*Review Paper:*

# Microalgae derived bioactive compounds and their biological activities and sustainable applications: A review

**Manivannan Govindasamy[1*], Nivaedhitha Mohan Kumar[2], Ponmurugan Karuppiah[3], Abinaya Subramanian[4] and Uma Eswaranpillai[5]**

1. Research Unit, Department of Psychiatry, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai – 602 105, Tamil Nadu, INDIA
2. Department of Microbiology, Saveetha Medical College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai – 602 105, Tamil Nadu, INDIA
3. Department of Botany and Microbiology, College of Science, King Saud University – 11451, Riyadh, SAUDI ARABIA
4. Department of Microbiology, Hindustan College of Arts and Science, Padur, Kelambakkam, Chennai – 603 103, Tamil Nadu, INDIA
5. Department of Botany, PSGR Krishnammal College for Women, Peelamedu, Coimbatore – 614004, Tamil Nadu, INDIA

*gmanivannan74@gmail.com

## Abstract

*Microalgae, considered as the foundation of aquatic ecosystems, had emerged as promising candidates for a wide range of sustainable applications. This review explores their diverse roles across environmental, industrial and biomedical sectors, emphasizing their unique physicochemical properties and rich metabolic profile. Microalgae produce a variety of bioactive compounds including proteins, lipids, pigments (chlorophyll, carotenoids, phycocyanin), polysaccharides, vitamins and minerals. Microalgal derived compounds exhibit significant biological activities such as antioxidant, anti-inflammatory, antibacterial, antiviral, anti-obesity and anticancer effects, offering potential for therapeutic and nutraceutical development. Particular focus is placed on their role in renewable energy, as microalgae serve as feedstocks for biofuels such as biodiesel, bioethanol, biomethane, biocrude oil and biohydrogen due to their high lipid content and rapid biomass productivity.*

*Despite their promising potential, several limitations hinder large-scale industrial application including high production costs, energy-intensive harvesting processes and the need for optimized cultivation systems. Advances in genetic engineering, metabolic pathway optimization and biorefinery integration are being explored to overcome these challenges. This review also outlines future directions for enhancing microalgae utilization through technological innovation, interdisciplinary collaborations and supportive policies. Microalgae represent a multifunctional and sustainable biological resource with transformative potential in green technologies, renewable energy, environmental remediation and human health, making a key component in addressing global sustainability challenges.*

**Keywords**: Microalgae, biochemical properties, bioactive compounds, biological activity, biofuels.

## Introduction

Microalgae are a diverse group of unicellular, photosynthetic organisms found across freshwater and marine ecosystems. Compared to macroalgae, they grow more rapidly and often contain higher lipid content under natural conditions[106,129]. Although over 50,000 species have been identified, only about 30,000 have been extensively studied[155,164,197]. While most microalgae are eukaryotic, some prokaryotic organisms such as *Spirulina* (a cyanobacterium) are also classified as microalgae due to their comparable photosynthetic and reproductive characteristics[158]. These organisms can tolerate a wide range of environmental conditions including temperature, salinity, light intensity and pH which allow them to thrive in diverse habitats like ponds, deserts and reservoirs[14].

The efficient photosynthesis plays a major role in global oxygen production and carbon dioxide absorption[17]. Owing to their metabolic flexibility, microalgae synthesize a wide array of bioactive compounds including polysaccharides, lipids, pigments, proteins, vitamins and antioxidants[22,46]. Nutritionally, microalgae are rich in proteins, polyunsaturated fatty acids (PUFAs), carotenoids, various vitamins (A, B1, B2, B6, B12, C and E), essential minerals, omega-3 and omega-6 fatty acids[13]. Their well-balanced nutrient profile and ease of digestion due to the absence of a cellulose cell wall make them ideal candidates for functional food applications[65]. Commercially, species such as *Chlorella*, *Dunaliella* and *Haematococcus* are already used as dietary supplements for their ability to accumulate valuable bioactive substances[67].

These compounds possess diverse biological properties including antioxidant, anti-inflammatory, anticancer, antidiabetic and antimicrobial effects[7,103,104,154]. Such bioactivities are often enhanced under stress which can be artificially induced through environmental or metabolic engineering strategies, including the OSMAC (One Strain–Many Compounds) approach[100,109]. Despite their potential, the commercial-scale production of microalgae remains constrained by challenges such as low biomass yield, energy-intensive harvesting methods and high operational costs[139]. However, recent developments in omics

https://doi.org/10.25303/2012rjbt2960313

technologies, high-throughput screening and marine biotechnology are facilitating the identification and large-scale production supporting their growing use in food, pharmaceuticals, cosmetics and environmental management[53].

In this present review, we highlighted the physico-chemical properties and rich bioactive profile of microalgae including proteins, lipids, pigments, polysaccharides and essential micronutrients. Their biological activities such as antioxidant, anti-inflammatory, anticancer and antimicrobial effects underscore their potential in health and therapeutic applications. Additionally, microalgae show promise in biofuel production and cosmetics. Despite their vast potential, further optimization is required to enhance metabolite yield, reduce production costs and facilitate large-scale commercialization. This review underscores the importance of continued research and technological advancements to unlock the full potential of microalgae in food, health, energy and environmental sectors

## Biochemical composition and properties of microalgae

The biochemical properties of microalgae vary significantly depending on species and cultivation conditions. One of their most notable traits is the high protein content with *Spirulina* containing over 60% protein[63]. The amino acid composition is generally consistent across species dominated by aspartic acid and glutamic acid while lower levels of cysteine, methionine, tryptophan and histidine are also present[40]. In addition to proteins, polyunsaturated fatty acids (PUFAs) including eicosapentaenoic acid (EPA), arachidonic acid (AA) and docosahexaenoic acid (DHA) play a crucial role in the nutritional profile of microalgae[15]. Microalgae are also rich in vitamins and minerals necessary for growth and metabolic functions.

For instance, *Spirulina* provides substantial amounts of potassium along with calcium, magnesium, iron, zinc, selenium, copper and other essential trace elements[25,63]. The cell wall structure also varies among species. While most microalgae possess a rigid cellulosic wall that complicates digestion in monogastric animals, *Spirulina* lacks this barrier, allowing for efficient enzymatic digestion without pre-treatment[18].

Another physico-chemical trait of microalgae is their pigment composition. They are a rich source of carotenoids such as β-carotene[118], lutein[79] and astaxanthin[161]. *Spirulina* in particular contains a wide array of pigments including chlorophyll-a, β-carotene, echinenone, zeaxanthin, myxoxanthophyll, canthaxanthin, diatoxanthin and phycobiliproteins like C-phycocyanin and allophycocyanin[107]. High concentrations of lutein are found in species such as *Chlorella fusca*, *Chlorococcum citriforme*, *Neospongiococcum gelatinosum* and *Muriellopsis* sp.[49] while violaxanthin and β-carotene are broadly distributed across various taxa[187]. Notably, *Haematococcus pluvialis* is the richest known source of astaxanthin among microalgae[18]. These diverse physico-chemical properties of microalgae determined by species and cultivation conditions highlight their significant nutritional and industrial potential.

## Microalgal proteins, lipids and their potential

Microalgae, found in both freshwater and marine environments are increasingly being recognized as a sustainable protein source for food applications. Their dry biomass typically contains 40% to 60% protein with species like *Spirulina* and *Chlorella* reaching up to 70% and 60% respectively[20,207]. A protein content exceeding 30% has been observed in microalgae such as *Scenedesmus*, *Chlamydomonas*, *Chlorella*, *Dunaliella*, *Euglena gracilis*, *Prymnesium parvum*, *Tetraselmis maculata*, *Spirulina* and *Anabaena cylindrica*[200]. High protein levels have been confirmed through various studies. For instance, *Dunaliella salina* was reported to have 57% protein[206] and *Tetraselmis* sp. as much as 65%[174]. These proteins contain all essential amino acids and are considered nutritionally comparable to conventional sources such as egg and soy.

Aspartic and glutamic acids are commonly found in higher amounts whereas methionine, tryptophan and other sulfur-containing amino acids are present in lower concentrations[16]. The amino acid profile and protein quality in microalgae can be influenced by species, growth phase, nutrient availability and environmental conditions such as light. Certain species including *Nannochloropsis gaditana* and *Euglena gracilis* have been shown to meet or exceed FAO/WHO essential amino acid standards under optimal conditions[126]. Digestibility, an important aspect of protein quality is also dependent on cell wall composition. Species like *Spirulina* which lack rigid cell walls, are more digestible whereas tougher walled species like *Chlorella* require mechanical or chemical disruption to improve enzyme access[188].

Cell disruption techniques have been shown to improve protein digestibility and increase the Protein Digestibility-Corrected Amino Acid Score (PDCAAS) values[173]. However, the presence of antinutritional compounds, including polyphenols and polysaccharides, can hinder digestibility by forming complexes that resist enzymatic hydrolysis[166]. Furthermore, microalgae have been genetically engineered to enhance protein synthesis. Techniques such as electroporation, lithium acetate–PEG transformation and glass bead agitation have successfully been applied to marine strains. Recombinant proteins including soybean trypsin inhibitors and viral proteins like VP28 have been effectively produced using these methods[31,59].

Microalgae are recognized for their high lipid content and have emerged as promising alternatives to fish oil for both aquaculture and human nutrition[212]. These lipids are rich in essential long-chain polyunsaturated fatty acids (PUFAs) particularly omega-3 and omega-6 fatty acids which are vital for health but cannot be synthesized by humans or many animals thus requiring dietary intake[182]. PUFAs contribute significantly to the synthesis of bioactive molecules such as prostaglandins and thromboxanes, which help to regulate blood cholesterol and triglyceride levels and provide protection against conditions like dermatitis and osteoarthritis[127]. Among these, docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) offer broad health benefits.

DHA supports cognitive function by enhancing neuronal activity, improving memory and aiding in the management of neurological disorders. The combined effects of DHA and EPA also support fetal development, reduce inflammation and help in the prevention and treatment of cardiovascular diseases[199]. *Schizochytrium* is a prominent microalgal species known for its high DHA content and has been confirmed safe for consumption[131]. Algal oil derived from *Schizochytrium* commercially known as "DHA Gold," has found applications beyond nutrition particularly in the cosmetics industry. It is used in skincare formulations to restore the skin's hydrolipidic barrier reflecting the growing importance of microalgal lipids as multifunctional bioactive compounds[152].

## Mycosporine-like Amino acids (MAAs)

Mycosporine-like amino acids (MAAs) are natural, water-soluble compounds predominantly found in marine organisms inhabiting tropical climates especially microalgae. These organisms have developed adaptive mechanisms to withstand intense solar radiation and high-salinity environments[153,195]. One such adaptation is MAA-based UV inhibition, an evolutionary trait acquired by cyanobacteria to protect themselves from harmful ultraviolet (UV) radiation[185]. MAAs are unique as they do not generate reactive oxygen species (ROS) during UV absorption making them ideal for photoprotection. Their multifunctional nature includes antioxidant, anti-inflammatory and anti-aging properties. They have been shown to inhibit protein glycation and collagenase activity earning recognition as valuable bioactive ingredients in skincare and cosmetics[194].

Their antioxidant potential is primarily attributed to their ability to scavenge and neutralize free radicals. MAAs mitigate the adverse effects of UV exposure such as sunburn, edema, blistering, phototoxic reactions and photosensitivity by preventing radiation from penetrating deep into the dermal layers[167]. As a result, they are being explored as promising natural alternatives to traditional drugs and synthetic sunscreens in cosmetic formulations. The antioxidant role of MAAs was first highlighted in 2004 with mycosporine-glycine shown to play a significant protective role against oxidative stress[163]. Under heat stress, coral species such as *Stylophora pistillata* produced elevated levels of superoxide dismutase while intracellular levels of Mycosporine-glycine decreased indicating its involvement in counteracting oxidative damage. In contrast, other MAAs remained stable. Furthermore, MAA precursors like 4-deoxygadusol and imino-mycosporines (shinorine, porphyra-334) exhibit strong resistance to oxidation[34,112]. *In vitro* studies including DPPH assays and tests on human skin cell lines, revealed that mycosporine-glycine provides superior antioxidant protection compared to other MAAs in part by inhibiting NF-κB signaling pathways[142,193]. Among the various MAA types, mono-substituted, di-substituted and glycosylated forms have demonstrated the highest antioxidant activities, further emphasizing their potential as effective multifunctional agents in skincare and therapeutic applications.

