



Microalgae-Derived Bioactive Compounds: An Overview of Extraction, Biological Activities, and Applications

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ABSTRACT

The global food sector is facing an increasing demand for natural and organic food, while the health sector is confronting pressure from antimicrobial resistance, chronic disorders and diseases associated with oxidative stress. Traditional resources have achieved only partial success in addressing these challenges because their low sustainability, limited availability, and side effects make it difficult to resolve the above-mentioned challenges. Microalgae including cyanobacteria have become prominent bioresource in many industries (pharmaceuticals, nutraceuticals, food and cosmetics) because of their ability to produce variety of high-value bioactive compounds. These organisms can be cultivated on non-arable land using wastewater with minimal freshwater requirements compared with terrestrial plants and can sequester carbon dioxide, making them a sustainable, environmentally friendly resource. This review summarizes the recent studies about the microalgae derived bioactive compounds and their bioactivity and their industrial applications. Microalgae synthesize different classes of metabolites including proteins and amino acids, polysaccharides, vitamins, pigments (mainly chlorophyll, phycobiliproteins and carotenoids), phenolic compounds and polyunsaturated fatty acids (PUFAs). These compounds typically exhibit antioxidant, antimicrobial, anticancer, photoprotective and anti-inflammatory activities. The diversity of metabolites found in microalgae is a result of evolutionary response to survive under abiotic stresses such as high salinity, extreme temperatures and pH, nutrient deficiencies and extreme ultraviolet radiation. This review also discusses the market potential, extraction strategies and cultivation methods for pilot-scale production of these compounds. Microalgae are proposed as a key future contributor to meeting global health and nutrition goals.



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Introduction

Recently, the urge to produce sustainable and nutrient-dense food has been rapidly increasing which developed a greater interest of scientists to find the alternative sustainable bioresources enriched with bioactive compounds. Microalgae are photosynthetic organisms that have short doubling time, high adaptability to diverse environmental conditions and accumulate various high-value metabolites which make them good candidates (Prates, 2025; Zhou et al., 2022). Unlike plants that need fertile land, high volumes of freshwater and specific seasons to grow, microalgae can be cultivated year-round using brackish water under controlled conditions to produce high-value compounds (Abdur Razzak et al., 2024). Around 7000 species of microalgae are reported so far and they can be found in sea water, freshwater and brackish habitats (Queiroz et al., 2020). For commercial purposes, microalgae can be cultivated in open ponds as well as in closed bioreactors but the latter option provides better cultivation control and a lower contamination risk (Abdur Razzak et al., 2024). Microalgal cells offer laborious extraction of bioactive compounds because of the presence of complex cell wall which makes it difficult

and economically challenging to extract metabolites by cell disruption during downstream processing (Nunes et al., 2023).

Currently, international microalgae market is estimated to be growing at an average annual rate of 6.8%, reaching about USD 2 billion by 2030 (Adarchenko et al., 2024). The global microalgae market was estimated at about USD 1.5 billion in 2023 and expected to be increased to USD 2.9 billion by 2030 (Shahid et al., 2024). Currently, the high demand for natural foods and organic raw materials for cosmetics and pharmaceuticals is the driving force behind this rise. Microalgae biomass contains numerous valuable metabolites such as pigments, lipids, proteins, vitamins and phenolic compounds (Osathanunkul et al., 2025; Silva et al., 2022). The global shift in consumer demand from synthetic products to cleaner, organic and natural products attract attention toward microalgae-based applications (Hachicha et al., 2022). This review integrates the existing literature to microalgae-derived bioactive compounds, their biochemical activity and industrial applications. This review highlights the challenges and possibilities of producing and extracting bioactive compounds from microalgae.

Types of Bioactive Compounds from Microalgae

Microalgae accumulate several metabolites through primary and secondary metabolic pathways. These metabolites help manage abiotic stress, provide photoprotection and facilitate cell division and growth at the cellular level (Vanthoor-Koopmans et al., 2013). Major classes of these metabolites are listed in Table 1 given below.

Table 1. Major metabolites produced by microalgae

Compound type	Examples	Microalgae strain	Biological functions	References
Polysaccharides	β -glucans, Sulphated polysaccharides	<i>Chlorella</i>	Antioxidant and antiviral properties	(Raposo et al., 2013; Tsvetanova & Yankov, 2022)
Carotenoids	Astaxanthin, β -carotene, lutein and fucoxanthin	<i>Haematococcus</i> , <i>Dunaliella</i> and <i>Phaeodactylum</i>	Act as antioxidants, anti-inflammatory and anti-cancerous agents	(Pereira et al., 2021; Shi et al., 2023)
Phycobiliproteins	Phycoerythrin and phycocyanin	<i>Spirulina</i> and <i>Porphyridium</i>	Antioxidant, anti-inflammatory and fluorescent properties	(Citi et al., 2024; Pham Thi Bich et al., 2021)
Polyunsaturated fatty acids (PUFAs)	docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA)	<i>Nannochloropsis</i> , <i>Schizochytrium</i> and <i>Pavlova</i>	Improve cardiac health and produce anti-inflammatory effects	(Calder, 2012; Remize et al., 2021)
Proteins or Peptides	Antimicrobial peptides and angiotensin-I-converting enzyme (ACE)-Inhibitory Peptides	<i>Chlorella</i> , <i>Spirulina</i> and diatoms	Antihypertensive, antimicrobial and antioxidant	(Batista et al., 2017; Becker, 2007)

Vitamins	Vitamin E, B12, K1 and β -carotene	<i>Dunaliella</i> , <i>Chlorella</i> and <i>Nannochloropsis</i>	Antioxidant and nutritional supplements	(Kholany et al., 2022; Santoro et al., 2019)
Sterols	β -sitosterol, fucosterol, campesterol	<i>Pavlova</i> and <i>Tetraselmis</i>	Reduce cholesterol levels and produce anti-inflammatory properties	(de Jesus Raposo et al., 2015)
Phenolic compounds	Gallic acid and quercetin	<i>Nannochloropsis</i> and <i>Phaeodactylum</i>	Antioxidant, anticancer and antimicrobial	(Kuntzler et al., 2018)
Mycosporine like amino acids (MAAs)	Shinorine and porphyra-334	<i>Cyanobacteria</i> and <i>Porphyridium</i>	Antioxidant and photoprotection	(Hachicha et al., 2022; Mehariya et al., 2021)

Polysaccharides

Microalgae accumulate different kinds of β -glucans and sulphated polysaccharides. These bioactive compounds show several biological activities (Raposo et al., 2013). The red microalgae *Porphyridium* produces sulphated polysaccharides that predominately exhibit antiviral and antioxidant properties (Tsvetanova & Yankov, 2022). These compounds act like heparin sulphate in order to prevent virus entry into host cell by blocking virus attachment to cell membrane. The sulphated polysaccharides extracted from *Porphyridium* when used against simplex virus type 1 and 2 showed significant antiviral activity with IC₅₀ value as low as 0.6 μ g/mL (Huleihel et al., 2001). Clinical trials have shown that β -glucans supplementation can provide benefits such as lower cholesterol, improved innate immunity and better blood glucose management (Sinangil et al., 2022). Apart from these benefits β -glucans are also reported to alter gut microbiota, increasing the beneficial bacteria while suppressing the pathogenic species.

Carotenoids

Carotenoids are orange, yellow and red organic pigments that has integral role photosynthesis and photoprotection. Astaxanthin, lutein, β -carotene and fucoxanthin are the major forms of pigments found in this class (Pereira et al., 2021). *Haematococcus pluvialis* accumulates astaxanthin which is approximately 14 times a more effective antioxidant than vitamin E (Shi et al., 2023). These exceptional results are attributed to the structure of astaxanthin which allows it to span the cell membrane and eliminate free radicals inside and outside the cell. These compounds improve cardiovascular health and show neuroprotection and anti-obesity properties (Genç et al., 2020). Diatoms produce fucoxanthin which has been studied for their biological activities including anticancer, antidiabetic and anti-obesity properties (Ren et al., 2021). Fucoxanthin helps combat obesity by inducing uncoupling protein 1 (UCP1) and increasing energy expenditure and restricting fat storage (Ren et al., 2021). β -carotene extracted from *Dunaliella salina* is a well-known natural colorant and a provitamin A source. A study reported that β -carotene accumulation was increased by up to 12.6% when *D. salina* was cultivated under stress conditions (Abd El-Baky & El-Baroty, 2013). Under stress conditions, β -carotene protects cells against photo-oxidative damage by nullifying the effects of reactive oxygen species (ROS) (Abd El-Baky & El-Baroty, 2013). Lutein is widely used as supplement for eye health and it is majorly consumed with other supplements to help prevent macular degeneration (Spinola & Díaz-Santos, 2020).

Additionally, lutein is deposited in the macula of eye, where it absorbs harmful blue light and protects retinal cells from oxidative stress.

