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Microalgae as sustainable nutraceutical reservoirs: A critical review of bioactive compounds, molecular mechanisms and therapeutic applications

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Abstract
Microalgae are among Earth's most vital organisms, responsible for generating a substantial portion of atmospheric oxygen through photosynthesis while thriving across remarkably diverse habitats from freshwater lakes and vast oceans to soil surfaces and tree bark. Their extraordinary structural versatility manifests across unicellular, colonial, and filamentous forms, enabling colonization of virtually every ecosystem on the planet. Particularly noteworthy are microalgae, whose resilience under environmental stress conditions drives the biosynthesis of an impressive arsenal of bioactive molecules, predominantly secondary metabolites. These include polysaccharides, polyunsaturated fatty acids, terpenoids, phenols, steroids, polyketides, and alkaloids compounds of profound nutritional and biological significance. Decades of scientific inquiry have firmly established microalgae as a microscale biotechnology powerhouse. They are capable of serving as a natural super factory for high-value biomolecules with compelling applications in human health and wellness. Against a backdrop of surging global population growth and the mounting limitations of conventional resource streams, microalgae emerge as a transformative alternative source of pharmaceuticals, functional foods, essential nutrients, and sustainable energy. Yet the vast majority of microalgal species remain unexplored, representing an immense and largely untapped reservoir of biological potential. Oceanic strains, in particular, constitute a veritable treasure trove of therapeutic agents, offering unprecedented pathways for novel drug discovery and the development of next-generation synthetic prototypes. As advanced biotechnology converges with optimized biomass cultivation and precision extraction technologies, microalgal products are poised to emerge as indispensable natural and medicinal commodities in the global marketplace.

Keywords: Microalgae, cyanobacteria, secondary metabolites, bioactive molecules

Introduction

Evaluating naturally derived products is essential for addressing the needs of a growing global population. The COVID-19 pandemic has highlighted the need to find new biological sources and reconsider previously identified bioactive compounds. Researchers have successfully isolated and described many active substances from microalgae. However, these discoveries have not led to significant commercial applications. This review aims to bring together what we know about the chemical diversity and documented biological activities of microalgae to spark renewed scientific interest in this area. Any effort to use natural resources for medicine and nutrition must follow rules of sustainability and ethical responsibility. Reaching this complex goal requires focusing scientific innovation on finding new and practical resource alternatives. In this context, microalgae stand out as a promising option for developing nutraceuticals. Besides their rich variety of bioactive substances, microalgae offer several beneficial biological traits, including reactive surface properties, the ability to photosynthesize, and strong biocompatibility (Ng & Chew *et al*., 2024) [93] (Fig.1). Recently, nanoparticles from microalgae have shown better performance in drug delivery applications, mainly due to their low toxicity, which opens new possibilities for diagnosing diseases and treating them (Ng & Chew *et al*., 2024) [93]. These organisms have existed on Earth for nearly 3.5 billion years, showing remarkable resilience in diverse environmental conditions, especially in marine and freshwater habitats. Still, their full commercial use is yet to be achieved. Additionally, microalgae production faces several practical challenges, such as difficulties in scaling up cultivation, achieving cost-effective biosynthesis of target compounds, and managing high costs in downstream extraction and purification.

According to the taxonomic framework by Fritsch (1935) [42], algae are generally divided into eleven major groups: Charophyta, Chlorarachniophyta, Chlorophyta, Cryptophyta, Cyanophyta, Dinophyta, Euglenophyta, Glaucophyta, Haptophyta, Heterokontophyta, and Rhodophyta. In this article, "microalgae" refers to all microscopic algal species, including cyanobacteria. Many microalgal species are known for their ability to produce a wide range of bioactive molecules. However, most remain scientifically uncharacterized. These organisms vary in size from a few to several hundred micrometers and represent an exceptionally diverse biological group (Ramos-Romero *et al*., 2021) [7]. They can thrive in various saline conditions in marine, freshwater, and brackish environments, as well as on land surfaces like soil and buildings, often forming symbiotic relationships (Wehr & Sheath, 2015). Their ability to adapt to challenging environmental conditions, along with metabolic flexibility under both stressed and normal physiological states, allows microalgae to activate secondary metabolic pathways and produce a wide array of bioactive compounds (Ramos-Romero *et al*., 2021) [7]. Some therapeutic substances produced by these organisms include polyphenols, phycobiliproteins, polysaccharides, dietary fiber, carotenoids, vitamins, sterols, and notably omega-3 polyunsaturated fatty acids (PUFAs), including

eicosapentaenoic acid (EPA, 20:5 n-3) and docosahexaenoic acid (DHA, 22:6 n-3) (Udayan *et al*., 2017) (Fig. 1). These compounds provide various health benefits, such as antioxidant effects, inflammation reduction, anti-tumor properties, weight management support, antimicrobial and antiviral activity, and detoxification. This wide-ranging biological potential makes microalgae valuable candidates for creating bioformulations applicable in the pharmaceutical, nutraceutical, cosmetic, and food industries (Ramos-Romero *et al*., 2021) [7]. Despite this potential, only a few species are cultivated on a commercial scale for biotechnological purposes (Martínez-Francés *et al*., 2018), and large-scale biomolecule production continues to lack sufficient research focus. At the same time, the ongoing global challenges of viral infections and metabolic disorders, like non-alcoholic fatty liver disease (NAFLD), have increased the demand for new bioactive agents and their mechanisms of action, and microalgae may provide timely solutions.