## Microalgal Pigments

Microalgae are known for their diverse and vibrant pigmentation resulting from a variety of bioactive pigments housed within their cells. These pigments are broadly categorized into two groups: liposoluble pigments such as chlorophylls and carotenoids and hydro-soluble pigments, primarily phycobilin's[209]. These compounds have attracted significant interest due to their wide-ranging bioactivities including antioxidant, neuroprotective, immunomodulatory and provitamin functions[145]. In recent years, the application of microalgal pigments in the cosmetics industry has gained momentum. Their strong antioxidant properties have rendered them particularly suitable for incorporation into anti-aging formulations including skincare creams. Species such as *Porphyridium cruentum* and cyanobacteria like *Arthrospira platensis*[64] have been reported to synthesize substantial amounts of phycobiliproteins comprising up to 8% of their dry biomass[32]. These water-soluble proteins are not only biologically active but also serve as effective fluorescent labels in biomedical and diagnostic applications due to their unique spectral characteristics (Figure 1).

**Chlorophyll:** Chlorophyll, one of the most abundant and functionally important pigments in microalgae plays a central role in photosynthesis and is widely utilized for its nutritional and therapeutic properties. It exists primarily in two forms chlorophyll *a* and *b*, both of which contribute significantly to light absorption in the red and blue spectra, thereby imparting the green coloration characteristic of photosynthetic organisms[50]. These pigments are essential for plant and algal survival and indirectly for the broader ecological balance[80]. Due to increasing consumer demand for natural additives, chlorophyll is now preferred over synthetic dyes as a green food colorant[196,216].

In addition to its coloring properties, chlorophyll exhibits significant biological activities including antioxidant, anti-inflammatory and antibacterial effects[39]. It has been reported to support haematopoiesis and promote wound healing making it a multifunctional bioactive compound[215]. Furthermore, derivatives of chlorophyll such as pheophorbide *b* and pheophytin *b* have demonstrated potent antioxidant activity, further enhancing the pigment's functional value in nutraceutical and cosmetic applications[102,198]. The chlorophyll content in various microalgal species varies considerably.

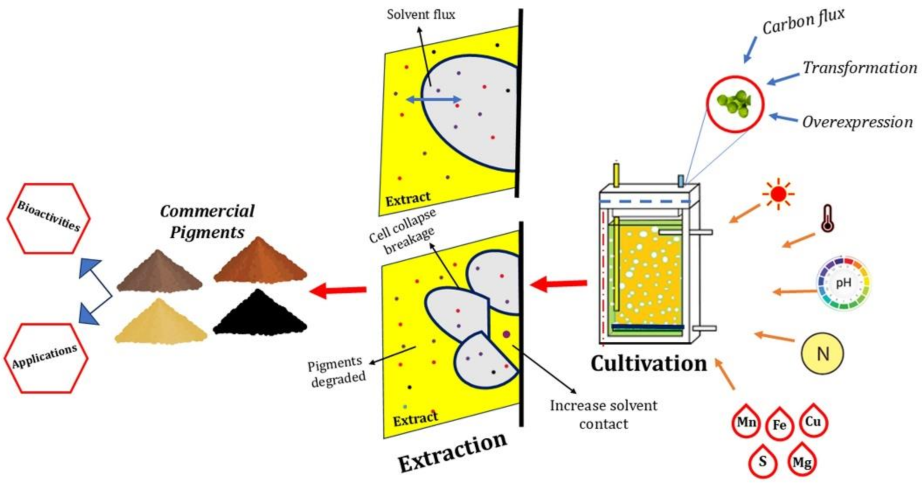


**Figure 1: Extraction and cultivation of commercial pigments from microalgae**

*Chlorella* species have been shown to accumulate pigments amounting to approximately 4.5% of their dry biomass[120]. Among eukaryotic microalgae strains such as *Micractinium ehime* IPOME-1, *Micractinium* sp. CCAP IPOME-2 and *Mychonastes rotundus* IPOME-3 have exhibited high chlorophyll yields, with values reaching 4.037 ± 0.0875%, 4.967 ± 0.1050% and 3.880 ± 0.1866% of dry weight respectively. In contrast, the prokaryotic strain *Oscillatoria* sp. IPOME-4 contained 2.096 ± 0.0209% chlorophyll[51]. Notably, *Nannochloropsis* sp. has been recognized as a highly promising strain for large-scale chlorophyll extraction and quantification due to its robust pigment production capacity[141].

**Carotenoids:** Carotenoids are a class of organic compounds essential to photosynthetic organisms where they function in light absorption and protection against photooxidative damage. These compounds are broadly classified into carotenes (hydrocarbons without oxygen) and xanthophylls (oxygen-containing carotenoids such as lutein). In addition to their roles in photosynthesis, carotenoids exhibit strong antibacterial and antioxidant activities contributing to cellular defense mechanisms. Owing to their health-promoting properties, carotenoids are increasingly applied in the food, pharmaceutical and cosmetic industries[24,147]. Commercially significant carotenoids include β-carotene, astaxanthin, lutein, zeaxanthin, canthaxanthin and fucoxanthin[69]. Others, such as lycopene, also hold nutritional and therapeutic relevance.

β-carotene known for its vibrant yellow-orange pigment plays a crucial role in chlorophyll stability and serves as a precursor to vitamin A[124]. Microalgae are a rich source of carotenoids accumulating compounds like β-carotene and other antioxidants that are vital for human health[26]. β-carotene is efficiently extracted from *Dunaliella salina* using supercritical carbon dioxide[111] while eicosapentaenoic acid (EPA) is obtained from *Nannochloropsis* through ethanolic extraction[86], enabling simultaneous extraction and separation. Microalgal xanthophylls are particularly valued for their bioavailability and bioactivity, making them suitable for applications in nutraceuticals, pharmaceuticals, cosmetics and animal feed[21,41]. Among them, β-carotene is widely used for its pro-vitamin A function, enhancing immune health and vision, while also serving as a cosmetic and food additive[37].

Astaxanthin, derived primarily from *Haematococcus pluvialis*, is recognized for its exceptional antioxidant strength and is approved in several countries for use in dietary supplements and aquaculture feeds. Its hepatoprotective, anti-inflammatory and anti-aging effects are well-documented[157]. Lutein, commonly incorporated into food and skincare products protects the retina by filtering harmful blue light and may prevent age-related visual impairments[45]. Fucoxanthin has shown potential in managing obesity, metabolic syndrome and cancer. When consumed with dietary fats, its absorption is enhanced. Its deacetylated form, fucoxanthinol, exhibits neuroprotective effects and is considered promising for use in pharmaceuticals and functional foods[110].

**Phycocyanin:** Phycocyanin are blue pigment protein complexes primarily derived from cyanobacteria and belong to the phycobiliprotein family which is characterized by large, water-soluble proteins capable of forming high molecular-weight complexes[144,210]. These pigments contribute significantly to the total protein content in microalgae, accounting for approximately 40–60% of the total soluble proteins within the cells. Based on their spectral properties and protein structures, microalgae-derived phycobiliproteins are generally classified into three types: phycoerythrin, phycocyanin and allophycocyanin[148].

Phycocyanin have gained considerable attention for their applications in the food, pharmaceutical and cosmetic industries particularly as natural colorants and functional ingredients. Their high fluorescence efficiency also enables their use as non-toxic fluorescent probes in immunoassays and molecular diagnostics[96].

*Spirulina* is recognized as a major source of C-phycocyanin (C-PC) while *Galdieria sulphuraria* is emerging as a promising candidate for heterotrophic phycocyanin production under controlled fermentation conditions[54]. Comparative studies have shown that phycocyanin extracted from *Phormidium rubidium* exhibits stronger antioxidant activity than that obtained from *Orcuttia tenuis*[186], highlighting species specific variations in bioactivity.

## Nutritional and bioactive potential of microalgae

Micronutrients such as vitamins and minerals are as essential to the body's metabolism as macronutrients like proteins, lipids and carbohydrates[73]. Acting as cofactors in numerous biochemical reactions, they support critical physiological functions including immunity, development and cellular repair. Vitamin deficiencies can lead to various diseases such as scurvy, beriberi and rickets[114]. Marine microalgae are widely recognized as excellent sources of vitamins. For example, *Spirulina sp.* contains significant amounts of bioactive compounds like vitamins A and B complexes which are involved in brain function, metabolism and immune defense[101]. Similarly, *Dunaliella tertiolecta* is rich in vitamins B2, B12 and E while *Tetraselmis suecica* can synthesize B-complex and vitamin C[95].

In addition, microalgae often contain precursors of vitamin A such as β-carotene and retinol which have been linked to anticancer properties that *Nannochloropsis oceanica* can produce vitamin D3 when exposed to UV-B light[55]. Powders made from *Chlorella* and *Nannochloropsis* provide ample amounts of vitamins B9 and B12 to meet daily human needs while cyanobacteria like *Spirulina* offer extremely high levels of vitamin K1 surpassing traditional sources like parsley[201].

Alongside their vitamin content, marine microalgae are rich in polysaccharides (PSs) which act as energy reserves. These PSs, particularly sulfated polysaccharides (SPS) have shown promising bioactivities such as antioxidant, anticancer, immunomodulatory, antiviral and anticoagulant effects[81]. Species like *Porphyridium sp.* and *Cochlodinium polykrikoides* produce SPS with strong anti-inflammatory properties including the inhibition of leukocyte migration and reduction of erythema[137].

These polysaccharides are mainly composed of monosaccharides like glucose, fructose, xylose and galactose along with minor components such as uronic acids and proteins. They are typically categorized as intracellular, extracellular or structural polysaccharides with extracellular forms (EPSs) receiving the most attention due to their rheological and biological functions[113]. Their structures often include hetero-polysaccharides complex carbohydrates with non-repeating sugar units and are sometimes associated with sulfate groups. Additionally, microalgal cell walls contain alpha-1,4-glucans and beta-1,3-glucans, the former being widely used in cosmetics due to their favourable properties[47]. Despite these diverse applications, the health promoting properties of these molecules remain underexplored highlighting the need for more research on the structure activity relationships of microalgal polysaccharides[33,123].

Moreover, microalgae are notable for their high lipid content especially long chain polyunsaturated fatty acids (PUFAs) such as omega-3 (EPA and DHA) and omega-6 types. These essential fatty acids cannot be synthesized by humans and must be obtained through the diet[182]. PUFAs play crucial roles in the synthesis of bioactive compounds like prostaglandins and thromboxanes which regulate blood lipids and help to prevent conditions such as dermatitis and osteoarthritis[127]. DHA supports brain function, memory and the management of neurological disorders while both EPA and DHA contribute to fatal development, anti-inflammatory responses and cardiovascular health[199].

Microalgal species such as *Schizochytrium*, *Crypthecodinium* and *Nannochloropsis* are established producers of PUFAs with superior stability and sensory qualities compared to fish oil[8,169] influencing PUFA production; for instance, *Nannochloropsis oculata* yielded high EPA at 20°C and bicarbonate supplementation increased PUFA content in *Pavlova lutheri*[60]. Conversely, high light intensity was found to reduce EPA and DHA in *Chlorella vulgaris*[60]. Notably, algal oil derived from *Schizochytrium* marketed as "DHA Gold," has been approved for use in cosmetics where it helps to restore the skin's hydrolipidic film underscoring the multifunctional potential of microalgal lipids beyond nutrition[131,152].