Phycobiliproteins

Phycobiliproteins are water soluble pigments responsible for light harvesting in microalgae. They are mostly found in blue-green algae (cyanobacteria) and red algae and have been widely used in pharmaceutical industry as anticancer and anti-inflammatory agents (Pham Thi Bich et al., 2021). Phycobiliproteins are also used as fluorescence tool in flow cytometry and immunofluorescence microscopy because of their unique spectral features, particularly their fluorescence. They have attracted considerable attention due to their antioxidant, antitumor and neuroprotective properties (Rojas-Franco et al., 2018). They have shown great potential in killing cancer cells without affecting normal cells with selective cytotoxicity reported in some cell lines. (Kt, 2024). This programmed cell death is attributed to induced apoptosis through mitochondrial pathways while cancer cell proliferation is restricted through cell cycle arrest (Kt, 2024; Rojas-Franco et al., 2018). Phycocyanin produced by *Spirulina*, when tested for its therapeutic potential, has been reported to show significant results against inflammatory diseases by inhibiting the production of pro-inflammatory cytokines (TNF- α and IL-6) (Citi et al., 2024).

Polyunsaturated Fatty Acids (PUFAs)

Microalgae biomass is enriched with valuable long-chain PUFAs particularly EPA and DHA (Remize et al., 2021). These fatty acids are known to boost immunity and support neurological and cardiovascular health (Calder, 2012). DHA, being crucial component of brain grey matter and retinal photoreceptors, regulates membrane fluidity and supports synaptic plasticity (Calder, 2012). For industrial scale PUFAs production, species such as *Schizochytrium sp.*, *Nannochloropsis gaditana*, and *Phaeodactylum tricornutum* are cultivated on a large scale (Santoro et al., 2019). DHA and EPA are documented to reduce the formation of pro-inflammatory eicosanoids (Łacheta et al., 2019). They perform this task by competing with arachidonic acid for incorporation into cell membranes, thereby reducing the formation of pro-inflammatory leukotrienes and prostaglandins. Microalgae-derived PUFAs are a promising alternative to high-demand fish oil (Liu et al., 2022). Microalgae are vegan friendly producers of these essential fatty acids because they eliminate concerns related to overfishing and mercury contamination (Remize et al., 2021).

Proteins and Peptides

Microalgae produce proteins with essential amino acids are comparable to those from animal sources (Peltomaa et al., 2017). Among various microalgal species *Spirulina* and *Chlorella* show the highest protein contents, of 50-70% and 40-60% of dry weight, respectively (Batista et al., 2017). The high protein content and essential amino acids profile are comparable to those of eggs and align quite well with human protein requirements (Batista et al., 2017; Becker, 2007). Peptides produced by microalgae have shown antioxidant, antimicrobial and anticancer properties (da Silva et al., 2019). These bioactive peptides are usually present in the form of complex proteins and can only be released by hydrolysis using proteases such as pepsin, trypsin, and alcalase (Barreira et al., 2019; da Silva et al., 2019). Bioactive peptides extracted from *Tetraselmis suecica* have shown antimicrobial activity against both Gram-positive and Gram-negative bacteria (Barreira et al., 2019). These bioactive peptides kill bacterial cells by disrupting their cell walls, leading to loss of cellular components and ultimately leading to cell death.

Vitamins

Microalgae have been documented to produce a variety of essential vitamins including provitamin A carotenoids, vitamin E, vitamin B12 and vitamin K1 (Sivaramakrishnan et al., 2025). *Dunaliella salina* is a rich source of provitamin A, with approximately 10-14% β -carotene by dry weight (Santoro et al., 2019). *Nannochloropsis* and *Chlorella vulgaris* contain significant quantities of B12, sufficient to fulfil daily nutritional requirements (Kholany et al., 2022). Microalgae can accumulate vitamin B12 which can be particularly important for vegans because it is usually absent from plant-based food sources and its deficiency can lead to neurological problems and anaemia (Kholany et al., 2022). Vitamin E produced by microalgae is a structural component of lipids in cell membranes and provides protection from oxidative damage while vitamin K1 is involved in bone metabolism and blood coagulation (Ajila et al., 2007).

Sterols

Microalgae synthesize a variety of phytosterols such as stigmasterol, β -sitosterol, fucosterol and campesterol. These bioactive compounds are well known to reduce cholesterol levels by inhibiting its absorption in gut through competition at the NPC1L1 transporter (de Jesus Raposo et al., 2015). Their mode of action is quite similar to that of sterols and stanols extracted from plants and they are widely used as food ingredients for regulating cholesterol (Bermejo et al., 2008; Pierre et al., 2019). Studies have reported a reduction of 8-10% in low-density lipoprotein (LDL) with consumption of 2g of phytosterols per day (Bermejo et al., 2008). In addition, fucosterol has been demonstrated to produce antidiabetic, anti-obesity and anti-Alzheimer's effects (Meinita et al., 2021). Fucosterol-mediated gains are due to various mechanisms including protection against amyloid-beta induced neurotoxicity, suppression of enzymes such as α -amylase and α -glucosidase and alteration of inflammatory-related metabolic pathways (Apone et al., 2019).

Phenolic Compounds

Phenolic compounds are typically accumulated by microalgae under stress conditions and they are well documented for their biological activities such as antioxidant, anti-inflammatory and antimicrobial properties (Kuntzler et al., 2018; Moreira et al., 2018). Phenolic compounds neutralize free radicals because of their ability to donate electrons and hydrogen, thereby providing protection against oxidative damage to cells (Goiris et al., 2012). The phenolic-enriched extracts knock down the genes involved in inflammation through the inhibition of the NF- κ B signalling pathway (Moldovan et al., 2017). Phenolic compounds extracted from microalgae are being used in the beauty products because of their anti-aging and photoprotective qualities (Kalasariya & Pereira, 2022). Anti-aging effects provided by phenolic compounds are attributed to their ability to suppress matrix metalloproteinases (MMPs) which are responsible for degrading collagen and elastin found in skin.

Mycosporine-like Amino Acids (MAAs)

MAAs are water-soluble amino acids that absorb UV radiations and dissipate the energy as heat without generating free radicals (Hachicha et al., 2022). MAAs can absorb UV radiation in the UV-A and UV-B regions, typically at wavelengths ranging from 310 nm to 362 nm (Hachicha et al., 2022; Sánchez-Muñoz et al., 2020). They have been shown to accelerate wound healing, promote oral photoprotection and anti-aging effects because of their antioxidant and anti-inflammatory properties (Mehariya et al., 2021; Sánchez-Muñoz et al., 2020). MAAs have been documented to protect human keratinocytes by inhibiting the formation of cyclobutane pyrimidine dimers (CPDs), thereby preventing the UV-induced mutations (Mehariya et al., 2021).

Alkaloids

Alkaloids are typically produced by a limited number of microalgal strains but have been shown to have significant biological properties (Lim et al., 2019).

Cyanobacteria synthesize dolastatin-10, which has the potential to treat leukaemia and other cancers in combination with other drugs. Dolastatin-10 stops cancer cell proliferation by inducing cell cycle arrest which is achieved by suppressing tubulin polymerization (Dufossé, 2008).

Cultivation and Extraction Methods

Cultivation Systems

Microalgae are commonly cultivated in two types of systems, namely open raceway ponds and closed photobioreactors (PBRs). Closed PBRs offer high biomass productivity and bioactive compound yield because of better control over cultivation conditions (temperature, pH, light intensity, nutrient level) whereas open raceway ponds are highly susceptible to contamination and environmental fluctuations but have lower management costs (Bhatnagar et al., 2023; da Silva et al., 2019). The selection of a cultivation system is highly dependent upon the target metabolite, closed PBRs are used for the production of high-value while open pond systems are preferably used for commercial applications (da Silva et al., 2019). Stress induced metabolites production is also being used for specific metabolites production. For example, nitrogen limitation is well documented to be associated with improved lipid and carbohydrate content but decreased the accumulation of proteins (Chen et al., 2017). This is a stress response in which microalgal cell stops cellular activities such as growth and division and utilizes available carbon to produce the energy storage compounds rather than proteins (Vanthoor-Koopmans et al., 2013).

Light availability and carbon source primarily influence metabolite production. Currently three major trophic modes (photoautotrophic, heterotrophic and mixotrophic) are used according to the requirements of the final product. Photoautotrophic cultivation involves light and aeration, whereas heterotrophic cultivation is performed in the absence of light, with the addition of an external organic carbon source and is usually aimed at higher biomass productivity. Mixotrophic cultivation is performed under light with an additional organic carbon source and aims to promote the pigment production that is usually lost in heterotrophy (Su et al., 2023). The cultivation mode greatly influences the final metabolic profile, with photoautotrophic conditions favouring the production of pigments and PUFAs, while the heterotrophic mode improves biomass productivity and overall lipid content (Su et al., 2023; Vanthoor-Koopmans et al., 2013).