Cyanobacteria, a group of prokaryotic algae that includes species like Spirulina, Anabaena, Nostoc, and Oscillatoria, are known for producing a wide range of secondary metabolites. These include lipopeptides (40%), amino acids (5.6%), fatty acids (4.2%), macrolides (4.2%), and amides (9%) (Prarthana & Maruthi, 2018). Lipopeptides alone show a variety of biological activities, including cytotoxic (41%), antitumor (13%), antibiotic (12%), and antiviral (4%) effects; the remaining 18% includes properties like antimalarial, antifungal, immunosuppressive, and herbicidal activities (Burja *et al*., 2001) [14] (Fig.2). As an adaptive reaction to harsh environmental conditions, these organisms use secondary metabolic pathways to produce structurally and chemically diverse compounds in significant amounts (Asthana *et al*., 2009) [5]. These peptides are typically created through non-ribosomal peptide and polyketide synthetase pathways, and genetic research on cyanobacteria has revealed remarkable genetic novelty behind the production of these bioactive molecules.

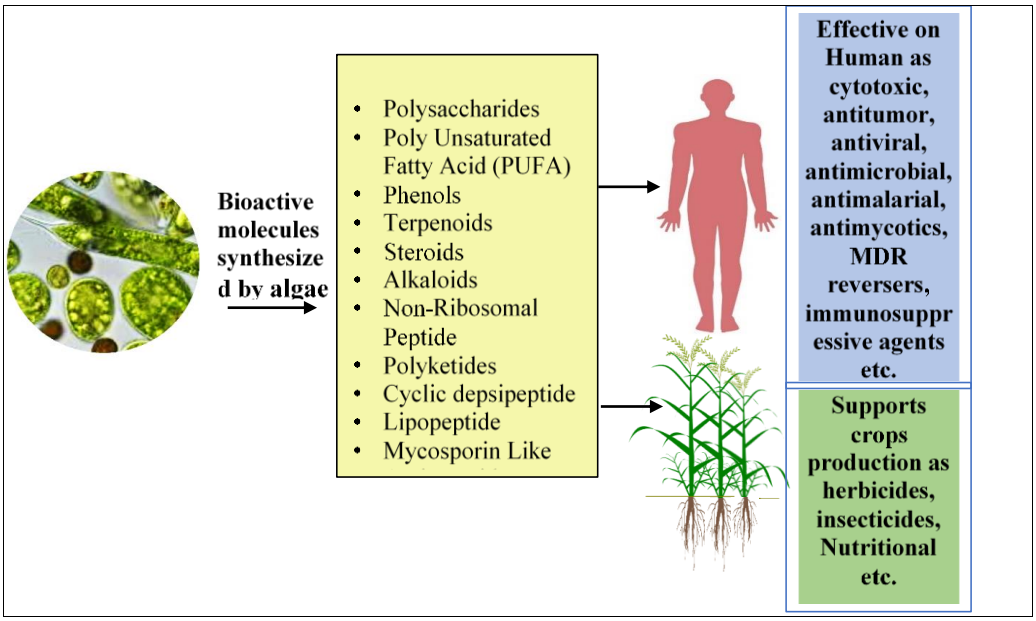

Fig 1: Different type of chemical diversity synthesized by microalgae having therapeutic potential (A graphical abstract)

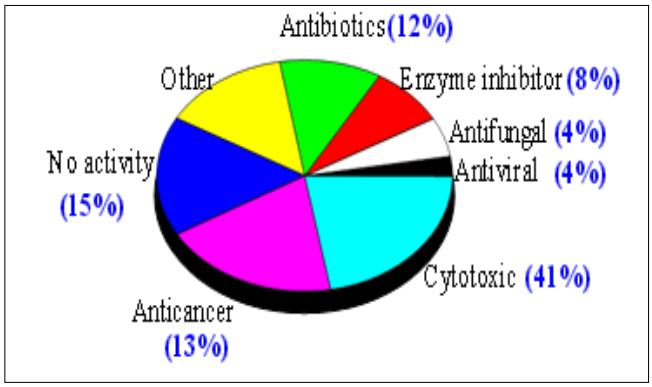

Fig 2: Different activity of Cyanobacterial metabolites (Burja *et al*., 2001) [14]

This genetic distinctiveness drives the species- and habitat-specific production of diverse compound families with valuable biological and pharmacological properties. Metcalf & Codd (2020) [89] noted that certain bioactive compounds exhibit cyanotoxic effects and may find application in agriculture as algicides, fungicides, weedicides, and herbicides. At the same time, cyanobacteria naturally synthesize compounds with antibacterial, anticancer, antifungal, antiplasmodial, antiviral, and immunosuppressive properties, drawing considerable scientific interest toward microalgae (Singh *et al*., 2011) [123]. Their high pharmaceutical potential has spurred growing enthusiasm for integrating microalgae into medical research and applications. Beyond their medicinal value, algae often described as "sunlight-driven oil factories" are regarded as a sustainable energy source due to their capacity to produce and store substantial quantities of lipids (Chisti, 2007) [23]. Research has shown that microalgae can yield 20 to 40 times more lipid than conventional oil crops (Li *et al*., 2011), positioning them as a promising biofuel feedstock. Certain algal species can accumulate lipids representing up to 80% of their dry biomass weight, underscoring their potential as a major renewable energy source (Li *et al*., 2011). Furthermore, many algal strains are capable of lipid accumulation under stress conditions and can be cultivated at scale, making them a viable alternative energy resource for the future (Rodolfi *et al*., 2009).