## Biological activities of microalgae bioactive compounds

**Antioxidant Activity:** Antioxidants are vital in human physiology, playing a key role in preventing oxidative stress-related diseases[151] (Figure 2). Microalgae have demonstrated remarkable antioxidant potential often surpassing conventional plant or fruit sources[160]. This activity is largely due to the presence of vitamins, carotenoids, polyphenols and flavonoids. Cyanobacteria, especially *Spirulina* contain high concentrations of phycobiliproteins which significantly boost their antioxidant activity[177]. *Spirulina* is particularly rich in carotenoids, phenolic compounds, phycocyanin and chlorophylls all of which contribute to its strong antioxidant capacity[19]. Likewise, microalgae such as *Scenedesmus* sp., *Chlorella vulgaris* and *Chlamydomonas reinhardtii* are known for their abundance of antioxidant compounds like flavonoids and carotenoids[44]. Phycobilin proteins water soluble pigments found in cyanobacteria and red algae absorb light across a broad spectrum (470–660 nm) and exhibit strong antioxidant effects due to their chromophore bound protein structure[93]. Sterols including desmosterol, sitosterol, ergosterol and occelasterol also enhance the antioxidant profile of microalgae with species like *Monoraphidium minutum* and *Ankistrodesmus fusiformis* recognized as major sterol producers[121,171].

https://doi.org/10.25303/2012rjbt2960313

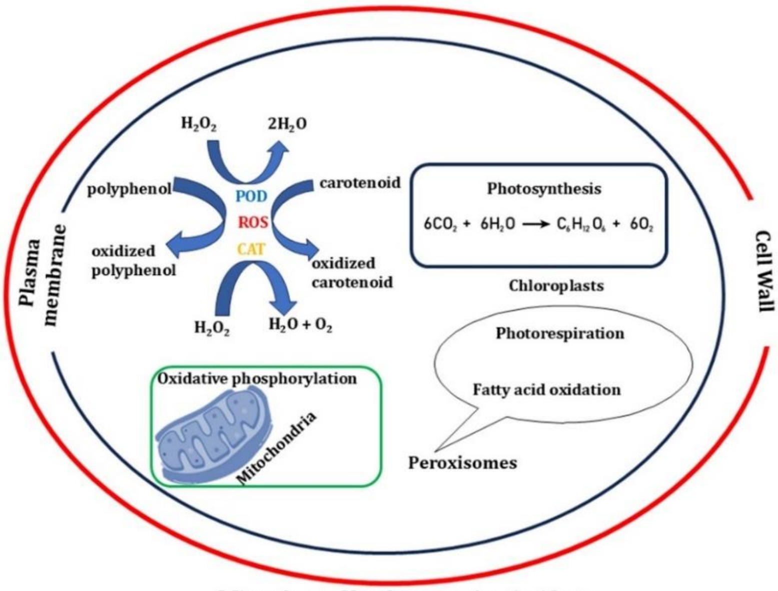


**Figure 2: Antioxidant mechanism from microalgae**

Other microalgae such as *Chlorella*, *Dunaliella* and *Haematococcus* further contribute to antioxidant research. *Chlorella* is valued for promoting health and preventing disease through its antioxidant content while *Dunaliella* offers easily digestible antioxidants and phenolic compounds supporting its role as a dietary supplement[82]. *Haematococcus lacustris* in particular is known for its rich astaxanthin content, it is a potent antioxidant with demonstrated benefits for cardiovascular, immune, skin and eye health[4].

**Anti-obesity Effect:** Obesity is defined by the excessive accumulation of fat in adipose tissues and is typically identified by a body mass index (BMI) of 30 or higher[93]. Recent studies have increasingly focused on the anti-obesity potential of microalgae derived extracts. *Euglena gracilis* rich in vitamins, minerals, unsaturated fatty acids and the dietary fiber β-1,3-glucan (paramylon) has been shown to reduce intracellular triglyceride (TG) levels in human adipose-derived stem cells (hASCs) by 17% to 74% in a concentration-dependent manner[66,85]. Similarly, an aqueous extract from *Spirulina maxima* demonstrated anti-obesity effects and promoted adipocyte browning in pre-adipocyte 3T3-L1 and C3H10T1/2 cell lines indicating its potential role in fat metabolism[176].

Another compound of interest is fucoxanthin, a carotenoid found in the diatom *Phaeodactylum tricornutum* which has been shown to inhibit lipid accumulation in 3T3-L1 adipocytes by modulating lipid metabolism-related genes such as PPARγ and UCP1[68]. Furthermore, both fucoxanthin and its metabolite fucoxanthinol have been identified as inhibitors of adipogenesis offering promising strategies for obesity management[135].

**Anti-inflammatory Activity:** Inflammation is the body's primary defense mechanism triggered by disturbances in cellular homeostasis, often caused by external threats. This response involves the release of pro-inflammatory mediators such as cytokines, chemokines, cyclooxygenase-2 (COX-2), prostaglandins and nitric oxide synthase (NOS), all of which have been linked to the development of various chronic diseases[146]. Microalgae have shown promise in modulating this response. For instance, *Micractinium sp.*, a freshwater microalga, significantly reduces the production of TNF-α and IL-6[192] while *Chloromonas reticulata* downregulates the expression of NOS and COX-2 genes, along with related pro-inflammatory mRNA levels[191].

Freshwater derived microalgal lipids have also been reported to inhibit COX activity thereby alleviating inflammation[142]. Phytosterols from *Nannochloropsis oculata* suppress both NOS and COX-2, reinforcing their anti-inflammatory role[170]. Moreover, essential fatty acids like fucoxanthin, EPA, DHA and other oxylipins found in microalgal lipids contribute to anti-inflammatory activity by targeting key regulatory pathways[61]. In addition, both microalgae and cyanobacteria synthesize diverse bioactive molecules with therapeutic potential. Peptides such as aeruginosin-865 from *Nostoc* [87] and cyanopeptolin 1020 from *Microcystis*[57] have demonstrated biological activity. Mycosporine-like amino acids including mycosporine-glycine and shinorine from *Chlamydomonas hedleyi* and *Anabaena variabilis*, help to protect cells under stress[184,208].

*Spirulina* is a rich source of phycocyanin and functional peptides (LDAVNR, MMLDF) known for its anti-inflammatory and antioxidant effects[211]. Polysaccharides like Sacran from *Aphanothece* and Nc-5-s from *Nostoc commune* exhibit strong immunomodulatory properties[133,140]. Furthermore, lipid compounds such as monogalacto and digalactosyl diacylglycerol and hydroxylated fatty acids like HEPE and HOTE from *Chlamydomonas debaryana* contribute to inflammatory regulation. Pigments like astaxanthin from *Haematococcus*, violaxanthin from *Chlorella* and fucoxanthin from *Phaeodactylum* offer additional anti-inflammatory effects. Secondary metabolites such as coibacin A from *Oscillatoria* and honaucins from *Leptolyngbya* highlight the rich pharmacological potential of these microorganisms[9,11,77].

**Antibacterial activity:** Due to increasing antibiotic resistance, microalgae have emerged as promising sources natural antibacterial agents. Various freshwater species including *Ephedra viridis*, *Microcystis aeruginosa*, *Chlorella vulgaris* and *Spirulina platensis*, have shown inhibitory effects against pathogens such as *Escherichia coli*, *Staphylococcus aureus* and *Salmonella typhi*[150]. *Planktochlorella nurekis* has also demonstrated activity against multiple strains including *Salmonella enterica* (var. *enteritidis* and *infantis*) and *Campylobacter jejuni*[99]. The antibacterial potential of microalgae is often attributed to bioactive lipids particularly saturated (SFAs), monounsaturated (MUFAs) and polyunsaturated fatty acids (PUFAs)[62].

Fatty acids such as lauric, myristic, pentadecanoic and stearic acids have been found to reduce the metabolic activity of Gram negative bacteria like *Pseudomonas aeruginosa* and *E. coli* PCM 2209[136]. Extracts from *Tetraselmis suecica* especially the 40% acetonitrile fraction exhibited significant antimicrobial activity against both Gram positive and Gram negative bacteria[75]. Similarly, fatty acid methyl esters (FAMEs) derived from *Isochrysis galbana*, *Scenedesmus* NT8c and *Chlorella* FN1 showed high inhibition of Gram positive bacterial growth. *Scenedesmus obliquus* extracts revealed potent antibacterial effects with minimum inhibitory concentrations (MICs) ranging from 15.6 to 125 μg/mL[2,134].

In a broader screening effort, lipid extracts from over 600 microalgae and cyanobacterial species demonstrated antimicrobial and antibiofilm capabilities, with certain methanol and ethyl acetate fractions achieving up to 80% biofilm inhibition[29]. The antibacterial activity of *Planktochlorella nurekis* has also been linked to its rich content of MUFAs and PUFAs which influence Gram positive bacterial growth[143]. Microalgae represent a promising source of natural antibacterial compounds effective against a wide range of pathogenic bacteria.

**Anticancer and Antiviral Activities:** Microalgae are a rich source of bioactive compounds with significant potential in anticancer and antiviral applications. Their species diversity contributes to the production of various metabolites with distinct therapeutic properties enabling the development of targeted cancer treatments[38]. Among these compounds, microalgal derived carotenoids such as astaxanthin and fucoxanthin have shown promising anticancer effects. Astaxanthin functions as a strong antioxidant, reducing genotoxicity and inhibiting cancer cell proliferation. It induces cell cycle arrest at the G0/G1 phase, enhances p27 expression and has demonstrated efficacy in gastric, prostate and colon cancer models[105]. Furthermore, it modulates NF-κB signaling and reduces oxidative stress contributing to tumor suppression[149].

Due to the high cost of synthetic production, natural sources like *Haematococcus pluvialis* and *Chlorella vulgaris* are preferred for astaxanthin extraction[132]. Fucoxanthin, extracted from *Undaria pinnatifida*, promotes apoptosis in leukemia, prostate and colon cancer cells by activating caspase-3 and inducing DNA fragmentation[94]. It also enhances the effects of other anticancer agents such as troglitazone. Extracts from *Chlorella ellipsoidea* have shown stronger apoptotic effects on colon cancer cells compared to *C. vulgaris*[30]. Carotenoids from *Dunaliella salina* and violaxanthin demonstrate antiproliferative activity in breast and liver cancer cell lines while *Gloeothece* sp. extracts exhibit antioxidant, anti-inflammatory and anticancer effects supporting their potential use as nutraceuticals[3].

In addition to their anticancer properties, several microalgae display antiviral activity. Freshwater species such as *Anabaena sphaerica*, *Chroococcus turgidus*, *Oscillatoria limnetica* and *Cosmarium sp.* have shown antiviral potential. *Spirulina platensis*, in particular, is effective against adenovirus type 40, herpes simplex virus type-1 (HSV-1) and HIV-1 due to the presence of sulfoquinovosyl diacylglycerol (SQDG)[10]. Pheophorbide a (PPba) has broad antiviral action by interacting with viral receptors and exerting effects post entry into host cells[130]. Carotenoids have also been found to mitigate virus induced cytokine storms[162]. Polysaccharides from microalgae block viral entry while naturally produced glycoproteins and lectins interfere with viral glycosylation and CD4 receptor binding particularly in the context of HIV[115].

Microalgae-derived compounds such as polysaccharides, glycoproteins, astaxanthin, lycopene, β-carotene, EPA, DHA, polyphenols and flavonoids showed considerable promise in cancer therapy[27]. Carotenoids like astaxanthin, β-carotene, lutein, lycopene and canthaxanthin have been reported to inhibit human lung cancer cell growth (NCI-H226) and to suppress growth factors in breast and endometrial cancer cells[168]. Various microalgae including *Nannochloropsis gaditana*, *Isochrysis galbana*, *Aphanizomenon flos-aquae* and *Spirulina platensis* have demonstrated anticancer effects[89,147] across multiple cancer types such as breast, colon, prostate, pancreas and endometrium. Extracts from *Granulocystopsis* sp. have shown significant cytotoxicity against prostate, breast, colorectal, melanoma and lung cancer cells[202].

## Biofuels production from microalgae

**Biodiesel:** Third generation biodiesel, derived from microalgae utilizes the photosynthetic carbon fixation process to accumulate lipids with some strains achieve lipid yields of up to 70%[217]. Microalgae offer notable advantages due to their aquatic growth requirements eliminating competition for arable land. These organisms possess a remarkable ability to assimilate both inorganic and organic carbon into biomass, which is rich in proteins, lipids and carbohydrates[35]. Marine and brackish water strains of microalgae are particularly advantageous as they minimize freshwater use and thrive on non-arable lands even under extreme environmental conditions. Their rapid growth rates and substantial biomass productivity make them a sustainable resource without threatening the human food supply[218].

Strains such as *Chlorella* sp. and *Scenedesmus* sp. have demonstrated significant potential for biofuel production[1]. Others including *Chlamydomonas reinhardtii*, *Scenedesmus obliquus*, *Chlorella vulgaris*, *Dunaliella* sp., *Scenedesmus dimorphus*, *Coelastrella* sp. and *Spirulina* sp., accumulate considerable amounts of lipids, protein and carbohydrates reinforcing their suitability as biofuel feedstocks[90,91,180]. The standard process of biodiesel production from microalgae includes strain selection based on lipid content with *Nannochloropsis* sp., *Chlorella sorokiniana* and *Chlorella protothecoides* being well studied examples exhibiting lipid levels between 15% and 40%[204]. Under stress conditions such as nutrient limitation or high salinity, lipid accumulation is enhanced[84].

Lipids are extracted using suitable solvents either directly or following biomass pretreatment. The extracted lipids are then converted into biodiesel through transesterification, a reaction involving alcohol and a catalyst to yield fatty acid esters[58]. This process also produces glycerol as a by-product accounting for approximately 10% of the total weight[165]. The conversion efficiency can reach up to 99% under optimized conditions[203]. A single-step transesterification process allows direct conversion of biomass to biodiesel[28] although this approach is currently economically unfeasible due to the high demand for solvents and catalysts[88].