A two-stage cultivation strategy is now prevalent, firstly, normal conditions are used to grow microalgae followed by a stress phase is introduced to induce metabolite accumulation (Su et al., 2023). This approach is appreciated because it provides higher biomass along with improved metabolites through the selective manipulation of cultivation conditions (Kt, 2024).

Extraction Methods

Cell disruption is the primary step in obtaining the microalgal extract and is usually followed by separation and purification. Cell disruption can be achieved mainly through mechanical (ultrasonication, bead milling and high-pressure homogenization) and non-mechanical methods (freeze-thaw, autoclaving, microwave and pulsed electric field). Cell disruption is a critical step because its efficacy greatly influences both the release of targeted metabolites and their quality (Schneider et al., 2022).

Traditional methods (maceration and Soxhlet extraction) are less sustainable because they require large volumes of organic solvents, longer times and higher costs (Schneider et al., 2022), whereas non-conventional methods are more sustainable, faster and more effective. The selection of the extraction method is highly dependent on the biochemical nature of the target compound, for example, polar solvents are well suitable for phenolic compounds, while non-polar solvents are highly efficient at extracting lipids and carotenoids.(Cheirsilp et al., 2023)

Ultrasound-Assisted Extraction (UAE)

In UAE, ultrasound waves are used to induce cavitation in the cell wall, which allows the release of bioactive compounds into the surrounding solvent. This process offers faster extraction and can be combined with solvents to improve the final yield. In UAE extraction, cavitation create a localized increase in temperature and pressure, which degrade the cell wall, producing micropores and increasing the rate of transfer of cellular contents into the extraction solvent (Sethi & Rathod, 2026).

Microwave-Assisted Extraction (MAE)

MAE is a time efficient technique in which microwave radiations produce heat that causes cell disruption in the sample, promoting mass transfer out of the cells. Microwave radiation generates heat, which ultimately reduces the cell's moisture content, causing the cell to dry and cell wall to rupturing, thereby facilitating the release of metabolite contents (Stavridou et al., 2024).

Supercritical Fluid Extraction (SFE)

In this technique supercritical CO₂ is used as solvent to extract lipophilic compounds such as carotenoids and fatty acids. It offers higher selectivity without the need for organic solvents. This technique achieves selective extraction of particular compounds by using the tunable solvating power of supercritical CO₂, which can be controlled by adjusting temperature and pressure (Yeh et al., 2023).

Enzyme-Assisted Extraction

Catalytic enzymes are used to break cell walls and release intracellular metabolites under optimum conditions. Enzymatic extraction enables processing without high thermal or pressure input, therefore this technique is highly suitable for heat sensitive compounds that may degrade under high temperature and pressure (Udaypal et al., 2024).

Pressurized Liquid Extraction (PLE)

PLE uses high temperature and pressure to enhance solvent extraction efficiency. It reduces both solvent usage and extraction time. The high temperature used in PLE improves the solubility of target compounds and reduces solvent viscosity, while high pressure increases the boiling point of the solvent and keeps it in a liquid state above its normal boiling point (Ashour & Omran, 2022).

Green extraction is considered an alternate to conventional methods where solvents such as ionic liquids (ILs), natural deep eutectic solvents (NADES), deep eutectic solvents (DES) are used. Sugars and organic acids are used to obtain NADES which are biodegradable, nontoxic and well suited for use in the pharmaceutical and food industries (Rotter et al., 2021). The sustainable goals of green extraction include reduced energy consumption, the discovery of renewable extraction solvents and minimal waste production (Ashour & Omran, 2022).

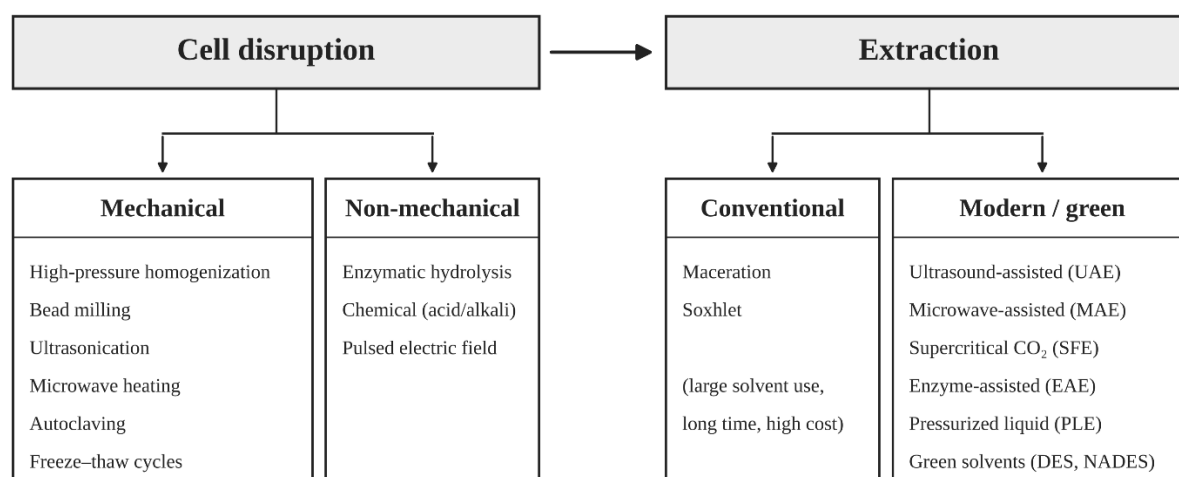


Figure 2. Methods for cell disruption and extraction of valuable compounds from microalgae.

Biological Activities and Health Benefits

Antioxidant Activity

Many bioactive compounds produced by microalgae show strong antioxidant activity by free metal chelation, neutralization of radical and downregulation of lipid peroxidation (Goiris et al., 2012). Among different classes of metabolites carotenoids, phenolic compounds, and phycobiliproteins are the potent antioxidants (Foo et al., 2017). These compounds exhibit antioxidant properties through the direct nullification of free radicals, the chelation of metal ions involved in the formation of free radicals and an increase in the cellular antioxidant enzymes (Foo et al., 2017; Goiris et al., 2012)

Astaxanthin produced by *Haematococcus pluvialis* showed higher antioxidant activity than other carotenoids (Shah et al., 2016). Astaxanthin's ability to scavenge free radicals is attributed to its structure where terminal rings contain hydroxyl and keto groups can donate hydrogen atoms or electrons to neutralize free radicals

which has that can donate (Shah et al., 2016; Shi et al., 2023). Microalgal extracts enriched with phenolic compounds have been reported to show DPPH and ABTS radical-scavenging activities, with IC₅₀ values as low as 45 µg/mL (Jerez-Martel et al., 2021). These findings put microalgae in a strong position for testing as a tool against oxidative stress in biological systems.

Anti-inflammatory activity

Microalgae contains many bioactive compounds that can suppress inflammatory metabolic pathways through the inhibition of cytokines and enzymes such as cyclooxygenase-2 (COX-2) and inducible nitric oxide synthase (iNOS) which are pro-inflammatory elements (Elbandy, 2022). Low production of these enzymes indirectly helps to reduce pain and inflammation by lowering the production of nitric oxide and prostaglandins, both of which act as key mediators of these processes. Another similar study reported that phycocyanin obtained from *Spirulina* suppressed COX-2 and iNOS production, while macrophages were significantly increased (Finamore et al., 2017). These anti-inflammatory effects are due to phycocyanin's ability to knock down inflammatory gene expressions by inhibiting NF-κB activation of (Finamore et al., 2017).

Antimicrobial Activity

Microalgal extracts have been found to contain biological compounds with effective antimicrobial activity against Gram-negative and Gram-positive bacteria (Alsenani et al., 2020). Fatty acid methyl esters (FAME) extracted from *Isochrysis galbana* and *Scenedesmus sp.* showed high inhibitory activity against Gram-negative bacteria (Cepas et al., 2021). These fatty acids disrupt bacterial cell walls, making them more permeable, thereby causing the bacteria to lost cellular content to die.

Another similar study showed that bioactive compounds such as lauric acid, stearic acid and myristic acid in the microalgal extract were effective against Gram-negative bacteria, while monounsaturated fatty acids (MUFAs) and PUFAs were shown to have antimicrobial effects against Gram-positive bacteria (Potocki et al., 2021). These selective antimicrobial properties of fatty acids are due to variations in their structure, although Gram-negative bacteria have an additional membrane other than cell wall that gives them extra protection against antimicrobial agents.

Anticancer Activity

Metabolites accumulated by microalgae have been reported to show anticancer potential through several mechanisms including apoptosis of cancer cells, suppression of cell proliferation, inhibition of angiogenesis. These microalgal compounds induce apoptosis through mitochondrial and death receptor pathways, leading to DNA fragmentation and caspase activation (Talero et al., 2015). Compounds such as fucoxanthin induced apoptosis in colon cancer cells and suppressed tumour growth while another compound, astaxanthin, damaged tumour cells DNA and suppressed cancer cells proliferation (Chuyen & Eun, 2017). Fucoxanthin has also been recognised to inhibit cancer stem cells involved in cancer relapse and metastasis (Terasaki et al., 2018).