Types of Biomolecules

1. *Polysaccharides*

Due to their broad biological activities, biocompatibility and structural diversity, they have become very important biomolecules in pharmacology and medicine. Polysaccharides are high molecular weight carbohydrate polymers consisting of monosaccharide units linked together by glycosidic bonds and may carry additional functional groups such as acyl groups, amino acids, or sulphates (Table 1). They play a fundamental role in living organisms as a major source of carbon and energy, while also finding widespread commercial application as thickening and gelling agents (Kraan & Kraan, 2012) [72]. Beyond these roles, polysaccharides exhibit a broad spectrum of biological activities, including immunomodulatory, antibacterial, antiviral, anticoagulant, antimutagenic, radioprotective, antioxidant, anti-ulcer, anticancer, and anti-inflammatory effects (Raposo *et al*., 2015) [33]. Microalgae are capable of producing polysaccharides in quantities ranging from 0.5 g/L to as high as 20 g/L (Markou & Nerantzis, 2013) [84]. A variety of polysaccharides including phycocolloids, carrageenan, agar, and alginates have been extracted from these microorganisms and are employed industrially as emulsifiers, viscosifiers, and gelling agents (Cardozo *et al*., 2007) [16]. Among these, alginates, which are derivatives of alginic acid obtained from the brown alga *Laminaria*, have found notable use as insecticides (Raja *et al*., 2013) [106]. Of particular significance are spirulan and Ca-spirulan, two polysaccharides isolated from *Spirulina* sp., which demonstrate broad-spectrum antiviral activity against HIV-1, HIV-2, *Haemophilus influenzae*, and numerous other enveloped viruses (Hayashi *et al*., 2009) [55]. Spirulan helps reduce viral infectivity by inhibiting the fusion of HIV-infected CD4+ lymphocytes with uninfected ones (Singh *et al*., 2011) [123]. Certain related microorganisms have also shown the capacity to inhibit the reverse transcriptase activity of HIV-1, functioning in a manner comparable to azidothymidine. Additionally, various marine-derived sulphated polysaccharides from algae have been shown to interfere with viral attachment to host cells and their subsequent fusion, a property that has recently been investigated in the context of COVID-19 and the coronavirus (Hans *et al*., 2020) [53]. Other genera, including *Porphyridium* sp., *Chlorella* sp., and *Nostoc* sp. (Table 1), are also recognized producers of polysaccharides with notable biological functions (Costa *et al*., 2021) [29].

Table 1: Isolated polysaccharides from microalgae and its biopotential

Algae	Identified Compound	Bioactivity	References
Chlorella vulgaris / Scenedesmus quadricauda	Sulfated polysaccharides	Protect against oxidative stress; anti-hyperglycemic (α-glucosidase inhibition)	(Guehaz *et al*., 2024) [48]
Chlorella stigmatophora / Phaeodactylum tricornutum	Crude polysaccharide extracts	Anti-inflammatory	(Guzman *et al*., 2003; Colusse *et al*., 2021) [27, 50]
Chlorella pyrenoidosa	Polysaccharides	Antitumoral; prebiotic modulation of gut microbiota	(Lv *et al*., 2022) [73]
Chlorella biomass	β-glucans	Gut eubiosis; immunomodulatory; promotes beneficial microbiota (Bifidobacterium, Lactobacillus)	(Liu *et al*., 2023; Zhang *et al*., 2024) [80, 135]
Chlorella vulgaris	Arabinomannans	Prebiotics; biostimulation of plant growth	(Pieper *et al*., 2012; Rachidi *et al*., 2021) [103, 105]
Chondrus crispus	Carrageenan gel	Block transmission of HIV, gonorrhea, genital warts, and herpes simplex viruses (HSV); antiviral against HIV-1 and HSV	(Krylova *et al*., 2022; Trufanov *et al*., 2024) [73, 129]
Brown algae	Alginate	Dietary fiber; reduces cholesterol levels; prevents absorption of toxic substances; prebiotic and metabolic disease prevention	(Ahmad *et al*., 2024; Bamigbade *et al*., 2025) [3, 10]
Gelidium sp. / Gracilaria	Sulfated polysaccharides (Agar)	Anti-tumor activity; antioxidant; anti-inflammatory; reduces glucose level in blood; suppresses pro-inflammatory cytokines	(Pei *et al*., 2021; Oliveira *et al*., 2024) [98, 101]

2. Proteins

2.1 Antifreeze Protein (AFP)

Antifreeze proteins are at the exciting interface of evolutionary biology and translational medicine. AFP's offer transformative potential, from saving life-saving donor organs to transforming reproductive medicine and improving cancer cryotherapy. Among the most remarkable molecular adaptations found in nature, the antifreeze proteins (AFPs) of polar microalgae stand out for their extraordinary ability to bind selectively to ice crystals and arrest the destructive process of protein recrystallization. As integral components of the ice-binding protein (IBP) family, these sophisticated biomolecules represent a cornerstone of psychrophilic adaptation, conferring upon these microscopic organisms the remarkable capacity to not only survive but thrive in some of the most inhospitable frozen environments on Earth (Bayer-Giraldi *et al*., 2014) [11]. Groundbreaking isolation efforts targeting Antarctic microalgae have yielded significant discoveries, most notably the recombinant AFP designated Cn-AFP from the diatom *Chaetoceros neogracile*, alongside AFPs recovered from *Pyramimonas gelidicola* achievements that have substantially advanced our molecular understanding of cryoprotective mechanisms (Jung *et al*., 2014) [64]. Beyond their ecological significance, AFPs harvested from algae and allied microorganisms are emerging as transformative agents across a striking range of biotechnological frontiers, including advanced food cryopreservation, engineering of freeze-tolerant transgenic crops, and even experimental atmospheric intervention. Their progressive incorporation into medical, cosmetic, and food formulations to counteract cold-induced cellular damage and dramatically extend product shelf life speaks to their enormous commercial and therapeutic relevance. As research continues to unravel the full extent of their functional versatility, AFPs are increasingly positioned as next-generation biomolecules with outstanding potential to reshape multiple high-value industries.

2.2 Glycoprotein

Glycoproteins are not simply "decorated proteins" the glycan part is an intrinsic determinant of their bioactivity influencing receptor binding, immune recognition, enzymatic function, cellular communication and pharmacological behavior. Among the most clinically relevant classes of biomolecules, glycoproteins range from the regulation of reproduction and immunity to life-saving drugs and vaccine antigens. Advances in glycomics, glycoengineering and synthetic glycobiology continue to reveal new therapeutic opportunities based on these remarkable bioactive molecules.