**Bioethanol:** Bioethanol production from microalgae involves the hydrolysis of microalgal biomass to release fermentable sugars, followed by microbial fermentation using organisms such as yeast[11]. An alternative strategy involves genetically engineered microalgae that produce ethanol directly in the culture medium[97]. Species including *Chlamydomonas reinhardtii*, *Scenedesmus obliquus*, *Chlorella vulgaris*, *Dunaliella* sp. and *Scenedesmus dimorphus* have demonstrated carbohydrate contents as high as 69.7%, making them ideal for bioethanol production via alcoholic fermentation[181,92]. Ethanol yields from microalgal biomass range between 0.07 and 0.5 g/L depending on carbohydrate concentration[92].

Microalgae contain glycogen, starch and cellulose which are suitable for ethanol fermentation due to their low hemicellulose levels and the absence of lignin[172]. The breakdown of these carbohydrates into fermentable sugars can be achieved through thermal, chemical or enzymatic hydrolysis followed by fermentation. Yeast (*Saccharomyces cerevisiae*) and the bacterium *Zymomonas mobilis* are commonly employed in this process to convert sugars into ethanol[125].

Due to the polysaccharide structure of microalgal biomass, extensive chemical or biological pre-treatment is often necessary as most fermenting microbes cannot directly degrade complex carbohydrates[74]. Nitrogen starvation is a widely used cultivation strategy to increase carbohydrate accumulation in microalgal cells which can elevate carbohydrate content up to 50% of dry biomass[48]. Additional approaches under investigation include dark fermentation and photo fermentation utilizing specific microalgal strains capable of performing these processes[43].

**Biomethane and biohydrogen:** Methane production from microalgal biomass can reach up to 0.56 L $CH_4$/g, influenced by factors such as biomass composition, particularly the carbon-to-nitrogen (C/N) ratio and the amount of hydrolysable organic matter[128]. An optimal C/N ratio, typically between 25:1 and 30:1, is essential to support microbial metabolism and efficient methane generation[190]. Pre-treatment methods including physical, chemical, thermal and enzymatic techniques are often employed to disrupt the rigid cell walls of green microalgae thereby enhancing methane yield[83].

In contrast, cyanobacteria lack rigid cell walls which may eliminate the need for such pretreatment[76]. Both intact and lipid extracted microalgae are used in anaerobic digestion. Lipid-extracted biomass especially from wastewater grown strains with lower lipid content, can be digested directly, although the resulting biogas may have reduced quality and calorific value[36]. Residual biomass from pigment or lipid extraction processes also holds potential for methane production[159]. Anaerobic co-digestion strategies have shown promise. For instance, co-digesting *Spirulina maxima* with sewage sludge doubled biogas production[138]. A semi-continuous co-digestion process involving microalgae and sewage sludge at elevated temperatures resulted in sufficient methane generation to sustain thermal requirements[119].

The addition of microalgal biomass to pig dung increased methane output particularly in samples with higher microalgal content[108]. Co-digestion of *Nannochloropsis salina* with lipid rich wastes such as fats, oils and grease, significantly enhanced methane production[70]. Similar results were observed when *Chlorella* sp. was co-digested with waste activated sludge, accelerating the biogas generation rate and improving yield[179]. Collectively, these findings highlight the benefits of anaerobic co-digestion with carbon rich substrates in methane production[72].

Microalgae also contribute to biohydrogen production via two main pathways: bio-photolysis and fermentation[178]. In dark fermentation (DF), anaerobic bacteria enzymatically degrade pretreated algal biomass rich in carbohydrates, proteins and lipids into fermentable sugars[183]. These are then fermented by acidogenic bacteria producing hydrogen, carbon dioxide and volatile fatty acids. Hydrogen can also be generated through acetate and butyrate metabolic pathways, involving specific enzymes[213]. Hydrogen yields from algal carbohydrates typically range from 160.1 to 448.0 mL $H_2$/g dry biomass accounting for 32.2–90.0% of the theoretical maximum[175].

Common DF-associated bacteria include *Bacillus* sp., *Clostridium* sp., *Klebsiella* sp. and *Enterobacter* sp. In photo-biological hydrogen production, certain microalgae harness sunlight to split water molecules releasing hydrogen and oxygen[213]. Both direct and indirect photolysis processes have been reported with species such as *Platymonas subcordiformis*, *Chlorococcum littorale*, *Anabaena* sp. and *Synechococcus* sp. being prominent candidates[71,156,189,214].

**Biocrude oil:** Hydrothermal liquefaction (HTL) is an advanced thermochemical technique used to convert microalgal biomass into biocrude oil under high temperature and pressure (Figure 3). In this process, the inherent moisture in biomass acts as a solvent eliminating the need for drying[50]. Optimized, HTL can recover over 80% of the microalgae's calorific value[122]. Lipids are the most efficiently converted metabolites followed by proteins and carbohydrates with bio-crude yield depending on biomass composition, process conditions and catalyst type[23]. Despite the promising yield, the resulting biocrude typically contains heteroatoms such as nitrogen and oxygen, which require catalytic upgrading to meet fuel quality standards. Additional refining at petroleum facilities is necessary to produce usable fuel products[78].

Most research involving marine microalgae and HTL is conducted in batch mode, although some studies have explored continuous operations[5,52]. An environmentally sustainable HTL approach involved the co-cultivation of microalgae (*Chlorella sorokiniana* DBWC2 and *Chlorella* sp. DBWC7) with bacteria (*Klebsiella pneumoniae* ORWB1 and *Acinetobacter calcoaceticus* ORWB31) addressing challenges related to wastewater treatment[98]. Analysis of the resulting biocrude using Gas Chromatography-Mass Spectrometry (GC-MS) and Fourier Transform Infrared spectroscopy (FTIR) revealed a high hydrocarbon content indicating superior oil quality. A distillate fraction yield of up to 30.62% with a boiling point range between 200–300 °C, suggests the potential for conversion into diesel, jet fuel or stove fuel[6,205]. This integrated strategy illustrates the dual benefits of producing high-quality biocrude while simultaneously contributing to wastewater remediation.

## Future Perspectives

The future of microalgae research and its applications holds immense promise across diverse sectors. Advancing cultivation technologies remains a key priority, with the goal of improving biomass yield while reducing production costs. Genetic engineering of microalgae offers significant potential for enhancing traits tailored to specific industrial and therapeutic applications. Efforts are increasingly directed toward scaling up bio-product manufacturing from microalgae for commercial use in energy, pharmaceuticals and food industries. In the renewable energy sector ongoing research aims to optimize biofuel production by improving lipid accumulation and process efficiency thereby making microalgal biofuels more economically viable.

Microalgae also show great promise in the fields of nutraceuticals and pharmaceuticals particularly in disease prevention and treatment due to their rich profile of bioactive compounds. Simultaneously, their roles in carbon capture and wastewater remediation are gaining attention for their potential to support environmental sustainability. Future strategies will involve the integration of cutting-edge technologies for the efficient extraction and processing of valuable metabolites from microalgae.

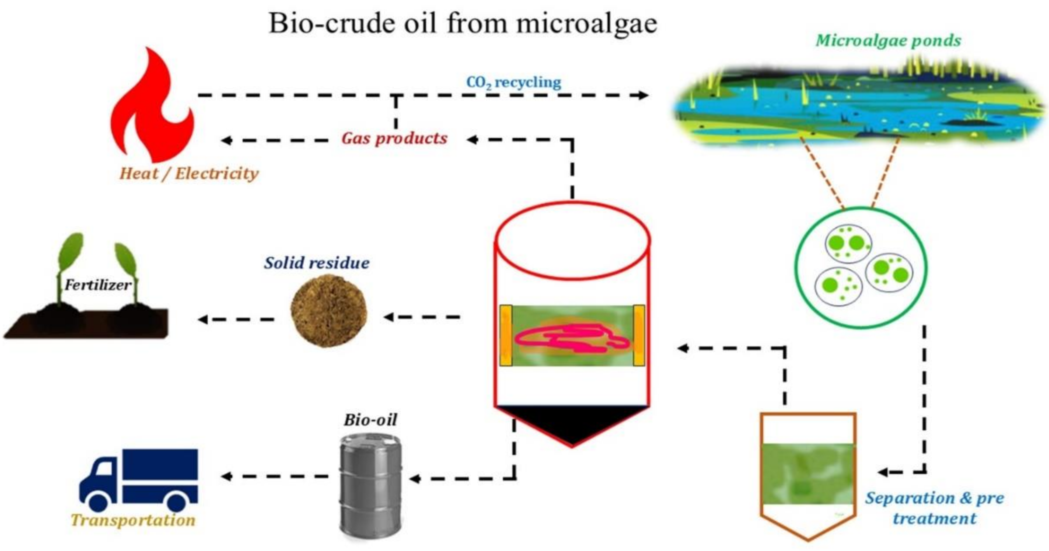


**Figure 3: Bio-crude oil synthesis from microalgae**

Increasing consumer awareness and market acceptance will be critical to expanding the commercial reach of microalgae-derived products. Strong collaboration among academic researchers, industry stakeholders and policymakers is essential to drive innovation and implementation. Moreover, the establishment of supportive policies and regulatory frameworks will be crucial in accelerating research efforts and facilitating the commercialization of microalgae-based solutions.

## Conclusion

Microalgae with their vast diversity and exceptional adaptability offer substantial potential for sustainable applications across various sectors. Their unique physico-chemical characteristics make them valuable contributors to human nutrition, healthcare, environmental protection and renewable energy production. Rich in bioactive compounds such as proteins, lipids, pigments and polysaccharides, microalgae exhibit notable health-promoting properties including antioxidant, anti-inflammatory and anticancer activities.

In the energy sector, microalgae play a pivotal role in advancing biofuel technologies, particularly in the production of biodiesel and bioethanol, offering promising solutions to reduce reliance on fossil fuels and to mitigate environmental impact. Overall, the multifunctional potential of microalgae underscores their importance as a versatile and sustainable resource for future innovations in health, energy and environmental management.

## References

1. Abou-Shanab R.A., Hwang J.H., Cho Y., Min B. and Jeon B.H., Characterization of microalgal species isolated from freshwater bodies as a potential source for biodiesel production, *Applied Energy*, **88(10)**, 3300–3306 **(2011)**

2. Alsenani F., Tupally K.R., Chua E.T., Eltanahy E., Alsufyani H., Parekh H.S. and Schenk P.M., Evaluation of microalgae and cyanobacteria as potential sources of antimicrobial compounds, *Saudi Pharmaceutical Journal*, **28**, 1834–1841 **(2020)**

3. Amaro H.M. et al, Gloeothece sp.-Exploiting a new source of antioxidant, anti-inflammatory and antitumor agents, *Marine Drugs*, **19**, 623 **(2021)**

4. Ampofo J. and Abbey L., Microalgae: bioactive composition, health benefits, safety and prospects as potential high-value ingredients for the functional food industry, *Foods*, **11(12)**, 1744 **(2022)**

5. Ariharan V.N., Meena Devi V.N., Gopukumar S.T. and Nagendra Prasad P., Physico-Chemical Properties of Biodiesel Obtained from Callophyllum innophyllum Oil, *Research Journal of Pharmaceutical, Biological and Chemical Sciences*, **5(1)**, 64–71 **(2014)**

6. Ariharan V.N., Meenadevi V.N. and Gopukumar S.T., Physico-chemical analysis of Cleome viscosa L. oil: A potential source for biodiesel, *Rasayan Journal of Chemistry*, **7(2)**, 129–132 **(2014)**

7. Ataie A., Shadifar M. and Ataee R., Polyphenolic antioxidants and neuronal regeneration, *Basic and Clinical Neuroscience*, **7(2)**, 81–90 **(2016)**

8. Aussant J., Guiheneuf F. and Stengel B.D., Impact of temperature on fatty acid composition and nutritional value in eight species of microalgae, *Applied Microbiology and Biotechnology*, **102**, 5279–5297 **(2018)**

9. Ávila-Román J., Talero E., de Los Reyes C., García-Mauriño S. and Motilva V., Microalgae-derived oxylipins decrease inflammatory mediators by regulating the subcellular location of NFκB and PPAR-γ, *Pharmacological Research*, **128**, 220–230 **(2018)**

10. Ayehunie S., Belay A., Baba T.W. and Ruprecht R.M., Inhibition of HIV-1 replication by an aqueous extract of *Spirulina platensis* (*Arthrospira platensis)*, *Journal of Acquired Immune Deficiency Syndromes*, **18(1)**, 7–12 **(1998)**

11. Azhar S.H.M., Abdulla R., Jambo S.A., Marbawi H., Gansau J.A., Faik A.A.M. and Rodrigues K.F., Yeasts in sustainable bioethanol production: A review, *Biochemistry and Biophysics Reports*, **10**, 52–61 **(2017)**