Immunomodulatory Activity

Polysaccharides produced by microalgae are well documented to improve immune function by activating T/B cells, macrophages and NK cells (Raposo et al., 2013). Polysaccharides exert immunomodulatory effects by targeting the pattern recognition receptors (Dectin-1, TLR-2 and TLR-4) located on immune cells (Osathanunkul et al., 2025).

A study analysing the activity of β -glucans obtained from *spirulina* and *chlorella* documented improved immune cell responses through dectin-1 receptors, stimulating downstream NF- κ B and MAPK pathways (Ahmad et al., 2021). Another study on sulphated polysaccharides derived from *Porphyridium* reported restrained polymorphonuclear leukocyte movement and reduced erythema development (Matsui et al., 2003). The above findings indicate that microalgae-derived compounds can be a potential tool for the treatment of inflammatory and autoimmune diseases but rigorous clinical studies are required prior to any strong claim.

Photoprotective Activity

Carotenoids and MAAs are potent compounds that can provide photoprotection by converting the absorbed UV rays into the heat without producing free radicals (Hachicha et al., 2022). This heat dissipation strategy is successful in preventing the generation of ROS which are responsible for damaging the DNA, protein and lipids in skin cells (Hachicha et al., 2022; Sánchez-Muñoz et al., 2020). MAAs being photostable compounds do not disintegrate or change on exposure to UV radiation, which makes them suitable ingredients for use in sunscreen (Mehariya et al., 2021). Lutein is widely used in the cosmetic industry because it provides photoprotection to the skin against UV radiations. Lutein

deposited in eye's macula helps to prevent damage from bright blue light and reduce the risk of oxidative damage as well as age-related macular degeneration (Spinola & Díaz-Santos, 2020).

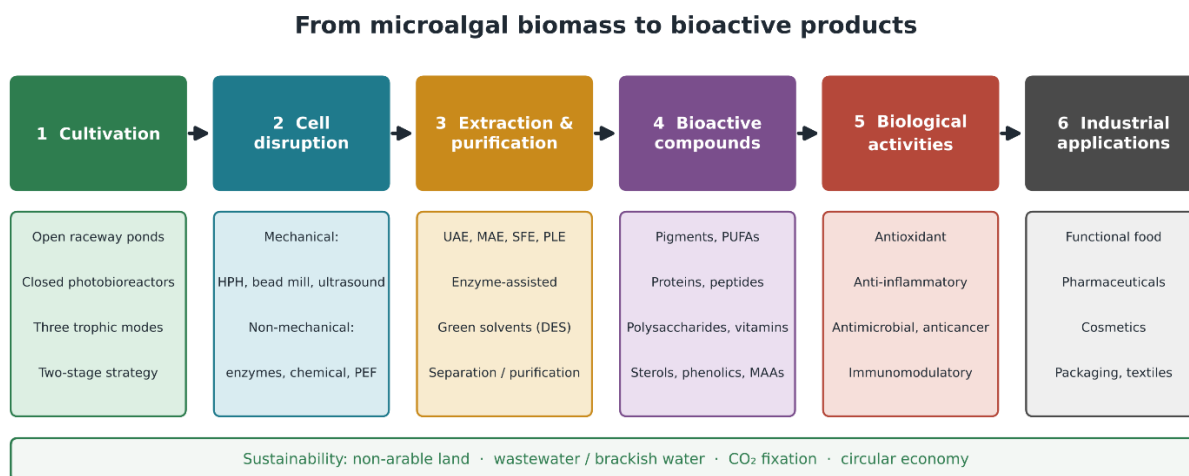


Figure 3. Overview of the pathway from microalgal cultivation, cell disruption and extraction to bioactive compounds, their biological activities and industrial applications.

Applications in Food, Pharmaceutical, and Cosmetic Industries

Functional Foods and Nutraceuticals

Bioactive compounds obtained from microalgae are receiving considerable attention for use in functional food formulations. *Spirulina* contains phenolic compounds, carotenoids phycocyanin, and chlorophylls that are used as antioxidants and colouring agents (Pham Thi Bich et al., 2021). *Chlorella* is well documented for containing compounds with antioxidant, immunomodulatory and anti-inflammatory properties (Becker, 2007). Supplementation of food products with compounds obtained from microalgae not only improves their nutritional profile but also exerts functional benefits such as improvement in shelf life through antioxidant activity (Batista et al., 2017; Lucas et al., 2018).

Microalgae especially *spirulina* have been blended with different food products to enhance their nutritional values and health benefits. Incorporation of *Spirulina* biomass into biscuits has been shown to increase protein content by 59% (Batista et al., 2017). These biscuits supplemented with *Spirulina* have also shown higher level of minerals such as iron and calcium than traditional bakery products. Microencapsulated *Spirulina* mixed with yogurt improved its nutritional profile and the protein content by 15% (da Silva et al., 2019). Apart from nutritional benefits, microencapsulation can also improve shelf life and can prevent bad flavour and odour by preventing the degradation of sensitive bioactive compounds from degradation during processing and storage (da Silva et al., 2019).

Spirulina snacks showed significant improvement in mineral, lipid and protein content without any negative sensory effects. These sensory studies have shown that microalgae-incorporated products can achieve higher acceptance among consumers by ensuring optimized supplementation to maintain nutritional benefits and sensory properties (Lucas et al., 2018).

Pharmaceutical Applications

Recently, the pharmaceutical industry has shown great interest in metabolites found in microalgae. Microalgae offer several compounds with biological activities that can be used as active ingredients in drugs for the cure and prevention of different diseases. Among different classes of metabolites, fatty acids have particularly shown significant antimicrobial, anticancer and antifungal properties and cosmetic industry is using them majorly in skin care products, sun protection and hair care formulations (Santoro et al., 2019). The use of microalgae in pharmaceuticals industry has extended into the drug development, driven by global demand for new therapeutic drugs, leading to development of novel antibiotics, anticancer drugs and anti-inflammatory drugs (Kholany et al., 2022; Talero et al., 2015).

Carotenoids are another interesting class with the ability to suppress colon cancer and liver fibrosis and to provide protection against UV rays (Kholany et al., 2022). Clinical trials testing astaxanthin have proved its potential in treating inflammatory conditions, cardiovascular disease and age-related macular degeneration (Bjørklund et al., 2022).

Cosmetic and Cosmeceutical Applications

The cosmetics industry has seen growing demand for naturally derived ingredients with anti-aging, sun protecting and moisturizing properties. Fucoxanthin and MAAs from microalgae have been seen to provide protection against high UV radiations and reduce oxidative damage in skin cells (de Jesus Raposo et al., 2015). These compounds represent a sustainable, natural tool, unlike synthetic UV filters which have been questioned due to environmental concerns and endocrine disrupting issues (de Jesus Raposo et al., 2015; Sánchez-Muñoz et al., 2020). Phycocyanin and phycoerythrin extracted from *Spirulina* and *Porphyridium* give natural blue and pink colours and also provide UV protection and anti-aging effects (Bermejo et al., 2008). The organic origin of these pigments makes them more favourable for use in clean-label cosmetic products for consumers with a high demand for natural and environmentally friendly products (Mourelle et al., 2017).

Exopolysaccharides (EPS) from microalgae have rheological applications and can be used as an effective alternative to hyaluronic acid (Pierre et al., 2019). These microalgae-derived EPS have shown to create water film and retain moisture for a prolonged period, which makes them ideal candidates for use in moisturizing and anti-aging skincare products.

Protein from microalgae can be useful in tissue regeneration and can stimulate collagen formation. These bioactive peptides found in microalgae are documented to support fibroblast growth and promote collagen formation, ultimately enhancing skin elasticity and reducing the development of wrinkles (Apone et al., 2019).

Textile and Packaging Applications

Bioactive compounds from microalgae can be combined with other organic materials to manufacture biodegradable packaging materials. Phycocyanin from *Spirulina* has been used as a bioindicator in food packaging because of its pH-sensitive colour change (Moreira et al., 2018). This pH sensitivity of phycocyanin provides visual monitoring for the customer to evaluate the freshness of food as this compound changes colour in response to pH changes.

The development of organic dyes from microalgae can help to eliminate the environment-related concerns (mainly water pollution) arising from synthetic dyes. The textile industry can use compounds with antimicrobial effects to manufacture products related to healthcare, hygiene, and sportswear (Gulati

et al., 2021). Textile industries can incorporate microalgae to develop special products that can prevent the transmission of pathogenic microorganisms and sportswear that resists the growth of odour-causing bacteria.

Market Potential and Commercial Products

Multiple applications of microalgae-derived compounds are the driving force behind the rapid rise in the global market for this bioresource. Astaxanthin, PUFAs (especially DHA and EPA), phycocyanin, and polysaccharides account for the major market value (Hachicha et al., 2022). *Chlorella* and *spirulina* occupy the major market share while the market for *Haematococcus*, *Nannochloropsis* and *Porphyridium* are growing rapidly because they offer high-value pigments and therapeutic polysaccharides (Mehariya et al., 2021). This market growth is a result of global investments from both private and public sectors into the microalgae industry, with growing companies and startups developing specialized products (Hachicha et al., 2022; Mehariya et al., 2021).