These bioactive conjugates of sugar and protein, represent a significant yet underexplored class of compounds within the microalgal biochemical repertoire. Proper post-translational modifications such as N-glycosylation are essential for their correct folding, stability, and bioactivity, underscoring the therapeutic relevance of advancing glycoprotein research in microalgal systems. However, their systematic investigation remains constrained by the persistent absence of standardized, high-yield cultivation protocols, as scaling up microalgal production from laboratory to large-scale systems remains a complex and costly challenge (Novoveská *et al*., 2023; Plouviez *et al*., 2024) [95, 104]. Despite these limitations, glycoproteins isolated from *Chlorella vulgaris* (Hasegawa *et al*., 2002) [54], *Desmococcus olivaceus* (Ördög *et al*., 2004), *Scenedesmus* sp. (Hee *et al*., 2004; Ördög *et al*., 2004) [56], *Dunaliella bardawil* (Fujii *et al*., 1993) [43], and *Dunaliella salina* (Hadi *et al*., 2008) [51] have demonstrated notable anticancer activity. More recently, microalgae such as *Chlamydomonas reinhardtii*, *Dunaliella bardawil*, and *Chlorella* species have emerged as efficient platforms for therapeutic glycoprotein production (Dehghani *et al*., 2022) [37], with microalgal bioactive compounds exhibiting pro-apoptotic effects across breast, lung, liver, cervical, and leukemia cancer models (Cheragh & Mabudi, 2023; Silva *et al*., 2024) [22, 120], positioning them as strong candidates for future pharmaceutical development.

3. *Lectins*

Lectins are a remarkably versatile class of bioactive molecules whose exquisite carbohydrate-binding specificity puts them at the forefront of multiple medical disciplines. From anticancer immunotherapy and antiviral microbicides to precision drug delivery and molecular diagnostics, lectins link fundamental glycobiology and cutting-edge therapeutic innovation. As our understanding of the glycome grows, lectins will find ever-increasing use as tools and therapeutics in 21st century medicine.

As bioactive complex protein is synthesised in algae *that* binds to carbohydrates without changing its properties (Lam & Ng, 2011) [74]. Due to a unique binding of Lectins and intestine epithelium, it enhances diffusion of drugs, therefore used as therapeutic agents (Chowdary & Rao, 2004) [25]. The cyanobacteria such as *Scytonema varium*, *Mycrocystis sp*., *Nostoc ellipsosporum*, and *Oscillatoria agardhii* are the main source of lectins, i.e., scytovirin, microvirin, agglutinin, and cyanovirin-N (Singh *et al*., 2017) [124]. Furthermore, lectins exhibit a great potential for antiviral activities and anticipating transmission of HIV, owing to the interaction of glycans with HIV gp120 (Huskens *et al*., 2010) [60].

4. Lipids *and Polyunsaturated Fatty Acids (PUFAs)*

From cardiovascular protection, neuroprotection, and cancer adjunct therapy to infant nutrition, anti-inflammatory resolution, and antimicrobial innovation, microalgae lipids and PUFAs represent a nutritional, pharmaceutical, and therapeutic treasure of immense and continuously growing medicinal significance. With advancements in algal biotechnology, synthetic biology, and biorefinery strategies, microalgae are positioned to become the leading sustainable platform for PUFA-based medicines and nutraceuticals of the future.

Microalgae (Table 2) are a valuable source of diverse fatty acids, particularly polyunsaturated fatty acids (PUFAs). Essential PUFAs such as ω-3 and ω-6 fatty acids play critical roles in preventing coronary heart disease, hypertension, type 2 diabetes, and other chronic conditions (Simopoulos, 1999) [121]. Key long-chain PUFAs including DHA, EPA, ARA, GLA, and CLA offer wide-ranging health benefits: DHA supports infant brain development, EPA exhibits anti-inflammatory and immune-modulatory effects, and GLA demonstrates antibacterial activity (Abedi & Sahari, 2014; Asthana *et al*., 2006) [1, 6]. These PUFAs also contribute to cellular functions such as oxygen transport, membrane fluidity, and heat adaptation (Cardozo *et al*., 2007) [16]. Notably, cholesterol-free Spirulina lipids show therapeutic potential against obesity, atherosclerosis, and diabetes (Cheong *et al*., 2010) [21]. Since vertebrates lack the Δ-12 and Δ-15 desaturase enzymes, essential fatty acids like linoleic acid (LA) and α-linolenic acid (ALA) precursors to AA, EPA, and DHA cannot be synthesized endogenously and must be obtained through diet. Some microalgae can accumulate lipids up to 90% of their dry weight, making them a promising dietary source (Mata *et al*., 2010) [86]. These lipids also exhibit anticarcinogenic, antibiotic, antifungal, and antiviral properties (Singh *et al*., 2017) [124]. In cyanobacteria, fatty acid synthesis occurs via a type II fatty acid synthase complex using an acyl carrier protein (ACP). Additionally, glycolipids carbohydrate-lipid complexes abundant in microalgal membranes have gained increasing research interest for their role as signal regulatory molecules in thylakoids. The primary microalgal glycolipids, including monogalactosyl, digalactosyl, and sulfoquinovosyl diacylglycerols, are notably rich in PUFAs (Costa *et al*., 2021; Kim *et al*., 2013) [29, 70].