12. Balunas M.J., Grosso M.F., Villa F.A., Engene N., McPhail K.L., Tidgewell K., Pineda L.M., Gerwick L., Spadafora C., Kyle D.E. and Gerwick W.H., Coibacins A–D, antileishmanial marine cyanobacterial polyketides with intriguing biosynthetic origins, *Organic Letters*, **14(15)**, 3878–3881 **(2012)**

13. Barkia N. and Saari N., Microalgae for high-value products towards human health and nutrition, *Marine Drugs*, **17(5)**, 304 **(2019)**

14. Barsanti L., Coltelli P., Evangelista V., Frassanito A.M., Passarelli V., Vesentini N. and Gualtieri P., Oddities and curiosities in the algal world, Algal Toxins: Nature, Occurrence, Effect and Detection, 353–391 **(2008)**

15. Barta D.G., Coman V. and Vodnar D.C., Microalgae as sources of omega-3 polyunsaturated fatty acids: Biotechnological aspects, *Algal Research*, **58**, 102410 **(2021)**

16. Batista A.P., Gouveia L., Bandarra N.M., Franco J.M. and Raymundo A., Comparison of microalgal biomass profiles as novel functional ingredient for food products, *Algal Research*, **2**, 164–173 **(2013)**

17. Becker E.W., Microalgae for aquaculture: Nutritional aspects, Handbook of Microalgal Culture: Applied Phycology and Biotechnology, 671–691 **(2013)**

18. Becker W., Microalgae for aquaculture: the nutritional value of microalgae for aquaculture, Handbook of Microalgal Culture: Biotechnology and Applied Phycology, 380–391 **(2003)**

19. Bito T., Okumura E., Fujishima M. and Watanabe F., Potential of *Chlorella* as a dietary supplement to promote human health, *Nutrients*, **12(9)**, 2524 **(2020)**

20. Bleakley S. and Hayes M., Algal proteins: Extraction, application and challenges concerning production, *Foods*, **6(5)**, 33 **(2017)**

21. Borowitzka M.A., High-value products from microalgae-Their development and commercialisation, *J. Appl. Phycol.*, **25**, 743–756 **(2013)**

22. Brennan L. and Owende P., Biofuels from microalgae-A review of technologies for production, processing and extractions of biofuels and co-products, *Renewable and Sustainable Energy Reviews*, **14**, 557–577 **(2010)**

23. Breton-Deval L., Méndez-Acosta H.O., González-Álvarez V., Snell-Castro R., Gutiérrez-Sánchez D. and Arreola-Vargas J., Agave tequilana bagasse for methane production in batch and sequencing batch reactors: Acid catalyst effect, batch optimization and stability of the semi-continuous process, *Journal of Environmental Management*, **224**, 156–163 **(2018)**

24. Britton G., Liaaen-Jensen S. and Pfander H., Carotenoids Volume 4, Natural Functions, Birkhäuser **(1998)**

25. Brown M.R., Mular M., Miller I., Farmer C. and Trenerry C., The vitamin content of microalgae used in aquaculture, *Journal of Applied Phycology*, **11**, 247–255 **(1999)**

26. Bryon A., Kurlovs A.H., Dermauw W., Greenhalgh R., Riga M., Grbić M., Tirry L., Osakabe M., Vontas J., Clark R.M. and Van Leeuwen T., Disruption of a horizontally transferred phytoene desaturase abolishes carotenoid accumulation and diapause in *Tetranychus urticae*, Proceedings of the National Academy of Sciences, **114**, E5871–E5880 **(2017)**

27. Bule M.H., Ahmed I., Maqbool F., Bilal M. and Iqbal H.M., Microalgae as a source of high-value bioactive compounds, *Frontiers in Bioscience*, **10**, 197–216 **(2018)**

28. Cao H., Zhang Z., Wu X. and Miao X., Direct biodiesel production from wet microalgae biomass of *Chlorella pyrenoidosa* through in situ transesterification, *BioMed Research International*, **2013**, 930686 **(2013)**

29. Cepas V. et al, Microalgae and cyanobacteria strains as producers of lipids with antibacterial and antibiofilm activity, *Marine Drugs*, **19**, 675 **(2021)**

30. Cha K.H., Koo S.Y. and Lee D.U., Antiproliferative effects of carotenoids extracted from *Chlorella ellipsoidea* and *Chlorella vulgaris* on human colon cancer cells, *Journal of Agricultural and Food Chemistry*, **56**, 10521–10526 **(2008)**

31. Chai X.J., Chen H.X., Xu W.Q. and Xu Y.W., Expression of soybean Kunitz trypsin inhibitor gene SKTI in *Dunaliella salina*, *Journal of Applied Phycology*, **25**, 139–144 **(2013)**

32. Chaiklahan R., Chirasuwan N., Srinorasing T., Attasat S., Nopharatana A. and Bunnag B., Enhanced biomass and phycocyanin production of *Arthrospira (Spirulina) platensis* by a cultivation management strategy: light intensity and cell concentration, *Bioresour. Technol.*, **343**, 126077 **(2022)**

33. Chandrarathna H.P.S.U., Liyanage T.D., Edirisinghe S.L., Dananjaya S.H.S., Thulshan E.H.T., Nikapitiya C., Oh C., Kang D.H. and De Zoysa M., Marine microalgae, *Spirulina maxima*-derived modified pectin and modified pectin nanoparticles modulate the gut microbiota and trigger immune responses in mice, *Marine Drugs*, **18**, 175 **(2020)**

34. Cheewinthamrongrod V., Kageyama H., Palaga T., Takabe T. and Waditee-Sirisattha R., DNA damage protecting and free radical scavenging properties of mycosporine-2-glycine from the Dead Sea cyanobacterium in A375 human melanoma cell lines, *Journal of Photochemistry and Photobiology B: Biology*, **164**, 289–295 **(2016)**

35. Chen H., Zheng Y., Zhan J., He C. and Wang Q., 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**, 1–20 **(2017)**

36. Chisti Y., Biodiesel from microalgae, *Biotechnology Advances*, **25**, 294–306 **(2007)**

37. Chiu H.F., Liao J.Y., Lu Y.Y., Han Y.C., Shen Y.C., Venkatakrishnan K., Golovinskaia O. and Wang C.K., Anti-proliferative, anti-inflammatory and pro-apoptotic effects of *Dunaliella salina* on human KB oral carcinoma cells, *Journal of Food Biochemistry*, **41**, e12349 **(2017)**

38. Choi H., Mascuch S.J., Villa F.A., Byrum T., Teasdale M.E., Smith J.E., Preskitt L.B., Rowley D.C., Gerwick L. and Gerwick W.H., Honaucins A-C, potent inhibitors of inflammation and bacterial quorum sensing: synthetic derivatives and structure-activity relationships, *Chemistry & Biology*, **19**, 589–598 **(2012)**

39. Chu W.L. and Phang S.M., Microalgae and cyanobacteria as a potential source of anticancer compounds, In Handbook of Algal Technology and Phytochemistry, 185–205 **(2019)**

40. Chuyen H.V. and Eun J.B., Marine carotenoids: Bioactivities and potential benefits to human health, *Crit. Rev. Food Sci. Nutr.*, **57**, 2600–2610 **(2017)**

41. Cmiková N. et al, Characterization of selected microalgae species as potential sources of nutrients and antioxidants, *Foods*, **13**, 2160 **(2024)**

42. Čmiková N. et al, Biochemical profiling and bioactivity of five selected microalgae species as potential sources of bioactive compounds for nutritional and biotechnological applications, *Journal of Food Biochemistry*, **2025**, 5171615 **(2025)**

43. Conde T.A. et al, Microalgal lipid extracts have potential to modulate the inflammatory response: A critical review, *International Journal of Molecular Sciences*, **22**, 9825 **(2021)**

44. Cornejo A., Muñoz R., Míguez J.L. and Porteiro J., A review on the production of bioethanol from microalgal biomass by fermentation, *Fuel*, **268**, 117048 **(2020)**

45. Coulombier N., Jauffrais T. and Lebouvier N., Antioxidant compounds from microalgae: A review, *Marine Drugs*, **19**, 549 **(2021)**

46. D'Alessandro E.B. and Antoniosi Filho N.R., Concepts and studies on lipid and pigments of microalgae: A review, *Renewable and Sustainable Energy Reviews*, **58**, 832–841 **(2016)**

47. Das P., Aziz S.S. and Obbard J.P., Two phase microalgae growth in the open system for enhanced lipid productivity, *Renewable Energy*, **36**, 2524–2528 **(2011)**

48. de Jesus Raposo M.F., de Morais R.M.S.C. and de Morais A.M.M.B., Health applications of bioactive compounds from marine microalgae, *Life Sciences*, **93**, 479–486 **(2013)**

49. de Jesus S.S., Gaglianone L.A. and Gonçalves M.D., Microalgae in the raw material supply chain for biofuels: A review, *Renewable and Sustainable Energy Reviews*, **145**, 111087 **(2021)**

50. Del Campo J.A., Moreno J., Rodríguez H., Vargas M.A., Rivas J. and Guerrero M.G., Carotenoid content of chlorophycean microalgae: Factors determining lutein accumulation in *Muriellopsis* sp. (Chlorophyta), *Journal of Biotechnology*, **76**, 51–59 **(2000)**

51. Demirbas A., Progress and recent trends in biodiesel fuels, *Energy Conversion and Management*, **50**, 14–34 **(2009)**

52. Dharma A., Sekatresna W., Zein R., Chaidir Z. and Nasir N., Chlorophyll and total carotenoid contents in microalgae isolated from local industry effluent in West Sumatera, Indonesia, *Der Pharma Chem.*, **9**, 9–11 **(2017)**

53. Dismukes G.C., Carrieri D., Bennette N., Ananyev G.M. and Posewitz M.C., Aquatic phototrophs: Efficient alternatives to land-based crops for biofuels, *Current Opinion in Biotechnology*, **19**, 235–240 **(2008)**

54. Dolganyuk V., Belova D., Babich O., Prosekov A., Ivanova S., Katserov D., Patyukov N. and Sukhikh S., Microalgae: A promising source of valuable bioproducts, *Biomolecules*, **10**, 1153 **(2020)**

55. Durvasula R.V. and Rao D.S., eds., Extremophiles: From biology to biotechnology, CRC Press **(2018)**

56. Ebrahimi P., Shokramraji Z., Tavakkoli S., Mihaylova D. and Lante A., Chlorophylls as natural bioactive compounds existing in food by-products: A critical review, *Plants*, **12**, 1533 **(2023)**

57. Edelmann M., Aalto S., Chamlagain B., Kariluoto S. and Piironen V., Riboflavin, niacin, folate and vitamin B12 in commercial microalgae powders, *Journal of Food Composition and Analysis*, **82**, 1–10 **(2019)**

58. Faltermann S., Hutter S., Christen V., Hettich T. and Fent K., Anti-inflammatory activity of cyanobacterial serine protease inhibitors aeruginosin 828A and cyanopeptolin 1020 in human hepatoma cell line Huh7 and effects in zebrafish (*Danio rerio*), *Toxins*, **8**, 219 **(2016)**

59. Farouk S.M., Tayeb A.M., Abdel-Hamid S.M. and Osman R.M., Recent advances in transesterification for sustainable biodiesel production, challenges and prospects: A comprehensive review, *Environmental Science and Pollution Research*, **31**, 12722–12747 **(2024)**

60. Feng S. et al, Preparation of transgenic *Dunaliella salina* for immunization against white spot syndrome virus in crayfish, *Archives of Virology*, **159**, 519–525 **(2014)**

61. Freddy G. and Dagmar B.S., LC-PUFA-enriched oil production by microalgae: Accumulation of lipid and triacylglycerols containing n-3 LC-PUFA is triggered by nitrogen limitation and inorganic carbon availability in the marine haptophyte *Pavlova lutheri*, *Marine Drugs*, **11**, 4246–4266 **(2013)**

62. Fu W., Nelson D.R., Yi Z., Xu M., Khraiwesh B., Jijakli K. and Salehi-Ashtiani K., Bioactive compounds from microalgae: Current development and prospects, *Studies in Natural Products Chemistry*, **54**, 199–225 **(2017)**

63. Gallego R., Montero L., Cifuentes A., Ibáñez E. and Herrero M., Green extraction of bioactive compounds from microalgae, *Journal of Analysis and Testing*, **2**, 109–123 **(2018)**

64. Garofalo R., Algae and aquatic biomass for a sustainable production of 2nd generation biofuels, AquaFUELs–Taxonomy, Biology and Biotechnology, **6**, 1–258 **(2009)**