(Gürses et al., 2016) reported that the global pigment and dye market was estimated to reach \$26.53 billion with a demand of 9.9 million tons by 2017. The market share of natural carotenoids is estimated at 24% compared with 76% for synthetic carotenoids because of the higher costs of natural products (Lim et al., 2019). However, this market is growing due to spiking consumer demand for organic natural products and the development of cost-effective technologies for the production of natural carotenoids (Lim et al., 2019; Sánchez-Muñoz et al., 2020).

Many microalgae-based commercial products are available in the market. DSM is a multinational corporation based in the Netherlands that uses *Nannochloropsis oculata* and *Dunaliella salina* extracts to manufacture skin care products (Mourelle et al., 2017). AstaReal Inc., Cyanotech Corporation, and Parry's nutraceuticals are major manufacturers of *Haematococcus*-derived astaxanthin products (Dufossé, 2008). These companies have developed vast facilities with advanced technologies for the efficient and economic manufacturing of microalgal products on a commercial scale.

Challenges and Future Perspectives

Technical Challenges

In addition to the promising potential offered by microalgae, there are some technical challenges that need to be rectified for the economical commercialization of algae-based products. Tedious downstream processing, low yield, lack of standardized protocols and high cost of extraction methods are major bottlenecks (Bhatnagar et al., 2023). The high cultivation cost (\$2-5/Kg in open ponds and \$5-15/Kg in closed PBRs) is another major obstacle to commercialization (Bhatnagar et al., 2023; Vanthoor-Koopmans et al., 2013). The aroma and dark colour of microalgae present another problem in food applications, although spray-drying microencapsulation can resolve these challenges to some extent (da Silva et al., 2019). Development of a highly efficient and economical extraction method remains a key problem. Conventional methods are inefficient because they offer low product recovery, require high effort and discard by-products after processing (Harnedy & FitzGerald, 2013). Therefore, it is necessary to develop standardized procedures with low cost, efficient compound recovery and low processing cost (Vanthoor-Koopmans et al., 2013). A biorefinery approach in which multiple extraction techniques are used to valorize all the components present in biomass can be a significant solution to make the algae-based industry economically viable.

Regulatory Considerations

Rules and regulations set by local or international regulatory authorities are also a major obstacle to commercialization. The use of microalgae derived compounds in the food and cosmetic industries requires extensive clinical testing to ensure safety. The approval of novel food from regulatory authorities is a laborious process and need substantial investments from safety studies to clinical trials which may take several years (Su et al., 2023).

Additionally, the lack of uniformity in international standards for quality checking, labelling and environmental safety among different countries introduces barriers to global trade (Schneider et al., 2022). Development of standardized regulatory frameworks can help to promote international trade in microalgae products and can make the introduction of new products to the market economically feasible.

Future Directions

The integration of synthetic biology, artificial intelligence and omics-based datasets can help transform microalgal biotechnology. CRISPR/Cas9 and similar genetic engineering techniques are currently in use particularly to increase the quality and concentration of metabolites (Miao et al., 2024).

These techniques enable the redirection of the metabolic flux towards the targeted metabolite for enhanced production with minimal accumulation of unwanted compounds. A multi-omics approach enables scientists to understand microalgal systems at the metabolic level for strain improvement (Stavridou et al., 2024). The integration of metabolomics, genomics, transcriptomics and proteomics provides the better understanding of cellular functions at the metabolic level and can be a helpful tool in identifying of potential targets for metabolic engineering.

Artificial intelligence (AI) and machine learning (ML) have been used to optimize cultivation conditions and other system requirements to achieve maximum growth and metabolite concentrations (Yeh et al., 2023). ML integrate with massive datasets can accurately analyse the cultivation process, which can help in early identification of contamination and stress. Microalgae-bacterial co-cultivation systems are also being used to improve growth and increase the production of high-value metabolites. The consortia that work on the principle of symbiosis can help in the efficient recycling of nutrients, the production of novel metabolites and the improvement of the overall robustness of the cultivation system (Udaypal et al., 2024).

Sustainability and Circular Economy

Microalgae are receiving global recognition as a sustainable bioresource because their cultivation closely matches global sustainability goals. They fix CO₂, produce high-value metabolites and are low cost to cultivate because they needed less water and land than terrestrial plants. Some species of microalgae are able to fix about 10-50 times more CO₂ per unit area, which indicates that the carbon fixation ability of microalgae is significantly higher than that of terrestrial plants (Ashour & Omran, 2022).

Microalgae applications in the manufacturing of bioplastics and biofuels and their ability to utilize CO₂ directly align with the concept of a circular economy (Cheirsilp et al., 2023). Microalgal systems that works by using wastewater and environmental CO₂ represent a synergistic system that can produce multiple high-bioactive compounds in a sustainable green way.

Microalgae can contribute to achieve the United Nations Sustainable Development Goals, namely zero hunger, good health, clean water and public health, life below water, responsible consumption and production, and climate action. Microalgae can produce important fatty acids, proteins and other bioactive compounds that can address the problem of food security and improve nutritional profile while minimising the negative impact of food production on the environment unlike traditional approaches (Rotter et al., 2021).

Conclusions

Microalgae are sustainable and environment friendly bioresource that can produce multiple effective high-value metabolites for industrial use. This review has mainly demonstrated the key bioactive compounds (PUFAs, polysaccharides, proteins and derivatives, pigments, sterols, phenolic compounds, vitamins, alkaloids and phycobiliproteins) produced by microalgae, their applications and biological potential.

Bioprospecting and omics-based technologies provide access to knowledge related to metabolic pathways, uncovering metabolites with anti-inflammatory, anti-cancer, antimicrobial, light protective and neuroprotective effects. Unique microalgal attributes including biodiversity, adaption to broad range of environmental conditions, year-round cultivation and production of high-value metabolites position microalgae as a suitable candidate for the production of high demand commercial products (Silva et al., 2022; Zhou et al., 2022).

However, to push the microalgal industry to its full potential there is need to rectify challenges like optimizing cultivation systems, improving biomass and metabolites yield, reducing processing cost. Future research should focus on the development of interdisciplinary approach considering synthetic biology, strains engineering and optimized cultivation to enhance growth and end product yield. The introduction of the concept of a biorefinery in microalgae cultivation where waste products from one step can be used as raw materials in another step, can make the overall process economically feasible.

Investment for development of advanced infrastructure, international collaborations and harmonization in international policies will be a driving force to translate lab-based procedures into commercial gains. As demand for natural product is rapidly increasing by consumers, microalgae present potential to produce natural, effective and sustainable bioactive compounds to meet global sustainability demands. The continued advancement of microalgal biotechnology, coupled with supportive regulatory frameworks and increasing consumer acceptance, will be essential for realizing the full potential of these remarkable organisms in addressing global health, nutrition, and environmental challenges.

Credit authorship contribution statement

Shiza Eman: Writing – original draft, Investigation, Methodology, Software, Formal analysis. **Abd ur Rehman:** Resources, Formal analysis, Project administration, Funding acquisition, Writing–Review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. During the preparation of this review, the author(s) used Claude to assist with literature searching and language editing. All AI-generated suggestions and references were checked against the original sources, and the author(s) take full responsibility for the content of the publication.

Data availability

Data will be made available on request.