5. *Secondary Metabolites*

Microalgae are in a unique position to tackle the most important pharmaceutical issues of the twenty-first century, such as antimicrobial resistance, cancer, neurodegeneration, and emerging viral pandemics because of their unmatched chemical diversity, biological potency, sustainable producibility, and genetic tractability. Microalgae will surely produce the next generation of popular medications as biotechnological technologies develop and marine bioprospecting expands. From FDA-approved anticancer drug conjugates inspired by dolastatins to clinically used vaccine adjuvants derived from squalene, to retinal-protective nutraceuticals like lutein and zeaxanthin to next-generation antiviral microbicides like cyanovirin-N, microalgal secondary metabolites represent a wonderful and largely unexplored pharmaceutical reservoir covering almost every category of drug action.

Table 2: Isolated PUFA from the microalgae and its bioactivity

Organisms	Chemical Nature	Bioactivity	References
Sargassum thunbergii / Seinaia closa	PUFA monogalactosyl diacylglycerols (MGDGs)	Nitric oxide inhibitor and anti-inflammatory	Huang *et al*., 2025[59]
Chlamydomonas, Chlorella vulgaris, Enteromorpha clathrata, Chondrus crispus	PUFA digalactosyl diacylglycerols (DGDGs)	Antibacterial, antimicrobial and anti-inflammatory activities	Costa *et al*., 2023; Regueiras *et al*., 2022 [30, 111]
Nostoc commune PCC 7806	PUFAs 1,2-diacyl-1-3-O-(6-sulfo-6-deoxy-α-D-glucopyranosyl)-sn-glycerol sulfoquinovosyl diacylglycerols (SQDGs)	1. Chloroplast membrane Signalling and coordination between chloroplast and cytosol. 2. Inhibit tumour cell growth and is a potent inhibitor of DNA polymerase 3. Antiviral	Singh *et al*., 2021; Chen *et al*., 2023 [20, 122]
Lobosphaera incisa	Arachidonic acid (ARA)	Inhibit tumour cell growth and is a potent inhibitor of DNA polymerase	Kokabi *et al*., 2020 [71]
Spirulina platensis / Arthrospira auratum	γ-Linolenic acid (GLA)	Lowering the blood pressure and involved in lipid metabolism	Sokary *et al*., 2024 [126]; Firdaus & Priambodo, 2025
Botryococcus braunii	Linoleic acid 18:2cis, 9,12-octadecadienoic acid	Treat skin-related disorders	Cochard *et al*., 2024
Chlorella vulgaris	Eicosapentaenoic acid (EPA; 20:5n3)	Potential source of EPA for health and pharmaceuticals	Djuricic & Calder, 2025; Garcia & Lopez, 2024
Chondrotus sp., Scenedesmus sp., Scenedesmus quadricauda sp.	α-Linolenic acid / Linoleic acid	Used for cardiovascular disease and reduce atherosclerosis risk, lower high blood pressure, lower cholesterol, and atherosclerosis	Cambiaggi *et al*., 2023; Parikh & Bhatt, 2022 [73]
Spirulina platensis, Arthrospira, Escherichia, Nostoc CCC537	Gamma linolenic acid	Lowering the blood pressure and involved in lipid metabolism	Sokary *et al*., 2024[126]; Nunez-Alderete *et al*., 2024 [96]

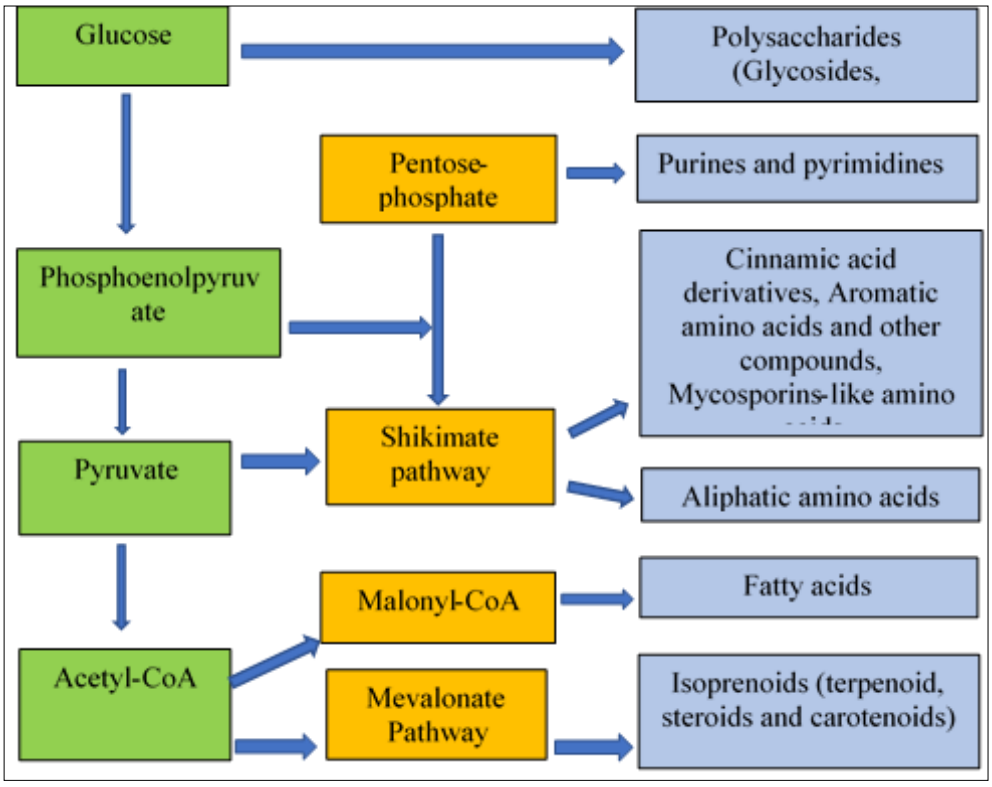

Fig 3: Main pathways involved in the biosynthesis of some secondary and primary metabolites (adapted from (Burja *et al*., 2001) [14].)