65. Garrido-Cardenas J.A., Manzano-Agugliaro F., Acien-Fernandez F.G. and Molina-Grima E., Microalgae research worldwide, *Algal Res.*, **35**, 50–60 **(2018)**

66. Geada P., Moreira C., Silva M., Nunes R., Madureira L., Rocha C.M.R., Pereira R.N., Vicente A.A. and Teixeira J.A., Algal proteins: Production strategies and nutritional and functional properties, *Bioresource Technology*, **332**, 125125 **(2021)**

67. Ghamiaa Abir, Oshah Zainab, Al Shak Asra and Elhefian Esam, Qualitative and Quantitative Phytochemical Analysis of Retama raetam (forssk) Leaves, *Res. J. Chem. Environ.*, **27(10)**, 67-71 **(2023)**

68. Gohara-Beirigo A.K., Matsudo M.C., Cezare-Gomes E.A., de Carvalho J.C.M. and Danesi E.D.G., Microalgae trends toward functional staple food incorporation: Sustainable alternative for human health improvement, *Trends in Food Science & Technology*, **2022**, 13 **(2022)**

69. Gong B., Ma S., Yan Y. and Wang Z., Progress on the biological characteristics and physiological activities of fucoxanthin produced by marine microalgae, *Frontiers in Marine Science*, **11**, 1357425 **(2024)**

70. Gong M. and Bassi A., Carotenoids from microalgae: A review of recent developments, *Biotechnology Advances*, **34**, 1396–1412 **(2016)**

71. Gouveia L. and Oliveira A.C., Microalgae as a raw material for biofuels production, *Journal of Industrial Microbiology and Biotechnology*, **36**, 269–274 **(2009)**

72. Gouveia L. et al, Microalgae biomass production using wastewater: Treatment and costs Scale-Up considerations, *Algal Research*, **16**, 167–176 **(2016)**

73. Griffiths M.J. and Harrison S.T.L., Lipid productivity as a key characteristic for choosing algal species for biodiesel production, *Journal of Applied Phycology*, **21**, 493–507 **(2009)**

74. Grossman A., Nutrient acquisition: The generation of bioactive vitamin B12 by microalgae, *Current Biology*, **26**, R319–R337 **(2016)**

75. Guldhe A., Singh B., Mutanda T., Permaul K. and Bux F., Advances in synthesis of biodiesel via enzyme catalysis: Novel and sustainable approaches, *Renewable and Sustainable Energy Reviews*, **29**, 914–924 **(2014)**

76. Guzmán F., Wong G., Román T., Cárdenas C., Alvárez C., Schmitt P., Albericio F. and Rojas V., Identification of

antimicrobial peptides from the microalgae *Tetraselmis suecica* (Kylin) Butcher and bactericidal activity improvement, *Marine Drugs*, **17**, 453 **(2019)**

77. Hoekman S.K. and Robbins C., Review of the effects of biodiesel on NOx emissions, *Fuel Processing Technology*, **96**, 237–249 **(2012)**

78. Hu Q., Sommerfeld M., Jarvis E., Ghirardi M., Posewitz M., Seibert M. and Darzins A., Microalgal triacylglycerols as feedstocks for biofuel production: Perspectives and advances, *The Plant Journal*, **54**, 621–639 **(2008)**

79. Huang W., Lin Y., He M., Gong Y. and Huang J., Induced high-yield production of zeaxanthin, lutein and β-carotene by a mutant of *Chlorella zofingiensis*, *Journal of Agricultural and Food Chemistry*, **66**, 891–897 **(2018)**

80. Humphrey A.M., Chlorophyll as a colour and functional ingredient, *J. Food Sci.*, **69**, C422–C425 **(2004)**

81. Hwang J., Yadav D., Lee P.C. and Jin J.O., Immunomodulatory effects of polysaccharides from marine algae for treating cancer, infectious disease and inflammation, *Phytotherapy Research*, **36**, 761–777 **(2022)**

82. Hyrslova I., Krausova G., Mrvikova I., Stankova B., Branyik T., Malinska H. and Doskocil I., Functional properties of *Dunaliella salina* and its positive effect on probiotics, *Marine Drugs*, **20**, 781 **(2022)**

83. Jacob-Lopes E., Scoparo C.H.G. and Franco T.T., Potential of microalgal bioreactors for bioenergy production, *Energy Conversion and Management*, **49**, 2756–2760 **(2008)**

84. Janssen J.H., Wijffels R.H. and Barbosa M.J., Lipid production in *Nannochloropsis gaditana* during nitrogen starvation, *Biology*, **8**, 5 **(2019)**

85. Ji T. et al, *Euglena* attenuates high-fat-diet-induced obesity and especially glucose intolerance, *Nutrients*, **16**, 3780 **(2024)**

86. Jiménez Callejón M.J., Robles Medina A., González Moreno P.A., Esteban Cerdán L., Orta Guillén S. and Molina Grima E., Simultaneous extraction and fractionation of lipids from the microalga *Nannochloropsis* sp. for the production of EPA-rich polar lipid concentrates, *Journal of Applied Phycology*, **32**, 1117–1128 **(2020)**

87. Kapuścik A., Hrouzek P., Kuzma M., Bártová S., Novák P., Jokela J., Pflüger M., Eger A., Hundsberger H. and Kopecký J., Novel aeruginosin-865 from *Nostoc* sp. as a potent anti-inflammatory agent, *Chem Bio Chem*, **14**, 2329–2337 **(2013)**

88. Kasim F.H., Harvey A.P. and Zakaria R., Biodiesel production by in situ transesterification, *Biofuels*, **1**, 355–365 **(2010)**

89. Khan M.I., Shin J.H. and Kim J.D., The promising future of microalgae: Current status, challenges and optimization of a sustainable and renewable industry for biofuels, feed and other products, *Microbial Cell Factories*, **17**, 1–21 **(2018)**

90. Khan S.A., Hussain M.Z., Prasad S. and Banerjee U.C., Prospects of biodiesel production from microalgae in India, *Renewable and Sustainable Energy Reviews*, **13**, 2361–2372 **(2009)**

91. Khan S., Das P., Abdul Quadir M., Thaher M.I., Mahata C., Sayadi S. and Al-Jabri H., Microalgal feedstock for biofuel production: Recent advances, challenges and future perspective, *Fermentation*, **9**, 281 **(2023)**

92. Kim J.Y. et al, Biodiesel from microalgae: Recent progress and key challenges, *Progress in Energy and Combustion Science*, **93**, 101020 **(2022)**

93. Kong C.S., Kim J.A. and Kim S.K., Anti-obesity effect of sulfated glucosamine by AMPK signal pathway in 3T3-L1 adipocytes, *Food and Chemical Toxicology*, **47**, 2401–2406 **(2009)**

94. Kotake-Nara E., Kushiro M., Zhang H., Sugawara T., Miyashita K. and Nagao A., Carotenoids affect proliferation of human prostate cancer cells, *Journal of Nutrition*, **131**, 3303–3306 **(2001)**

95. Koyande A.K., Chew K.W., Rambabu K., Tao Y., Chu D.T. and Show P.L., Microalgae: A potential alternative to health supplementation for humans, *Food Science and Human Wellness*, **8**, 16–24 **(2019)**

96. Kuddus M., Singh P., Thomas G. and Al-Hazimi A., Recent developments in production and biotechnological applications of C-phycocyanin, *BioMed Research International*, **2013**, 742859 **(2013)**

97. Kumar B.R., Deviram G., Mathimani T., Duc P.A. and Pugazhendhi A., Microalgae as rich source of polyunsaturated fatty acids, *Biocatalysis and Agricultural Biotechnology*, **17**, 583–588 **(2019)**

98. Kumar K., Ghosh S., Angelidaki I., Holdt S.L., Karakashev D.B., Morales M.A. and Das D., Recent developments on biofuels production from microalgae and macroalgae, *Renewable and Sustainable Energy Reviews*, **65**, 235–249 **(2016)**

99. Kumar N., Sharma G., Chandel H., Shyam K., Thakur S., Vaswani P. and Saxena G., Microalgae in wastewater treatment and biofuel production: recent advances, challenges and future prospects, *Omics Insights in Environmental Bioremediation*, **2022**, 237–271 **(2022)**

100. Kusmayadi A., Huang C.Y., Leong Y.K., Yen H.W., Lee D.J. and Chang J.S., Utilizing microalgal hydrolysate from dairy wastewater-grown *Chlorella sorokiniana* SU-1 as sustainable feedstock for polyhydroxybutyrate and β-carotene production by engineered *Rhodotorula glutinis* #100-29, *Bioresource Technology*, **384**, 129277 **(2023)**

101. Kusmayadi A., Leong Y.K., Yen H.W., Huang C.Y. and Chang J.S., Microalgae as sustainable food and feed sources for animals and humans–Biotechnological and environmental aspects, *Chemosphere*, **271**, 129800 **(2021)**

102. Lanfer-Marquez U.M., Barros R.M. and Sinnecker P., Antioxidant activity of chlorophylls and their derivatives, *Food Res. Int.*, **38**, 885–891 **(2005)**

103. Lauritano C., Andersen J.H., Hansen E., Albrigtsen M., Escalera L., Esposito F., Helland K., Hanssen K.O., Romano G.

and Ianora A., Bioactivity screening of microalgae for antioxidant, anti-inflammatory, anticancer, anti-diabetes and antibacterial activities, *Frontiers in Marine Science*, **3**, 68 **(2016)**

104. Lauritano C., Helland K., Riccio G., Andersen J.H., Ianora A. and Hansen E.H., Lysophosphatidylcholines and chlorophyll-derived molecules from the diatom *Cylindrotheca closterium* with anti-inflammatory activity, *Marine Drugs*, **18**, 166 **(2020)**

105. Lee J.Y. et al, Anticancer effects of astaxanthin and alpha-tocopherol in esophageal cancer cell lines, *Korean Journal of Helicobacter and Upper Gastrointestinal Research*, **11**, 170–175 **(2011)**

106. Lee K., Eisterhold M.L., Rindi F., Palanisami S. and Nam P.K., Isolation and screening of microalgae from natural habitats in the midwestern United States of America for biomass and biodiesel sources, *Journal of Natural Science, Biology and Medicine*, **5**, 333 **(2014)**

107. Leema J.M., Kirubagaran R., Vinithkumar N.V., Dheenan P.S. and Karthikayulu S., High value pigment production from *Arthrospira (Spirulina) platensis* cultured in seawater, *Bioresource Technology*, **101**, 9221–9227 **(2010)**

108. Leite G.B., Abdelaziz A.E.M. and Hallenbeck P.C., Algal biofuels: Challenges and opportunities, *Bioresource Technology*, **145**, 134–141 **(2013)**

109. Li H., Chen S., Liao K., Lu Q. and Zhou W., Microalgae biotechnology as a promising pathway to ecofriendly aquaculture: a state-of-the-art review, *Journal of Chemical Technology & Biotechnology*, **96**, 837–852 **(2021)**

110. Li Y., Liu L., Sun P., Zhang Y., Wu T., Sun H., Cheng K.W. and Chen F., Fucoxanthinol from the diatom *Nitzschia laevis* ameliorates neuroinflammatory responses in lipopolysaccharide-stimulated BV-2 microglia, *Marine Drugs*, **18**, 116 **(2020)**

111. Ludwig K., Rihko-Struckmann L., Brinitzer G., Unkelbach G. and Sundmacher K., β-Carotene extraction from *Dunaliella salina* by supercritical $CO_2$, *Journal of Applied Phycology*, **33**, 1435–1445 **(2021)**

112. Ma Q., Role of Nrf2 in oxidative stress and toxicity, *Annual Review of Pharmacology and Toxicology*, **53**, 401–426 **(2013)**

113. Magnabosco C., Santaniello G. and Romano G., Microalgae: A Promising Source of Bioactive Polysaccharides for Biotechnological Applications, *Molecules*, **30**, 9 **(2025)**

114. Mahata C., Das P., Khan S., Thaher M.I., Abdul Quadir M., Annamalai S.N. and Al Jabri H., The potential of marine microalgae for the production of food, feed and fuel (3F), *Fermentation*, **8**, 316 **(2022)**

115. Mahendran M.S., Djearamane S., Wong L.S., Kasivelu G. and Dhanapal A.C.T.A., Antiviral properties of microalgae and cyanobacteria, *Journal of Experimental Biology and Agricultural Sciences*, **9**, S43–S48 **(2021)**

116. Manirafasha E., Ndikubwimana T., Zeng X., Lu Y. and Jing K., Phycobiliprotein: potential microalgae-derived pharmaceutical and biological reagent, *Biochemical Engineering Journal*, **109**, 282–296 **(2016)**