References

1. Abd El-Baky, H. H., & El-Baroty, G. S. (2013). The Potential Use of Microalgal Carotenoids as Dietary Supplements and Natural Preservative Ingredients. *Journal of Aquatic Food Product Technology*, 22(4), 392-406. <https://doi.org/10.1080/10498850.2011.654381>
2. Abdur Razzak, S., Bahar, K., Islam, K. M. O., Haniffa, A. K., Faruque, M. O., Hossain, S. M. Z., & Hossain, M. M. (2024). Microalgae cultivation in photobioreactors: sustainable solutions for a greener future. *Green Chemical Engineering*, 5(4), 418-439. <https://doi.org/10.1016/j.gce.2023.10.004>
3. Adarchenko, I., Kurbatova, A., Porotnikova, N., Savenkova, E., Kumar, V., & Skorokhodova, Y. (2024). Advanced Technologies for Bioeconomy: The Case of Microalgae Production. *Foresight and STI Governance*, 18(2), 69-83. <https://ideas.repec.org/a/hig/fsight/v18y2024i2p69-83.html>
4. Ahmad, M. F., Ahmad, F. A., Khan, M. I., Alsayegh, A. A., Wahab, S., Alam, M. I., & Ahmed, F. (2021). Ganoderma lucidum: A potential source to surmount viral infections through β -glucans immunomodulatory and triterpenoids antiviral properties. *International Journal of Biological Macromolecules*, 187, 769-779. <https://doi.org/10.1016/j.ijbiomac.2021.06.122>
5. Ajila, C., Naidu, K., Bhat, S., & Rao, U. (2007). Bioactive compounds and antioxidant potential of mango peel extract. *Food Chemistry*, 105(3), 982-988. <https://doi.org/10.1016/j.foodchem.2007.04.052>
6. Alsenani, F., Tupally, K. R., Chua, E. T., Eltanahy, E., Alsufyani, H., Parekh, H. S., & Schenk, P. M. (2020). Evaluation of microalgae and cyanobacteria as potential sources of antimicrobial compounds. *Saudi Pharmaceutical Journal*, 28(12), 1834-1841. <https://doi.org/10.1016/j.jsps.2020.11.010>
7. Apone, F., Barbulova, A., & Colucci, M. G. (2019). Plant and Microalgae Derived Peptides Are Advantageously Employed as Bioactive Compounds in Cosmetics. *Frontiers in Plant Science*, 10. <https://doi.org/10.3389/fpls.2019.00756>
8. Ashour, M., & Omran, A. M. M. (2022). Recent Advances in Marine Microalgae Production: Highlighting Human Health Products from Microalgae in View of the Coronavirus Pandemic (COVID-19). *Fermentation*, 8(9), 466. <https://doi.org/10.3390/fermentation8090466>
9. Barreira, J. C. M., Arraibi, A. A., & Ferreira, I. C. F. R. (2019). Bioactive and functional compounds in apple pomace from juice and cider manufacturing: Potential use in dermal formulations. *Trends in Food Science & Technology*, 90, 76-87. <https://doi.org/10.1016/j.tifs.2019.05.014>
10. Batista, A. P., Niccolai, A., Fradinho, P., Fragoso, S., Bursic, I., Rodolfi, L., Biondi, N., Tredici, M. R., Sousa, I., & Raymundo, A. (2017). Microalgae biomass as an alternative ingredient in cookies: Sensory, physical and chemical properties, antioxidant activity and in vitro digestibility. *Algal Research*, 26, 161-171. <https://doi.org/10.1016/j.algal.2017.07.017>
11. Becker, E. W. (2007). Micro-algae as a source of protein. *Biotechnology Advances*, 25(2), 207-210. <https://doi.org/10.1016/j.biotechadv.2006.11.002>
12. Bermejo, P., Piñero, E., & Villar, Á. M. (2008). Iron-chelating ability and antioxidant properties of phycocyanin isolated from a protean extract of *Spirulina platensis*. *Food Chemistry*, 110(2), 436-445. <https://doi.org/10.1016/j.foodchem.2008.02.021>
13. Bhatnagar, P., Gururani, P., Joshi, S., Singh, Y. P., Vlaskin, M. S., & Kumar, V. (2023). Enhancing the bio-prospects of microalgal-derived bioactive compounds in food industry: a review. *Biomass Conversion and Biorefinery*, 14(19), 23275-23291.

<https://doi.org/10.1007/s13399-023-04410-7>

14. Bjørklund, G., Gasmi, A., Lenchyk, L., Shanaida, M., Zafar, S., Mujawdiya, P. K., Lysiuk, R., Antonyak, H., Noor, S., & Akram, M. (2022). The role of astaxanthin as a nutraceutical in health and age-related conditions. *Molecules*, 27(21), 7167.
15. Calder, P. C. (2012). The role of marine omega-3 (<i>n</i>-3) fatty acids in inflammatory processes, atherosclerosis and plaque stability. *Molecular Nutrition & Food Research*, 56(7), 1073-1080. <https://doi.org/10.1002/mnfr.201100710>
16. Cepas, V., Gutiérrez-Del-Río, I., López, Y., Redondo-Blanco, S., Gabasa, Y., Iglesias, M. J., Soengas, R., Fernández-Lorenzo, A., López-Ibáñez, S., Villar, C. J., Martins, C. B., Ferreira, J. D., Assunção, M. F. G., Santos, L. M. A., Morais, J., Castelo-Branco, R., Reis, M. A., Vasconcelos, V., López-Ortiz, F., Lombó, F., & Soto, S. M. (2021). Microalgae and Cyanobacteria Strains as Producers of Lipids with Antibacterial and Antibiofilm Activity. *Marine Drugs*, 19(12), 675. <https://doi.org/10.3390/md19120675>
17. Cheirsilp, B., Maneechote, W., Srinuanpan, S., & Angelidaki, I. (2023). Microalgae as tools for bio-circular-green economy: Zero-waste approaches for sustainable production and biorefineries of microalgal biomass. *Bioresource Technology*, 387, 129620. <https://doi.org/10.1016/j.biortech.2023.129620>
18. Chen, H., Zheng, Y., Zhan, J., He, C., & Wang, Q. (2017). Comparative metabolic profiling of the lipid-producing green microalga *Chlorella* reveals that nitrogen and carbon metabolic pathways contribute to lipid metabolism. *Biotechnology for biofuels*, 10(1), 153.
19. Chuyen, H. V., & Eun, J.-B. (2017). Marine carotenoids: Bioactivities and potential benefits to human health. *Critical Reviews in Food Science and Nutrition*, 57(12), 2600-2610. <https://doi.org/10.1080/10408398.2015.1063477>
20. Citi, V., Torre, S., Flori, L., Usai, L., Aktay, N., Dunford, N. T., Lutz, G. A., & Nieri, P. (2024). Nutraceutical Features of the Phycobiliprotein C-Phycocyanin: Evidence from *Arthrospira platensis* (Spirulina). *Nutrients*, 16(11), 1752. <https://doi.org/10.3390/nu16111752>
21. da Silva, S. C., Fernandes, I. P., Barros, L., Fernandes, Â., José Alves, M., Calhella, R. C., Pereira, C., Barreira, J. C. M., Manrique, Y., Colla, E., Ferreira, I. C. F. R., & Filomena Barreiro, M. (2019). Spray-dried *Spirulina platensis* as an effective ingredient to improve yogurt formulations: Testing different encapsulating solutions. *Journal of Functional Foods*, 60, 103427. <https://doi.org/10.1016/j.jff.2019.103427>
22. [Record #9 is using a reference type undefined in this output style.]
23. Dufossé, L. (2008). Pigments from microalgae and microorganisms: Sources of food colorants. In (pp. 399-426).
24. Elbandy, M. (2022). Anti-Inflammatory Effects of Marine Bioactive Compounds and Their Potential as Functional Food Ingredients in the Prevention and Treatment of Neuroinflammatory Disorders. *Molecules*, 28(1), 2. <https://doi.org/10.3390/molecules28010002>
25. Finamore, A., Palmery, M., Bensehaila, S., & Peluso, I. (2017). Antioxidant, Immunomodulating, and Microbial-Modulating Activities of the Sustainable and Ecofriendly <i>Spirulina</i>. *Oxidative Medicine and Cellular Longevity*, 2017(1). <https://doi.org/10.1155/2017/3247528>
26. Foo, S. C., Yusoff, F. M., Ismail, M., Basri, M., Yau, S. K., Khong, N. M. H., Chan, K. W., & Ebrahimi, M. (2017). Antioxidant capacities of fucoxanthin-producing algae as influenced by their carotenoid and phenolic contents. *Journal of Biotechnology*, 241, 175-183. <https://doi.org/10.1016/j.jbiotec.2016.11.026>
27. Genç, Y., Bardakci, H., Yücel, Ç., Karatoprak, G. Ş., Küpeli Akkol, E., Hakan Barak, T., & Sobarzo-Sánchez, E. (2020). Oxidative Stress and Marine Carotenoids: Application by Using Nanoformulations. *Marine Drugs*, 18(8), 423. <https://doi.org/10.3390/md18080423>
28. Goiris, K., Muylaert, K., Fraeye, I., Foubert, I., De Brabanter, J., & De Cooman, L. (2012).

