* (Gram-negative), Gram-positives spp.	Membrane disruption leading to bacteriostatic.	(Hussein et al., 2020)
ALA (α-linolenic acid, 18:3 n-3)	*Chlorella* sp.	Gram-negative bacteria	Increases membrane permeability, causing lysis	(Hussein et al., 2020)
EPA (20:5 n-3)	*Nannochloropsis oculata*	Gram-negative bacteria	Membrane disruption leading to bacterial lysis	(Hussein et al., 2020)
GLA (γ-linolenic acid, 18:3 n-6)	*Arthrospira platensis*	Gram-positive bacteria	Membrane insertion and destabilization; oxidative stress induction	(Ilieva et al., 2024a)

TABLE 5 Some peptide derived from microalgae and cyanobacteria along with their antimicrobial activity.

Peptide	Source organism (Microalga/Cyanobacteria)	Reported antimicrobial targets	References
AQ-1766 (LWFYTMWH)	*Tetraselmis suecica*	*E. coli*, *Salmonella typhimurium*, *Pseudomonas aeruginosa*, *Bacillus cereus*, MRSA, *Listeria monocytogenes*, and *Micrococcus luteus*	(Guzmán et al., 2019)
P6 (RKLLRVIKDLIK)	*Aureococcus anophagefferens*	*E. coli*, *Staphylococcus aureus*, *Micrococcus luteus*, and *Pichia pastoris*	(Zhang et al., 2024)
Kawaguchipeptins A and B and Norharmane-HCl [9H-pyrido (3,4-b) indole-HCl]	*Nodularia harveyana*	*E. coli*, *P. aeruginosa*, *S. aureus*, and *B. subtilis*	(Ishida et al., 1997)
Aeruginazole A	*Microcystis* sp.	*Bacillus subtilis* and *S. aureus*	(Raveh and Carmeli, 2010)
Lyngbyazothrins A–D	*Lyngbya* sp.	*B. subtilis*, *E. coli*, *P. aeruginosa*, and *Serratia marcescens*	(Dussault et al., 2016)
Laxaphycin B (synergizes with Laxaphycin A)	*Anabaena laxa*	Broad (bacteria and fungi)	(Frankmölle et al., 1992)
Schizotrin A	*Schizothrix* sp.	*B. subtilis* (strong), weak vs *S. aureus*	(Cao et al., 2020)
Microcystin	*Synechocystis*, *Synechococcus*	*P. aeruginosa*, *S. aureus*	(Barboza et al., 2017)
Brunsvicamides A B and C	*Tychonema* sp.	*S. aureus*	(Weiss et al., 2000)
Pahayokolide A	*Lyngbya* sp. (now *Moorea*)	*Bacillus megaterium*, *B. cereus*	(Xue et al., 2018)

preserving food quality, enhancing nutritional value, and extending the shelf life of a wide variety of products such as cereals, fruits, vegetables, meat, and seafood. One of the key advantages of these coatings is their ability to minimize moisture loss, maintain fruit firmness, and delay senescence, thereby ensuring longer freshness during storage (Morales-Jiménez et al., 2020; Shirai et al., 2025; Moreira A. S. et al., 2023).

Recent studies have confirmed the efficacy of microalgae-enriched coatings. A recent study by Onias et al. assessed the postharvest quality of Tommy Atkins mangoes with cassava and corn starch films enriched with *Spirulina platensis*. Mangoes were treated with six different coatings and stored for 12 days at 10 °C and 63% relative humidity. The B5 coating (3% cassava starch + 3% *Spirulina*) maximally enhanced the soluble solid content up to the eighth day, firmness was maintained, and weight loss was minimal. The B6 coating (3% corn starch + 3% *Spirulina*) was the best, enhancing the vitamin C content to 25 mg/100 g on day 11, maintaining firmness at 15 *N*, and inhibiting weight loss of <4% (Onias et al., 2016).