117. Maoka T., Carotenoids as natural functional pigments, *Journal of Natural Medicines*, **74**, 1–16 **(2020)**

118. Marino T., Casella P., Sangiorgio P., Verardi A., Ferraro A., Hristoforou E., Molino A. and Musmarra D., Natural beta-carotene: A microalgae derivate for nutraceutical applications, *Chemical Engineering Transactions*, **79**, 103–108 **(2020)**

119. Markou G. and Georgakakis D., Cultivation of filamentous cyanobacteria (blue-green algae) in agro-industrial wastes and wastewaters: a review, *Applied Energy*, **88**, 3389–3401 **(2011)**

120. Markou G. and Nerantzis E., Microalgae for high-value compounds and biofuels production: A review with focus on cultivation under stress conditions, *Biotechnol. Adv.*, **31**, 1532–1542 **(2013)**

121. Martin-Creuzburg D. and Merkel P., Sterols of freshwater microalgae: potential implications for zooplankton nutrition, *Journal of Plankton Research*, **38**, 865–877 **(2016)**

122. Mata T.M., Martins A.A. and Caetano N.S., Microalgae for biodiesel production and other applications: A review, *Renewable and Sustainable Energy Reviews*, **14**, 217–232 **(2010)**

123. Matsui S.M., Muizzudin N., Arad S.M. and Marenus K., Sulfated polysaccharides from red microalgae: Anti-inflammatory properties in vitro and in vivo, *Applied Biochemistry and Biotechnology*, **104**, 13–22 **(2003)**

124. Matsuno T., Aquatic animal carotenoids, *Fisheries Science*, **67**, 771–789 **(2001)**

125. McNeff C.V., McNeff L.C., Yan B., Nowlan D.T., Rasmussen M. and Gyberg A.E., A continuous catalytic system for biodiesel production, *Applied Catalysis A: General*, **343**, 39–48 **(2008)**

126. Medina C., Rubilar M., Shene C., Torres S. and Verdugo M., Protein fractions with techno-functional and antioxidant properties from *Nannochloropsis gaditana* microalgal biomass, *Journal of Biobased Materials and Bioenergy*, **9**, 417–425 **(2015)**

127. Mehariya S., Goswami R.K., Karthikeysan O.P. and Verma P., Microalgae for high-value products: A way towards green nutraceutical and pharmaceutical compounds, *Chemosphere*, **280**, 130553 **(2021)**

128. Menegazzo M.L. and Fonseca G.G., Biomass recovery and lipid extraction processes for microalgae biofuels production: A review, *Renewable and Sustainable Energy Reviews*, **107**, 87–107 **(2019)**

129. Menegazzo M.L., Nascimento V.M., Hestekin C.N., Hestekin J.A. and Fonseca G.G., Evaluation of *Chlorella sorokiniana* cultivated in outdoor photobioreactors for biodiesel production, *Biofuels*, **13(4)**, 483–488 **(2022)**

130. Miller M.B., Haubrich B.A., Wang Q., Snell W.J. and Nes W.D., Evolutionarily conserved Δ25(27)-olefin ergosterol biosynthesis pathway in the alga *Chlamydomonas reinhardtii*, *Journal of Lipid Research*, **53**, 1636–1645 **(2012)**

131. Mimouni V., Couzinet-Mossion A., Ulmann L. and Wielgosz-Collin G., Lipids from microalgae, Microalgae in Health and Disease Prevention, Academic Press, 109–131 **(2018)**

132. Monajjemzadeh F. and Farjami A., Common problems in stress testing of pharmaceutical preparations, *Journal of Molecular Pharmaceutics & Organic Process Research*, **2**, e117 **(2014)**

133. Motoyama K., Tanida Y., Hata K., Hayashi T., Hashim I.I.A., Higashi T., Ishitsuka Y., Kondo Y., Irie T. and Kaneko S., Anti-inflammatory effects of novel polysaccharide sacran extracted from cyanobacterium *Aphanothece sacrum* in various inflammatory animal models, *Biological & Pharmaceutical Bulletin*, **39**, 1172–1178 **(2016)**

134. Mukherjee C., Suryawanshi P.G., Kalita M.C., Deka D., Aranda D.A. and Goud V.V., Polarity-wise successive solvent extraction of *Scenedesmus obliquus* biomass and characterization of the crude extracts for broad-spectrum antibacterial activity, *Biomass Conversion and Biorefinery*, **14(2)**, 2467–2483 **(2024)**

135. Mulders K.J., Lamers P.P., Martens D.E. and Wijffels R.H., Phototrophic pigment production with microalgae: biological constraints and opportunities, *Journal of Phycology*, **50**, 229–242 **(2014)**

136. Najdenski H.M. et al, Antibacterial and antifungal activities of selected microalgae and cyanobacteria, *International Journal of Food Science & Technology*, **48**, 1533–1540 **(2013)**

137. Ngo D.H. and Kim S.K., Sulfated polysaccharides as bioactive agents from marine algae, *International Journal of Biological Macromolecules*, **62**, 70–75 **(2013)**

138. Nigam P.S. and Singh A., Production of liquid biofuels from renewable resources, *Progress in Energy and Combustion Science*, **37**, 52–68 **(2011)**

139. Novoveská L., Nielsen S.L., Eroldoğan O.T., Haznedaroglu B.Z., Rinkevich B., Fazi S., Robbens J., Vasquez M. and Einarsson H., Overview and challenges of large-scale cultivation of photosynthetic microalgae and cyanobacteria, *Marine Drugs*, **21**, 445 **(2023)**

140. Olafsdottir A., Thorlacius G.E., Omarsdottir S., Olafsdottir E.S., Vikingsson A., Freysdottir J. and Hardardottir I., A heteroglycan from the cyanobacterium *Nostoc commune* modulates LPS-induced inflammatory cytokine secretion by THP-1 monocytes through phosphorylation of ERK1/2 and Akt, *Phytomedicine*, **21**, 1451–1457 **(2014)**

141. Oo Y.N., Su M.C. and Kyaw K.T., Extraction and determination of chlorophyll content from microalgae, *International Journal of Advanced Research Publications*, **1(5)**, 298 **(2017)**

142. Oren A. and Gunde-Cimerman N., Mycosporines and mycosporine-like amino acids: UV protectants or multipurpose secondary metabolites?, *FEMS Microbiology Letters*, **269**, 1–10 **(2007)**

143. Otocki L., Oklejewicz B., Kuna E., Szpyrka E., Duda M. and Zuczek J., Application of green algal *Planktochlorella nurekis* biomasses to modulate growth of selected microbial species, *Molecules*, **26(13)**, 4038 **(2021)**

144. Pagels F., Guedes A.C., Amaro H.M., Kijjoa A. and Vasconcelos V., Phycobiliproteins from cyanobacteria: Chemistry and biotechnological applications, *Biotechnology Advances*, **37(3)**, 422–443 **(2019)**

145. Parmar R.S. and Singh C., A comprehensive study of eco-friendly natural pigment and its applications, *Biochemistry and Biophysics Reports*, **13**, 22–26 **(2018)**

146. Petersen H.J. and Smith A.M., The role of the innate immune system in granulomatous disorders, *Frontiers in Immunology*, **4**, 120 **(2013)**

147. Potvin G. and Zhang Z., Strategies for high-level recombinant protein expression in transgenic microalgae: A review, *Biotechnology Advances*, **28(6)**, 910–918 **(2010)**

148. Prabakaran G., Sampathkumar P., Kavisri M. and Moovendhan M., Extraction and characterization of phycocyanin from *Spirulina platensis* and evaluation of its anticancer, antidiabetic and anti-inflammatory effect, *International Journal of Biological Macromolecules*, **153**, 256–263 **(2020)**

149. Prabhu P.N., Ashokkumar P. and Sudhandiran G., Antioxidative and antiproliferative effects of astaxanthin during the initiation stages of 1,2-dimethylhydrazine-induced experimental colon carcinogenesis, *Fundamental & Clinical Pharmacology*, **23**, 225–234 **(2009)**

150. Pradhan J.P., Das S.D. and Das B.K., Antibacterial activity of freshwater microalgae: A review, *African Journal of Pharmacy and Pharmacology*, **8**, 809–818 **(2014)**

151. Prarthana J. and Maruthi K.R., Fresh water algae as a potential source of bioactive compounds for aquaculture and significance of solvent system in extraction of antimicrobials, *Asian Journal of Scientific Research*, **12(1)**, 18–28 **(2018)**

152. Pulz O. and Gross W., Valuable products from biotechnology of microalgae, *Applied Microbiology and Biotechnology*, **65**, 635–648 **(2004)**

153. Raj S., Kuniyil A.M., Sreenikethanam A., Gugulothu P., Jeyakumar R.B. and Bajhaiya A.K., Microalgae as a source of mycosporine-like amino acids (MAAs); advances and future prospects, *International Journal of Environmental Research and Public Health*, **18**, 12402 **(2021)**

154. Raja K., Suresh K., Anbalagan S., Ragini Y.P. and Kadirvel V., Investigating the nutritional viability of marine-derived protein for sustainable future development, *Food Chemistry*, **448**, 139087 **(2024)**

155. Rajkumar R., Yaakob Z. and Takriff M.S., Potential of the micro and macro algae for biofuel production: A brief review, *Bioresources*, **9(1)**, 1606-1633 **(2014)**

156. Ramachandran T., Khan R., Ghosh A., Hussien M., Kumar Y.A., Reddy N.P. and Moniruzzaman M., Sustainable carbon electrode materials from biomass for redox flow batteries, *Biomass and Bioenergy*, **198**, 107846 **(2025)**

157. Rao A.R., Sindhuja H., Dharmesh S.M., Sankar K.U., Sarada R. and Ravishankar G.A., Effective inhibition of skin cancer, tyrosinase and antioxidative properties by astaxanthin and astaxanthin esters from the green alga *Haematococcus pluvialis*,

*Journal of Agricultural and Food Chemistry*, **61**, 3842–3851 **(2013)**

158. Ravishankar G.A., Sarada R., Vidyashankar S., VenuGopal K.S. and Kumudha A., Cultivation of micro-algae for lipids and hydrocarbons and utilization of spent biomass for livestock feed and for bio-active constituents, In Biofuel Co-products as Livestock Feed, 423 **(2012)**

159. Rawat I., Ranjith Kumar R., Mutanda T. and Bux F., Biodiesel from microalgae: A critical evaluation from laboratory to large scale production, *Applied Energy*, **103**, 444–467 **(2013)**

160. Reboul E., Thap S., Perrot E., Amiot M.J., Lairon D. and Borel P., Effect of the main dietary antioxidants (carotenoids, γ-tocopherol, polyphenols and vitamin C) on α-tocopherol absorption, *European Journal of Clinical Nutrition*, **61(10)**, 1167–1173 **(2007)**

161. Ren Y., Sun H., Deng J., Huang J. and Chen F., Carotenoid production from microalgae: Biosynthesis, salinity responses and novel biotechnologies, *Marine Drugs*, **19(12)**, 713 **(2021)**

162. Reynolds D., Huesemann M., Edmundson S., Sims A., Hurst B., Cady S., Beirne N., Freeman J., Berger A. and Gao S., Viral inhibitors derived from macroalgae, microalgae and cyanobacteria: A review of antiviral potential throughout pathogenesis, *Algal Research*, **57**, 102331 **(2021)**

163. Rezanka T., Temina M., Tolstikov A.G. and Dembitsky V.M., Natural microbial UV radiation filters—Mycosporine-like amino acids, *Folia Microbiologica*, **49**, 339–352 **(2004)**

164. Richmond A., Biological principles of mass cultivation of photoautotrophic microalgae, Handbook of Microalgal Culture: Applied Phycology and Biotechnology, 169–204 **(2013)**

165. Rodrigues A., Bordado J.C. and Galhano dos Santos R., Upgrading the glycerol from biodiesel production as a source of energy carriers and chemicals—A technological review for three chemical pathways, *Energies*, **10(11)**, 1817 **(2017)**

166. Rodríguez De Marco E., Steffolani M.E., Martínez C.S. and León A.E., Effects of *Spirulina* biomass on the technological and nutritional quality of bread wheat pasta, *LWT–Food Science and Technology*, **58**, 102–108 **(2014)**

167. Ryu J., Park S.J., Kim I.H., Choi Y.H. and Nam T.J., Protective effect of porphyra-334 on UVA-induced photoaging in human skin fibroblasts, *International Journal of Molecular Medicine*, **34**, 796–803 **(2014)**

168. Saadaoui I., Rasheed R., Abdulrahman N., Bounnit T., Cherif M., Al Jabri H. and Mraiche F., Algae-derived bioactive compounds with anti-lung cancer potential, *Marine Drugs*, **18(4)**, 197 **(2020)**