- Antioxidant potential of microalgae in relation to their phenolic and carotenoid content. *Journal of Applied Phycology*, 24(6), 1477-1486. <https://doi.org/10.1007/s10811-012-9804-6>
29. Gulati, R., Sharma, S., & Sharma, R. K. (2021). Antimicrobial textile: recent developments and functional perspective. *Polymer Bulletin*, 79(8), 5747-5771. <https://doi.org/10.1007/s00289-021-03826-3>
30. Gürses, A., Açıkyıldız, M., Güneş, K., & Gürses, M. S. (2016). Classification of Dye and Pigments. In A. Gürses, M. Açıkyıldız, K. Güneş, & M. S. Gürses (Eds.), *Dyes and Pigments* (pp. 31-45). Springer International Publishing. https://doi.org/10.1007/978-3-319-33892-7_3
31. Hachicha, R., Elleuch, F., Ben Hlima, H., Dubessay, P., de Baynast, H., Delattre, C., Pierre, G., Hachicha, R., Abdelkafi, S., Michaud, P., & Fendri, I. (2022). Biomolecules from Microalgae and Cyanobacteria: Applications and Market Survey. *Applied Sciences*, 12(4), 1924. <https://doi.org/10.3390/app12041924>
32. Harnedy, P. A., & FitzGerald, R. J. (2013). Extraction of protein from the macroalga *Palmaria palmata*. *LWT - Food Science and Technology*, 51(1), 375-382. <https://doi.org/10.1016/j.lwt.2012.09.023>
33. Huleihel, M., Ishanu, V., Tal, J., & Arad, S. (2001). Antiviral effect of red microalgal polysaccharides on Herpes simplex and Varicella zoster viruses. *Journal of Applied Phycology*, 13(2), 127-134. <https://doi.org/10.1023/a:1011178225912>
34. [Record #69 is using a reference type undefined in this output style.]
35. Kalasariya, H. S., & Pereira, L. (2022). Dermo-Cosmetic Benefits of Marine Macroalgae-Derived Phenolic Compounds. *Applied Sciences*, 12(23), 11954. <https://www.mdpi.com/2076-3417/12/23/11954>
36. Kholany, M., Coutinho, J. A. P., & Ventura, S. P. M. (2022). Carotenoid Production from Microalgae: The Portuguese Scenario. *Molecules*, 27(8), 2540. <https://doi.org/10.3390/molecules27082540>
37. Kt, D. H. R. (2024). Exploring the versatile applications of Spirulina: A comprehensive research review. *International Journal of Advanced Biochemistry Research*, 8(11S), 87-93. <https://doi.org/10.33545/26174693.2024.v8.i11sb.2799>
38. Kuntzler, S. G., Almeida, A. C. A. d., Costa, J. A. V., & Morais, M. G. d. (2018). Polyhydroxybutyrate and phenolic compounds microalgae electrospun nanofibers: A novel nanomaterial with antibacterial activity. *International Journal of Biological Macromolecules*, 113, 1008-1014. <https://doi.org/10.1016/j.ijbiomac.2018.03.002>
39. Łacheta, D., Olejarz, W., Włodarczyk, M., & Nowicka, G. (2019). Effect of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) on the regulation of vascular endothelial cell function. *Postępy Higieny i Medycyny Doświadczalnej*, 73, 467-475. <https://doi.org/10.5604/01.3001.0013.5064>
40. Lim, K. J. A., Cabajar, A. A., Lobarbio, C. F. Y., Taboada, E. B., & Lacks, D. J. (2019). Extraction of bioactive compounds from mango (*Mangifera indica* L. var. Carabao) seed kernel with ethanol–water binary solvent systems. *Journal of Food Science and Technology*, 56(5), 2536-2544. <https://doi.org/10.1007/s13197-019-03732-7>
41. Liu, Y., Ren, X., Fan, C., Wu, W., Zhang, W., & Wang, Y. (2022). Health Benefits, Food Applications, and Sustainability of Microalgae-Derived N-3 PUFA. *Foods*, 11(13). <https://doi.org/10.3390/foods11131883>
42. Lucas, B. F., Morais, M. G. d., Santos, T. D., & Costa, J. A. V. (2018). Spirulina for snack enrichment: Nutritional, physical and sensory evaluations. *LWT*, 90, 270-276. <https://doi.org/10.1016/j.lwt.2017.12.032>
43. Matsui, M. S., Muizzuddin, N., Arad, S., & Marenus, K. (2003). Sulfated Polysaccharides from Red Microalgae Have Antiinflammatory Properties In Vitro and In Vivo. *Applied Biochemistry and Biotechnology*, 104(1), 13-22. <https://doi.org/10.1385/abab:104:1:13>

44. Mehariya, S., Goswami, R. K., Karthikeysan, O. P., & Verma, P. (2021). Microalgae for high-value products: A way towards green nutraceutical and pharmaceutical compounds. *Chemosphere*, 280, 130553. <https://doi.org/10.1016/j.chemosphere.2021.130553>
45. Meinita, M. D. N., Harwanto, D., Tirtawijaya, G., Negara, B., Sohn, J. H., Kim, J. S., & Choi, J. S. (2021). Fucosterol of Marine Macroalgae: Bioactivity, Safety and Toxicity on Organism. *Mar Drugs*, 19(10). <https://doi.org/10.3390/md19100545>
46. Miao, C., Du, M., Du, H., Xu, T., Wu, S., Huang, X., Chen, X., Lei, S., & Xin, Y. (2024). Enhanced Eicosapentaenoic Acid Production via Synthetic Biological Strategy in *Nannochloropsis oceanica*. *Marine Drugs*, 22(12), 570. <https://doi.org/10.3390/md22120570>
47. Moldovan, S., Ferrandiz, M., Franco, E., Mira, E., Capablanca, L., & Bonet, M. (2017). Printing of cotton with eco-friendly, red algal pigment from *Gracilaria* sp. *IOP Conference Series: Materials Science and Engineering*, 254, 192011. <https://doi.org/10.1088/1757-899x/254/19/192011>
48. Moreira, J. B., Terra, A. L. M., Costa, J. A. V., & Morais, M. G. d. (2018). Development of pH indicator from PLA/PEO ultrafine fibers containing pigment of microalgae origin. *International Journal of Biological Macromolecules*, 118, 1855-1862. <https://doi.org/10.1016/j.ijbiomac.2018.07.028>
49. Mourelle, M., Gómez, C., & Legido, J. (2017). The Potential Use of Marine Microalgae and Cyanobacteria in Cosmetics and Thalassotherapy. *Cosmetics*, 4(4), 46. <https://doi.org/10.3390/cosmetics4040046>
50. Nunes, A. L. F., Lima, V. S., Miranda, J. R., Resende, M. E. T., Silva, C. A. S. d., Martins, M. A., & Coimbra, J. S. d. R. (2023). Cell disruption of microalgae: advances and perspectives. *Ciência Rural*, 54(5), e20220330.
51. Osathanunkul, M., Thanaporn, S., Karapetsi, L., Nteve, G. M., Pratsinakis, E., Stefanidou, E., Lagiotis, G., Avramidou, E., Zorxzobokou, L., Tsintzou, G., Athanasiou, A., Mpelai, S., Constandinidis, C., Pantiora, P., Merino, M., Mullor, J. L., Dobrovic, L., Cerasino, L., Ogawa, T., Tsaousi, M., Rodrigues, A. M. C., Cardoso, H., Pires, R., Figueiredo, D., Costa, I. F., Anjos, C., Labrou, N. E., & Madesis, P. (2025). Diversity of Bioactive Compounds in Microalgae: Key Classes and Functional Applications. *Marine Drugs*, 23(6), 222. <https://doi.org/10.3390/md23060222>
52. Peltomaa, E., Johnson, M., & Taipale, S. (2017). Marine Cryptophytes Are Great Sources of EPA and DHA. *Marine Drugs*, 16(1), 3. <https://doi.org/10.3390/md16010003>
53. Pereira, A. G., Otero, P., Echave, J., Carreira-Casais, A., Chamorro, F., Collazo, N., Jaboui, A., Lourenço-Lopes, C., Simal-Gandara, J., & Prieto, M. A. (2021). Xanthophylls from the Sea: Algae as Source of Bioactive Carotenoids. *Marine Drugs*, 19(4), 188. <https://doi.org/10.3390/md19040188>
54. Pham Thi Bich, D., Nguyen Thi Hoai, H., Vu Thanh, C., Phung Van, H., Tran Quoc, B., & Nguyen Ngoc, L. (2021). IN VITRO ANTIOXIDANT ACTIVITY OF C-PHYCOCYANIN PURIFIED FROM *Spirulina platensis* DRY BIOMASS. *Journal of Science Natural Science*, 66(3), 99-107. <https://doi.org/10.18173/2354-1059.2021-0051>
55. Pierre, G., Delattre, C., Dubessay, P., Jubeau, S., Vialleix, C., Cadoret, J.-P., Probert, I., & Michaud, P. (2019). What Is in Store for EPS Microalgae in the Next Decade? *Molecules*, 24(23), 4296. <https://doi.org/10.3390/molecules24234296>
56. Potocki, L., Oklejewicz, B., Kuna, E., Szpyrka, E., Duda, M., & Zuczek, J. (2021). Application of Green Algal Planktochlorella nurekis Biomasses to Modulate Growth of Selected Microbial Species. *Molecules*, 26(13), 4038. <https://doi.org/10.3390/molecules26134038>
57. Prates, J. A. M. (2025). Applications of Bioactive Compounds from Marine Microalgae in Health, Cosmetics, and Functional Foods. *Applied Sciences*, 15(11), 6144. <https://doi.org/10.3390/app15116144>