De Medeiros Teodosio et al. examined the use of microalgae-based coatings for *Spondias tuberosa* fruit with *Chlorella* sp. and pomegranate seed oil (PSO) in another study. The fruits were stored at 14 ± 2 °C and 85 ± 5% RH for 12 days. The 2% *Chlorella* sp. coating was the most effective in slowing down ripening, firmness, and weight being preserved, and the color being greener compared to uncoated control fruits (de Medeiros Teodosio et al., 2021). This demonstrates the potential of *Chlorella*-based coatings in ensuring postharvest shelf life under cold storage. In a similar context, de Oliveira et al. studied the application of *Chlorella* sp. coatings for keeping Tommy Atkins mangoes stored at room temperature (23 °C). Peel and pulp color parameters showed that ripening was slowed with higher *Chlorella* concentrations. Mangoes treated with 2% *Chlorella* sp. contained more organic acids, and they were firmer, hence maintaining their quality for

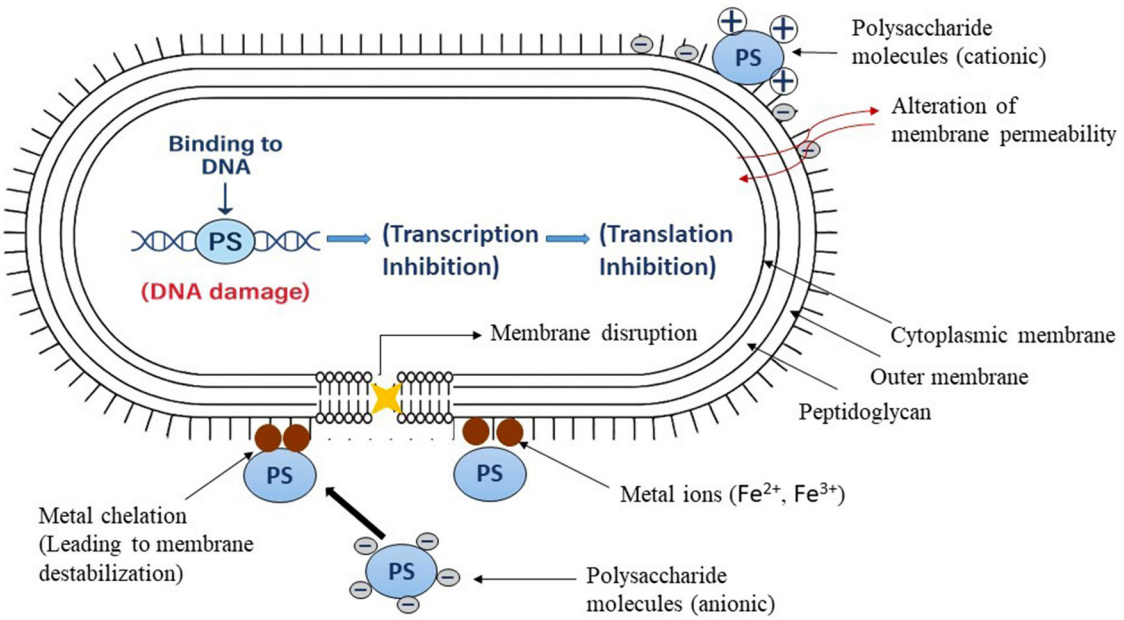

FIGURE 5
The antibacterial action of polysaccharides in bacterial cells resulting in cell death (Teixeira-Santos et al., 2021).

10 days under 42% RH conditions (Oliveira et al., 2018; Alves et al., 2025). These results justify the industrial application of *Chlorella*-derived biofilms for keeping fruit quality under non-refrigerated storage.

5.2 Nanotechnology in microalgal-based food preservatives

Nanotechnology is another cutting-edge field in which microalgae are revolutionizing. Because of their size-dependent optical characteristics, nanodots (NDs) have drawn interest for use in food and biological science applications (Pyne et al., 2022). By altering their size and structure, they can be made to better absorb and emit light, providing special possibilities for creating biosensors and smart packaging materials (De Vries et al., 2015). The biogenic synthesis of nanoparticles using microalgae is a green chemistry technology that stands out among other synthesis methods. This method can create non-toxic and sustainable nanoparticles with a variety of compositions and physicochemical properties appropriate for use in the food system (Das et al., 2016). Microalgae-derived nanoparticles exhibit advantageous characteristics for applications in antimicrobial coatings, active packaging, and as carriers for bioactive chemicals. These nanoparticles improve oxidative stability and microbial suppression when added to edible films or sprayed on food surfaces. These applications provide a sustainable answer to contemporary food preservation issues by substituting naturally derived components for artificial additives.