169. Sahin D., Tas E. and Altindag U.H., Enhancement of docosahexaenoic acid (DHA) production from *Schizochytrium* sp. S31 using different growth medium conditions, *AMB Express*, **8**, 1–8 **(2018)**

170. Sanjeewa K.K.A., Fernando I.P.S., Samarakoon K.W., Lakmal H.H.C., Kim E.A., Kwon O.N. and Jeon Y.J., Anti-inflammatory and anti-cancer activities of sterol-rich fraction of cultured marine microalga *Nannochloropsis oculata*, *Algae*, **31(3)**, 277–287 **(2016)**

171. Sansone C. and Brunet C., Promises and challenges of microalgal antioxidant production, *Antioxidants*, **8(7)**, 199 **(2019)**

172. Sathish A. and Sims R.C., Biodiesel from mixed culture algae via a wet lipid extraction procedure, *Bioenergy Research*, **5**, 209–221 **(2012)**

173. Schaafsma G., The protein digestibility–corrected amino acid score, *The Journal of Nutrition*, **130**, 1865S–1867S **(2000)**

174. Schwenzfeier A., Wierenga P.A. and Gruppen H., Isolation and characterization of soluble protein from the green microalgae *Tetraselmis* sp., *Bioresource Technology*, **102(19)**, 9121–9127 **(2011)**

175. Scott S.A., Davey M.P., Dennis J.S., Horst I., Howe C.J., Lea-Smith D.J. and Smith A.G., Biodiesel from algae: Challenges and prospects, *Current Opinion in Biotechnology*, **21(3)**, 277–286 **(2010)**

176. Seo Y.J., Kim K.J., Choi J., Koh E.J. and Lee B.Y., *Spirulina maxima* extract reduces obesity through suppression of adipogenesis and activation of browning in 3T3-L1 cells and high-fat diet-induced obese mice, *Nutrients*, **10(6)**, 712 **(2018)**

177. Shanab S.M., Mostafa S.S., Shalaby E.A. and Mahmoud G.I., Aqueous extracts of microalgae exhibit antioxidant and anticancer activities, *Asian Pacific Journal of Tropical Biomedicine*, **2(8)**, 608–615 **(2012)**

178. Sharma Y.C., Singh B. and Upadhyay S.N., Advancements in development and characterization of biodiesel: A review, *Fuel*, **87(12)**, 2355–2373 **(2008)**

179. Sheehan J., Dunahay T., Benemann J. and Roessler P., A look back at the U.S. Department of Energy's aquatic species program: Biodiesel from algae, National Renewable Energy Laboratory, NREL/TP-580-24190 **(1998)**

180. Siddiki S.Y.A. et al, Microalgae biomass as a sustainable source for biofuel, biochemical and biobased value-added products: An integrated biorefinery concept, *Fuel*, **307**, 121782 **(2022)**

181. Siddiqui S.A., Wu Y.S., Saikia T., Ucak İ., Afreen M., Shah M.A. and Ayivi R.D., Production and growth of microalgae in urine and wastewater: A review, *Environmental Chemistry Letters*, **21(5)**, 2789–2823 **(2023)**

182. Simopoulos A.P., The importance of the ratio of omega-6/omega-3 essential fatty acids, *Biomedicine & Pharmacotherapy*, **56(8)**, 365–379 **(2002)**

183. Singh A., Pant D., Korres N.E., Nizami A.S., Prasad S. and Murphy J.D., Key issues to consider in microalgae biofuels: A review, *Energy and Environmental Science*, **3(5)**, 486–503 **(2010)**

184. Singh S.P., Klisch M., Sinha R.P. and Häder D.P., Effects of abiotic stressors on synthesis of the mycosporine-like amino acid shinorine in the cyanobacterium *Anabaena variabilis* PCC 7937, *Photochemistry and Photobiology*, **84(6)**, 1500–1505 **(2008)**

185. Sinha R.P. and Häder D.P., UV-protectants in cyanobacteria, *Plant Science*, **174**, 278–289 **(2008)**

186. Sonani R.R., Singh N.K., Kumar J., Thakar D. and Madamwar D., Concurrent purification and antioxidant activity of phycobiliproteins from *Lyngbya* sp. A09DM: An antioxidant and anti-aging potential of phycoerythrin in *Caenorhabditis elegans*, *Process Biochemistry*, **49(10)**, 1757–1766 **(2014)**

187. Soontornchaiboon W., Joo S.S. and Kim S.M., Anti-inflammatory effects of violaxanthin isolated from microalga *Chlorella ellipsoidea* in RAW 264.7 macrophages, *Biological and Pharmaceutical Bulletin*, **35(7)**, 1137–1144 **(2012)**

188. Soto-Sierra L., Stoykova P. and Nikolov Z.L., Extraction and fractionation of microalgae-based protein products, *Algal Research*, **36**, 175–192 **(2018)**

189. Soudagar M.E.M., Mohanavel V., Sharma A., Nagabhooshanam N., Srinivasan R., Karthik K. and Seikh A.H., Recover waste greywater to algae biomass for catalytic conversion of higher hydrogen production via supercritical water gasification reaction, *Biomass and Bioenergy*, **194**, 107642 **(2025)**

190. Suali E. and Sarbatly R., Conversion of microalgae to biofuel, *Renewable and Sustainable Energy Reviews*, **16(6)**, 4316–4342 **(2012)**

191. Suh S.S., Hong J.M., Kim E.J., Jung S.W., Chae H., Kim J.E., Kim J.H., Kim I.C. and Kim S., Antarctic freshwater microalga, *Chloromonas reticulata*, suppresses inflammation and carcinogenesis, *International Journal of Medical Sciences*, **16(2)**, 189 **(2019)**

192. Suh S.S., Hong J.M., Kim E.J., Jung S.W., Kim S.M., Kim J.E., Kim I.C. and Kim S., Anti-inflammation and anti-cancer activity of ethanol extract of Antarctic freshwater microalga, *Micractinium* sp., *International Journal of Medical Sciences*, **15(9)**, 929 **(2018)**

193. Suh S.S., Hwang J., Park M., Seo H.H., Kim H.S., Lee J.H., Moh S.H. and Lee T.K., Anti-inflammation activities of mycosporine-like amino acids (MAAs) in response to UV radiation suggest potential anti-skin aging activity, *Marine Drugs*, **12**, 5174–5187 **(2014)**

194. Suh S.S., Park M., Hwang J., Kil E.J., Jung S.W., Lee S. and Lee T.K., Seasonal dynamics of marine microbial community in the South Sea of Korea, *PLoS One*, **10(6)**, e0131633 **(2015)**

195. Sun Y., Li H., Hu J., Li J., Fan Y.W., Liu X.R. and Deng Z.Y., Qualitative and quantitative analysis of phenolics in *Tetrastigma hemsleyanum* and their antioxidant and antiproliferative activities, *Journal of Agricultural and Food Chemistry*, **61(44)**, 10507–10515 **(2013)**

196. Sun Y., Yang C. and Tsao R., Nomenclature and general classification of antioxidant activity/capacity assays, In Measurement of Antioxidant Activity & Capacity: Recent Trends and Applications, Apak R., Capanoglu E. and Shahidi F., eds., John Wiley & Sons, Hoboken, NJ, USA, Chapter 1, 1–19 **(2018)**

197. Surendhiran D. and Vijay M., Microalgal biodiesel–A comprehensive review on the potential and alternative biofuel, *Research Journal of Chemical Sciences*, **2**, 71–82 **(2012)**

198. Suryavanshi S., Sharma D., Checker R., Thoh M., Gota V., Sandur S.K. and Sainis K.B., Amelioration of radiation-induced hematopoietic syndrome by an antioxidant chlorophyllin through increased stem cell activity and modulation of hematopoiesis, *Free Radical Biology and Medicine*, **85**, 56–70 **(2015)**

199. Swanson D., Block R. and Mousa S.A., Omega-3 fatty acids EPA and DHA: health benefits throughout life, *Advances in Nutrition*, **3(1)**, 1–7 **(2012)**

200. Tang H., Abunasser N., Garcia M.E.D., Chen M., Ng K.S. and Salley S.O., Potential of microalgae oil from *Dunaliella tertiolecta* as a feedstock for biodiesel, *Applied Energy*, **88(10)**, 3324–3330 **(2011)**

201. Tarento T.D.C., McClure D.D., Vasiljevski E., Schindeler A., Dehghani F. and Kavanagh J.M., Microalgae as a source of vitamin K1, *Algal Research*, **36**, 77–87 **(2018)**

202. Tavares-Carreón F., De la Torre-Zavala S., Arocha-Garza H.F., Souza V., Galán-Wong L.J. and Avilés-Arnaut H., *In vitro* anticancer activity of methanolic extract of *Granulocystopsis* sp., a microalgae from an oligotrophic oasis in the Chihuahuan desert, *Peer J*, **8**, e8686 **(2020)**

203. Teo S.H., Islam A. and Taufiq-Yap Y.H., Algae derived biodiesel using nanocatalytic transesterification process, *Chemical Engineering Research and Design*, **111**, 362–370 **(2016)**

204. Thanh N.T. et al, Fundamental understanding of in-situ transesterification of microalgae biomass to biodiesel: A critical review, *Energy Conversion and Management*, **270**, 116212 **(2022)**

205. Thiruvenkadam S., Izhar S. and Danquah M.K., A critical review on sustainable bioenergy production from microalgal biomass, *Frontiers in Energy Research*, **2**, 60 **(2014)**

206. Tibbetts S.M., Melanson R.J., Park K.C., Banskota A.H., Stefanova R. and McGinn P.J., Nutritional evaluation of whole and lipid-extracted biomass of the microalga *Scenedesmus* sp. AMDD isolated in Saskatchewan, Canada for animal feeds, *Current Biotechnology*, **4(4)**, 530–546 **(2015)**

207. Timira V., Meki K., Li Z., Lin H., Xu M. and Pramod S.N., A comprehensive review on the application of novel disruption techniques for proteins release from microalgae, *Critical Reviews in Food Science and Nutrition*, **62**, 4309–4325 **(2022)**

208. Torres A., Enk C.D., Hochberg M. and Srebnik M., Porphyra-334, a potential natural source for UVA protective sunscreens, *Photochemical & Photobiological Sciences*, **5(4)**, 432–435 **(2006)**

209. Udayan A. et al, Production of microalgae with high lipid content and their potential as sources of nutraceuticals, *Phytochemistry Reviews*, **22(4)**, 833–860 **(2023)**

210. Udayan A., Sreekumar N. and Arumugam M., Statistical optimization and formulation of microalga cultivation medium for improved omega 3 fatty acid production, *Systems Microbiology and Biomanufacturing*, **2(2)**, 369–379 **(2022)**

211. Vo T.S., Ryu B. and Kim S.K., Purification of novel anti-inflammatory peptides from enzymatic hydrolysate of the edible microalgal *Spirulina maxima*, *Journal of Functional Foods*, **5(3)**, 1336–1346 **(2013)**

212. Waikar Mohnish and Sadgir Parag, Synergizing Environmental Sustainability: Unveiling the Nexus between Life Cycle Analysis and Circular Economy in the Water Sector, *Res. J. Chem. Environ.*, **28(4)**, 53-58 **(2024)**

213. Williams P.J.L.B. and Laurens L.M.L., Microalgae as biodiesel and biomass feedstocks: Review and analysis of the biochemistry, energetics and economics, *Energy and Environmental Science*, **3(5)**, 554–590 **(2010)**

214. Worku L.A., Bachheti R.K. and Alemu W.K., A review of application of Paramylon (β-1, 3-Glucan) in plant growth and production, *Natural Product Communications*, **20(4)**, 1934578X 251333910 (**2025**)

215. Zepka L.Q., Jacob-Lopes E. and Roca M., Catabolism and bioactive properties of chlorophylls, *Current Opinion in Food Science*, **26**, 94–100 **(2019)**

216. Zhang D., Robinson K., Mihai D.M. and Washington I., Sequestration of ubiquitous dietary derived pigments enables mitochondrial light sensing, *Scientific Reports*, **6**, 34320 **(2016)**

217. Zhang S., Zhang L., Xu G., Li F. and Li X., A review on biodiesel production from microalgae: Influencing parameters and recent advanced technologies, *Frontiers in Microbiology*, **13**, 970028 **(2022)**

218. Zhang X., Rong J., Chen H., He C. and Wang Q., Current status and outlook in the application of microalgae in biodiesel production and environmental protection, *Frontiers in Energy Research*, **2**, 32 **(2014)**.

(Received 20th July 2025, accepted 18th August 2025)

*****