The secondary metabolites are usually synthesised during the late growth phase (idiophase) of microorganisms. Although its synthesis appears to be species as well as strain specific and directly related to the niche where they grow. Moreover, certain wild-type organisms have genes to produce diverse secondary metabolites. In such cases, some primary metabolism stages lack regulation, consequently the over synthesis of intermediates and product of primary pathways. Under stress of these accumulated metabolic pools, these intermediates may stimulate subsidiary pathways to form secondary metabolites (Fig. 3) (Burja *et al*., 2001) [14]. Although the majority of secondary

metabolites is synthesised by a limited number of core biosynthetic pathways, including lipopeptides (Burja *et al*., 2001) [14]. Various modifications and combinations in primary metabolic pathways developed the structural diversity for biomolecules, and were adopted by producing cells via the process of natural selection. The advantageous selected compound with new capability will be adopted, as in *Lyngbya majucula* (Nagle *et al*., 1996) [91]. These non-essential biomolecules having unique chemical structures with exclusive bioactivity and beneficial for human health, agriculture, and economy. Many bio potential secondary metabolites produced by microalgae are given in the Table 3, these organisms also produce many potential glycoproteins, antibiotics as well as antifreeze protein (Skjånes *et al*., 2013) [125]. These molecules have immense therapeutic properties such as anticarcinogenic, antiviral, antibacterial, antifungal, antiinflammatory, antitumoral, cytotoxic, immunosuppressor, and enzyme inhibitor that credited to the presence of novel metabolites. Although a percentage of these microbes still have to explore and signify their biomolecules commercially.

6. *Phenol*

Microalgal phenolic compounds produced by species such as *Spirulina*, *Chlorella*, and various marine microalgae, hold significant medicinal value primarily through their potent antioxidant activity, stress linked to cancer, cardiovascular disease, and neurodegeneration. Beyond antioxidant action, they exhibit notable anti-inflammatory and emerging anti-diabetic etc.

Table 3: An overview of secondary metabolites from microalgae and their potential uses (Singh *et al*., 2017) [124].

Microalgae	Nature of Metabolites	Bioactivity
Arthrospira platensis, Nostoc muscorum, Phormidium foveolarum, Spirulina platensis	Phenolic compounds.	Used as functional food Prevents vascular damage & cardiovascular diseases Antioxidant, UV-B screening compound
Synechocystis sp, *Anabaena* sp, *Nostoc* sp, *Spirulina* sp, *Phaeodactylum tricornutum, Pavlova lutheri, Nostoc commune*	Fatty acids	Potent as liquid fuels. Have high content of PUFA, protein, and vitamins. Toxicity. As herbal medicine for cancer, viruses, burns, and chronic fatigue treatmen.
Synechocystis sp	Terpenoids	Source of hydrocarbon biofuel. Protects from herbivory, fragrances, and flavors.
Anabaena doliolum Scytonema javanicum	Mycosporineglycine, Shinorine, Porphyra-334	Protected against high temperature, UV-B, and photo oxidative stress. An osmolytes and ROS scavenger
Nostoc muscorum Phormidium foveolarum Spirulina platensis	α & β-Carotene, Carotenoids, Cryptoxanthin, Lutein, Lycopene, Zeaxanthin,	Protects PSII, light harvesting complexes, increase antioxidant properties, utilize in food industry and work against cancer.
Scytonema	Scytonemin	Anti-inflammatory and antiproliferative agent.
Chondrus ocellatus	Agar, Carragenans, and Lectins	Used as antitumor, antiviral, anticoagulant, and immunomodulation agent. Drug delivery system.
Synechococcus elongates PCC7942 *Cylindrospermopsis raciborskii* 339-T3, *Fischerella, Microcystis aeruginosa NPCD-1, Microcystis panniformis SCP702*	Halogenated compounds	Potential to work against bacteria, viruses, fungus, insects and shows antifouling, antiproliferative, anti-inflammatory, cytotoxic, antifeedant, and ichthyotoxic responses.
Anabaena vaginicola, Nostoc calcicola	Phytohormones	Used as biofuel. Provide strong defence enzymes against different stresses.
Microcystis sp, *Anabaena* sp, *Oscillatoria* sp, *Anabaenopsis* sp, *Nostoc* sp, *Hapalosiphon* sp, *Lyngbya polychroa*	Toxins	Potential pharmaceutical active compounds work as biocides like antibiotics, anticancerous, and anti-inflammatory.

Structurally, phenolic compounds have at least one phenolic ring and their halogenated forms show strong biological activity (Cabrita *et al*., 2010) [15]. The diversity among its structure observed like flavanones, flavonols, chalcones, flavones, flavan-3-ols, flavanonols, etc. Under unfavourable conditions, compounds like phytoalexins, lignin, flavonoids, furanocoumarins, tannins, and anthocyanins are intricate in the defence mechanism (Stengel *et al*., 2011) [28]. Phlorotannins (eight interconnected flavonoid rings) are the assembly of tannins (Fig 6) and phloroglucinols (Wang *et al*., 2014) [130], isolated from brown algae (Le Gall *et al*., 2015) [76], and have antioxidant properties (Gómez *et al*., 2016). Furthermore, the phlorotannin group are fucols, phlorethols, fucophlorethols, fuhalols, halogenated, and sulfated phlorotannins have been observed by Chandini *et al*., 2008.All these molecules have great potential to cure diseases caused by free radicals under oxidative stress. Phenolics known as a are stress compound as it is involved in defence mechanisms against metal toxicity (Connan & Stengel, 2011) [28], biotic stresses like grazing (Coleman *et al*., 2007) [26], settlement of bacteria (Lau & Qian, 2000) [75], and abiotic stresses like UV irradiation (De La Coba *et al*., 2009) [34]. Moreover, these molecules have many therapeutic