6 Comparison with plant-based extracts

While both microalgal and plant-based extracts are highly valued for their natural preservative properties, their biochemical composition is not always the same. Terrestrial plants such as rosemary, oregano, and green tea are rich in well-known antioxidants like phenolic acids, flavonoids, and essential oils (Calderón-Oliver and Ponce-Alquicira, 2021). Whereas microalgae offer unique compounds such as astaxanthin, fucoxanthin, and phycobiliproteins metabolites that are rarely found in plants. Astaxanthin is reported to be significantly more effective than vitamin C and vitamin E in neutralizing reactive oxygen species (Chini Zittelli et al., 2023; Yadav et al., 2025).

Moreover, microalgae can be cultivated under controlled photobioreactor or open-pond conditions without the use of agricultural lands, ensuring consistent quality and bioactive content. Plants are more prone to seasonal and environmental fluctuations. On the other hand, plant-based extracts benefit from centuries of safe use in food systems, well-established regulatory approval, and lower production costs. This historical familiarity gives plant extracts a head start in consumer trust and acceptance, while microalgae still need to overcome perception barriers and production scalability challenges.

7 Consumer acceptance

Consumer perception plays an important role in the market success of a product. While plant extracts enjoy high familiarity

and acceptance, microalgal products are often perceived as novel or unconventional. The unfamiliarity of microalgal food leads to skepticism regarding their taste, safety, and overall appeal. Consumer perception of microalgae varies greatly across regions. In East Asia (Japan, China, Korea), people are already familiar with algal food, therefore, consumer acceptance is high in comparison to Western countries (Wassmann et al., 2024). Blending microalgal extracts with plant-based ingredients can enhance familiarity while retaining functional benefits. Educational campaigns, transparent labeling, and the promotion of health benefits such as high antioxidant content, omega-3 enrichment, and sustainability can help shift consumer perception. Products targeting health-conscious demographics, including athletes, vegetarians, and individuals seeking functional foods may experience higher adoption rates.

8 Safety considerations and potential toxicity

While microalgal antioxidant-rich extracts are already finding applications in the food, cosmetic, and nutraceutical sectors, the precise assessment of antioxidant activity remains challenging. Some bioactive compounds such as free fatty acids (FFAs) and polyunsaturated fatty acids (PUFAs) are chemically unstable (Kiani et al., 2022). These can be overcome with the use of advanced formulation technologies like nanoencapsulation, emulsification, or co-formulation with synergistic agents.

Microalgal extracts require a thorough safety evaluation before widespread adoption in the food industry. Certain species among cyanobacteria can produce harmful metabolites such as microcystins, anatoxins, or saxitoxins, which are toxic to humans and animals (Nowruzi and Porzani, 2021; Chittora et al., 2020). Therefore, strain selection and cultivation under controlled, monitored conditions are critical to ensure food-grade safety. Another consideration is the high nucleic acid content in some microalgal biomass, which may increase uric acid levels when consumed in excess, potentially contributing to gout or kidney problems (Martínez-Ruiz et al., 2025). Ensuring the use of food-safe solvents and complete removal of extraction residues is essential for safe application of microalgal bioactive. Before industry-wide adoption, it is required to conduct systematic studies including in-product challenges, stability assessments in real matrices, toxicology and allergenicity evaluation, and compliance with food safety regulations (e.g., FSSAI, GRAS).

9 Conclusion and future prospects

Microalgae have been found to be an extremely promising source of natural bioactive compounds consisting of antioxidants (e.g., carotenoids, phenolics), antimicrobials (e.g., fatty acids, polysaccharides, etc.), and other functional biomolecules (Sangela et al., 2022). Considering recent advances in large-scale microalgal cultivation, eco-friendly extraction technologies, it is possible that microalgal-derived preservatives could progressively replace certain synthetic preservatives within the next decade. However, achieving full market penetration will require overcoming challenges related to production costs and batch-to-batch variability in bioactive content. Establishing comprehensive safety and efficacy profiles through regulatory approval processes would increase consumer acceptance.

Future studies should focus on optimizing the delivery systems in addition to searching for innovative strains and stress-induced cultivation protocols to enhance the yield and activity of microalgal bioactive compounds. If these challenges are addressed through integrated biorefinery approaches and optimized supply chains, microalgal preservatives could become competitive natural alternatives in food industries.

Author contributions

LS: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. PKumari: Conceptualization, Data curation, Methodology, Validation, Visualization, Writing – review & editing. PKumar: Formal analysis, Investigation, Methodology, Writing – review & editing. AY: Formal analysis, Investigation, Methodology, Writing – review & editing. RB: Investigation, Methodology, Project administration, Resources, Writing – review & editing. PS: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MM: Conceptualization, Investigation, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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