58. Queiroz, M. I., Vieira, J. G., & Maroneze, M. M. (2020). Morphophysiological, structural, and metabolic aspects of microalgae. In *Handbook of Microalgae-Based Processes and Products* (pp. 25-48). Elsevier.
59. Raposo, M., De Moraes, R., & Bernardo de Moraes, A. (2013). Bioactivity and Applications of Sulphated Polysaccharides from Marine Microalgae. *Marine Drugs*, 11(1), 233-252. <https://doi.org/10.3390/md11010233>
60. Remize, M., Brunel, Y., Silva, J. L., Berthon, J.-Y., & Filaire, E. (2021). Microalgae n-3 PUFAs Production and Use in Food and Feed Industries. *Marine Drugs*, 19(2), 113. <https://doi.org/10.3390/md19020113>
61. Ren, Y., Sun, H., Deng, J., Huang, J., & Chen, F. (2021). Carotenoid Production from Microalgae: Biosynthesis, Salinity Responses and Novel Biotechnologies. *Marine Drugs*, 19(12), 713. <https://doi.org/10.3390/md19120713>
62. Rojas-Franco, P., Franco-Colín, M., Camargo, M. E. M., Carmona, M. M. E., Ortiz-Butrón, M. d. R. E., Blas-Valdivia, V., & Cano-Europa, E. (2018). Phycobiliproteins and phycocyanin of *Arthrospira maxima* (*Spirulina*) reduce apoptosis promoters and glomerular dysfunction in mercury-related acute kidney injury. *Toxicology Research and Application*, 2. <https://doi.org/10.1177/2397847318805070>
63. Rotter, A., Barbier, M., Bertoni, F., Bones, A. M., Cancela, M. L., Carlsson, J., Carvalho, M. F., Ceglowska, M., Chirivella-Martorell, J., Conk Dalay, M., Cueto, M., Dailianis, T., Deniz, I., Díaz-Marrero, A. R., Drakulovic, D., Dubnika, A., Edwards, C., Einarsson, H., Erdoğan, A., Eroldogan, O. T., Ezra, D., Fazi, S., FitzGerald, R. J., Gargan, L. M., Gaudêncio, S. P., Gligora Udovič, M., Ivošević DeNardis, N., Jónsdóttir, R., Kataržytė, M., Klun, K., Kotta, J., Ktari, L., Ljubešić, Z., Lukić Bilela, L., Mandalakis, M., Massa-Gallucci, A., Matijošytė, I., Mazur-Marzec, H., Mehiri, M., Nielsen, S. L., Novoveská, L., Overlingė, D., Perale, G., Ramasamy, P., Rebours, C., Reinsch, T., Reyes, F., Rinkevich, B., Robbins, J., Röttinger, E., Rudovica, V., Sabotič, J., Safarik, I., Talve, S., Tasdemir, D., Theodotou Schneider, X., Thomas, O. P., Toruńska-Sitarz, A., Varese, G. C., & Vasquez, M. I. (2021). The Essentials of Marine Biotechnology. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.629629>
64. [Record #49 is using a reference type undefined in this output style.]
65. Santoro, I., Nardi, M., Benincasa, C., Costanzo, P., Giordano, G., Procopio, A., & Sindona, G. (2019). Sustainable and Selective Extraction of Lipids and Bioactive Compounds from Microalgae. *Molecules*, 24(23), 4347. <https://doi.org/10.3390/molecules24234347>
66. Schneider, X. T., Stroil, B. K., Tourapi, C., Rebours, C., Gaudêncio, S. P., Novoveska, L., & Vasquez, M. I. (2022). Responsible Research and Innovation Framework, the Nagoya Protocol and Other European Blue Biotechnology Strategies and Regulations: Gaps Analysis and Recommendations for Increased Knowledge in the Marine Biotechnology Community. *Marine Drugs*, 20(5), 290. <https://doi.org/10.3390/md20050290>
67. Sethi, S., & Rathod, V. (2026). Recent advancements in ultrasound-assisted biomolecule extraction from prokaryotic and eukaryotic cells: a review. *Preparative Biochemistry & Biotechnology*, 56(2), 135-161.
68. Shah, M. M. R., Liang, Y., Cheng, J. J., & Daroch, M. (2016). Astaxanthin-Producing Green Microalga *Haematococcus pluvialis*: From Single Cell to High Value Commercial Products. *Frontiers in Plant Science*, 7. <https://doi.org/10.3389/fpls.2016.00531>
69. Shahid, A., Mubashar, M., Zulekha, R., Sultan, M. M., Li, J., & Zhang, X. (2024). Emerging trends in cyanobacterial biotechnology for sustainable development. *Cyanobacteria Biotechnology: Sustainability of Water-Energy-Environment Nexus*, 1-22.
70. Shi, H., Deng, X., Ji, X., Liu, N., & Cai, H. (2023). Sources, dynamics in vivo, and application of astaxanthin and lutein in laying hens: A review. *Animal Nutrition*, 13, 324-333. <https://doi.org/10.1016/j.aninu.2023.02.008>

71. Silva, M., Kamberovic, F., Uota, S. T., Kovan, I.-M., Viegas, C. S. B., Simes, D. C., Gangadhar, K. N., Varela, J., & Barreira, L. (2022). Microalgae as Potential Sources of Bioactive Compounds for Functional Foods and Pharmaceuticals. *Applied Sciences*, 12(12), 5877. <https://doi.org/10.3390/app12125877>
72. Sinangil, Z., Taştan, Ö., & Baysal, T. (2022). Beta-Glucan as a Novel Functional Fiber: Functional Properties, Health Benefits and Food Applications. *Turkish Journal of Agriculture - Food Science and Technology*, 10(10), 1957-1965. <https://doi.org/10.24925/turjaf.v10i10.1957-1965.5430>
73. Sivaramakrishnan, R., Kanwal, S., Incharoensakdi, A., Nirmal, N., & Srimongkol, P. (2025). Exploring the nutraceutical and functional food potential of microalgae: Implications for health and sustainability. *Journal of Agriculture and Food Research*, 22, 102148. <https://doi.org/https://doi.org/10.1016/j.jafr.2025.102148>
74. [Record #19 is using a reference type undefined in this output style.]
75. Stavridou, E., Karapetsi, L., Nteve, G. M., Tsintzou, G., Chatzikonstantinou, M., Tsaousi, M., Martinez, A., Flores, P., Merino, M., Dobrovic, L., Mullor, J. L., Martens, S., Cerasino, L., Salmaso, N., Osathanunkul, M., Labrou, N. E., & Madesis, P. (2024). Landscape of microalgae omics and metabolic engineering research for strain improvement: An overview. *Aquaculture*, 587, 740803. <https://doi.org/10.1016/j.aquaculture.2024.740803>
76. Su, M., Bastiaens, L., Verspreet, J., & Hayes, M. (2023). Applications of Microalgae in Foods, Pharma and Feeds and Their Use as Fertilizers and Biostimulants: Legislation and Regulatory Aspects for Consideration. *Foods*, 12(20), 3878. <https://doi.org/10.3390/foods12203878>
77. Talero, E., García-Mauriño, S., Ávila-Román, J., Rodríguez-Luna, A., Alcaide, A., & Motilva, V. (2015). Bioactive Compounds Isolated from Microalgae in Chronic Inflammation and Cancer. *Marine Drugs*, 13(10), 6152-6209. <https://doi.org/10.3390/md13106152>
78. Terasaki, M., Mima, M., Kudoh, S., Endo, T., Maeda, H., Hamada, J., Osada, K., Miyashita, K., & Mutoh, M. (2018). Glycine and succinic acid are effective indicators of the suppression of epithelial-mesenchymal transition by fucoxanthinol in colorectal cancer stem-like cells. *Oncology Reports*, 40(1), 414-424.
79. Tsvetanova, F., & Yankov, D. (2022). Bioactive Compounds from Red Microalgae with Therapeutic and Nutritional Value. *Microorganisms*, 10(11), 2290. <https://doi.org/10.3390/microorganisms10112290>
80. Udaypal, U., Goswami, R. K., & Verma, P. (2024). Strategies for improvement of bioactive compounds production using microalgal consortia: An emerging concept for current and future perspective. *Algal Research*, 82, 103664. <https://doi.org/10.1016/j.algal.2024.103664>
81. Vanthoor-Koopmans, M., Wijffels, R. H., Barbosa, M. J., & Eppink, M. H. M. (2013). Biorefinery of microalgae for food and fuel. *Bioresource Technology*, 135, 142-149. <https://doi.org/10.1016/j.biortech.2012.10.135>
82. Yeh, Y.-C., Syed, T., Brinitzer, G., Frick, K., Schmid-Staiger, U., Haasdonk, B., Tovar, G. E. M., Krujatz, F., Mädler, J., & Urbas, L. (2023). Improving microalgae growth modeling of outdoor cultivation with light history data using machine learning models: A comparative study. *Bioresource Technology*, 390, 129882. <https://doi.org/10.1016/j.biortech.2023.129882>
83. Zhou, L., Li, K., Duan, X., Hill, D., Barrow, C., Dunshea, F., Martin, G., & Suleria, H. (2022). Bioactive compounds in microalgae and their potential health benefits. *Food Bioscience*, 49, 101932. <https://doi.org/10.1016/j.fbio.2022.101932>