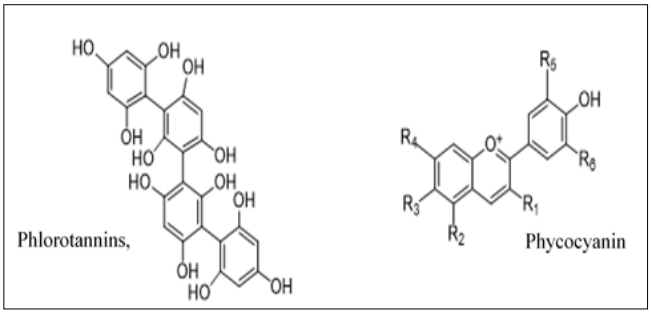

Fig 4: Example of phenolic bioactive molecules (Wang *et al*., 2014[130]; Stengel *et al*., 2011) [28]

7. *Phytoene/Terpenoids*

Microalgal terpenoids are excellent prospects for next-generation drug discovery and nutraceutical development because of their therapeutic flexibility, the scalability of photobioreactor-based production, and developments in metabolic engineering to increase yield. Terpenoids are classified into seven categories based on their five-carbon isoprene building blocks: hemiterpenes (C5), monoterpenes (C10), sesquiterpenes (C15), diterpenes (C20), triterpenes (C30), tetraterpenes (C40), and polyterpenes (greater than C40). These compounds play a fundamental role in plant growth and developmental processes, while also contributing to pollinator attraction, scent production, and flavor characteristics. Beyond these ecological functions, terpenoids exhibit considerable biological activity. Notably, the substantial presence of geranyl acetone highlights their allelopathic potential, reinforcing their significance as secondary bioactive metabolites (Gershenzon & Dudareva, 2007) [44]. Among their most valuable applications are their therapeutic properties and use in pest management, with several isolated bioactive terpenoids documented in Table 3. Additionally, terpenoids have found emerging utility as fuel additives, being blended with conventional fossil gasoline in spark ignition engines (Hellier *et al*., 2013) [57].

8. *Sterols*

An important component of the animal cell membrane that contributes to its fluidity. It is synthesised as a by-product during isoprene biosynthesis. Reitz & Hamilton, (1968) [112] identified firstly the sitosterol and cholesterol in *Anacystis nidulans* and *Fremyella diplosiphon.* At the same time De Souza & Nes, (1968) [35] identified seven different unsaturated sterols in *Phormidium luridurn*. These sterols show essential roles in various eukaryotic biochemical processes e.g., steroid hormone biosynthesis, maintaining fluidity of membrane lipids (Martin-Creuzburg & von Elert, 2009) [85] and are good food for aquacultured zooplanktons, bivalves, fishes, etc. (Cardozo *et al*., 2007) [16]. They have three -hydroxy tetracycles with a methyl- or ethyl-substituted hydrocarbon chain (C7-C11) and a C4, C14 methyl substitution pattern in polycyclic form with unsaturation (C5, C7, C8). An isolated sterol from marine brown algae, particularly fucosterol (Hannan *et al*., 2020) [52], has been examined for its health benefits, including anti-diabetes, anti-obesity, anti-Alzheimer's, anti-aging, anticancer, and hepatic protection. Among many others, which are attributed to their antioxidant defence system, apoptosis and cell survival, metabolism, and homeostasis. It has estimated that microalgae could yield phytosterol 678–6035 kg. ha-^{1}. Y^{-1} and it is more than the current production from rapeseed plants (Randhir *et al*., 2020) [107].

9. *Alkaloids*

Microalgal alkaloids are a chemically diverse group of nitrogen-containing secondary metabolites that have emerged as a promising frontier in marine pharmacology, despite being less studied than their terrestrial plant counterparts. Their biosynthesis is frequently connected to stress responses, nitrogen metabolism, and ecological defense mechanisms. Alkaloids, structurally classified as indoles, quinolines, isoquinolines, pyrrolidines, pyrrolidines, pyrrolizidines, tropanes, and terpenoids and steroids. Cyanobacteria (Table 4), especially marine ones, are known to produce a large variety of alkaloids against predators. Around 300 alkaloids are reported from marine cyanobacteria so far, and are highly toxic to eukaryotic organisms. Most of them are hybrids of peptides and polyketide–peptide and biosynthesized by large multi-modular enzymes. These alkaloids commonly sequestered from the filamentous order *Nostocales* especially from the genera such as *Lyngbya*, *Oscillatoria*, and *Symploca* sp. (Gerwick *et al*., 2001) [45]. Some of the cyanobacterial alkaloids, representing various sub-classes, are listed in Tables 4 and 5.

Table 4: Some selected alkaloids from marine cyanobacteria

Marine isolate	Compounds	Chemical nature	References
Lyngbya majuscule	Hectochlorin	Lipopeptide	Youssef *et al*., 2022
Symploca sp.	Largazole	Macrocyclic depsipeptide	Nawaz *et al*., 2023[92]
Geitlerinema sp.	Harman	β-carboline	Duygu & Çelik, 2023[40]
Anabaena sp.; *Cylindrospermopsis* sp. *Aphanizomenon* sp. *Planktothrix* sp. *Lyngbya* sp.	Saxitoxin	3,4-Propinoperhydropurine	Zhou *et al*., 2024[137]
Lyngbya majuscule	Curacin A	N-containing lipid	Salleh *et al*., 2023[115]
Symploca hydnoides	Symplostatin 1	Peptolide	Phyo *et al*., 2022[102]
Phormidium sp.	Phormidinines	2-Alkylpyridine	Morioka *et al*., 2021[90]
Lyngbya majuscula	Lyngbyatoxin A	Diazoninoindol	Nawaz *et al*., 2023[92]

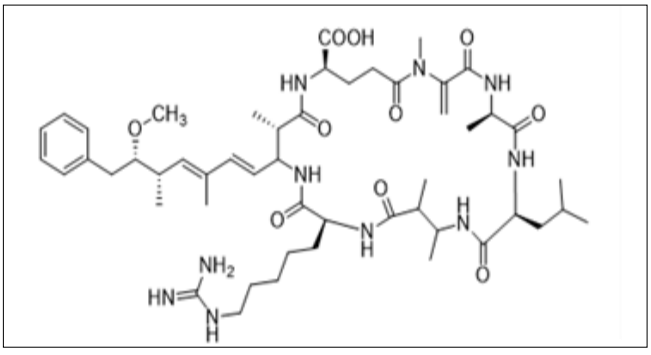

Fig 5: Microcystin-LR (A Non-ribosomal Polypeptides) (Maurya *et al*., 2019) [87]

10. *Non-Ribosomal Peptides and Polyketides*

The enzyme non-ribosomal peptide synthases (NRPS) and polyketide synthases (PKS) are responsible for biosynthesis of non-ribosomal peptides (NRPs) (Fig. 5) and polyketides (PKs), respectively (Maurya *et al*., 2019) [87]. The gene clusters have been identified in the cyanobacterialgenera *Lyngbya*, *Microcystis*, *Planktothrix*, *Nodularia*, *Nostoc*, *Pleurocapsa*, and *Anabaena* (Wang *et al*., 2014) [130], however, the most common are *Pleurocapsa* and *Nostoc* sp. There are almost 300 proteinogenic and nonproteinogenic substrates used by these peptide-synthesizing enzymes (Kehr *et al*., 2011) [68]. Widely distributed PKS type I in bacteria is responsible for polyketide chain elongation, processing, and termination (Dutta *et al*., 2014) [39].

Moreover, this unique natural combinatorial biosynthetic pathway is important for growth, symbiotic relations, and defence against biotic and abiotic stresses. These peptides and polyketides are possessing various therapeutic activities and have applied for the treatment of various acute and chronic diseases.

11. *Cyclic depsipeptides (CDPs)*

Microalgal cyclic depsipeptides are a class of hybrid peptide-polyketide natural products that are structurally distinct and pharmacologically compelling. They are primarily produced by the enzymatic machinery of non-ribosomal peptide synthetase (NRPS) and polyketide synthase (PKS) in cyanobacterial microalgae, such as *Lyngbya*, *Symploca*, *Oscillatoria*, *Nostoc*, and *Anabaena* species, giving them remarkable structural rigidity, metabolic stability, and membrane permeability that support their varied and powerful biological activities. CDPs are a family of cyclic peptides in which the amino-and hydroxy acid residues joined by amide and ester bonds (at least one), giving to wide range in structural diversity. Its unusual non-amino acid building blocks are responsible for diversity in their ring structures and their side chains (Fig 6). The most common CDPs are e.g. microcystins and the lyngbyatoxins. Some of them established already into useful viable products, such as cryptophycin-1, a microtubule inhibitor isolated from *Nostoc* sp *GSV 224*. Majusculamide C, a microfilament-depolymerizing agent from *Lyngbya majuscula*, having fungicidal potential and may have use against resistant fungal-induced diseases in domestic plants and agricultural crops (Carter *et al*., 1984) [17]. Dudawalamides A–D are antiparasitic CDP from *Moorea producens* (Almaliti *et al*., 2017) [4]. Kohamamides A, B, and C from *Okeania* sp (Iwasaki *et al*., 2017) both are marine cyanobacteria.

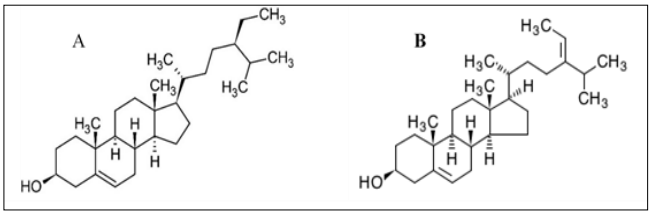

Fig 6: bioactive cholesterol (A) Sitosterol (24α-ethyl cholesterol), (B) Fucosterol (24-ethylidine cholesterol) Reitz & Hamilton, (1968) [112]

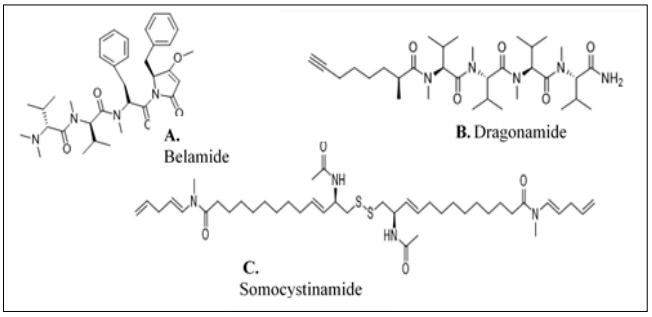

Fig 7: Showing examples of lipopeptide isolated from cyanobacteria (Burja *et al*., 2001) [14].

12. *Lipopeptides*

The covalent conjugation of a lipophilic fatty acid chain to a cyclic or linear peptide backbone biosynthesized primarily via non-ribosomal peptide synthetase (NRPS) and fatty acid synthase (FAS) enzymatic assemblies in cyanobacterial microalgae, such as *Lyngbya*, *Anabaena*, *Oscillatoria*, *Microcystis*, and *Nostoc* species. This structural architecture confers exceptional amphiphilic biological targets and oncology. These molecules derived from linkage of an amino acid fragment and fatty acid-derivatives. Along with their bioactivity, these compounds have affinity for liposomes and cell membranes. They have special characteristics to pass through the blood tissue and blood brain barriers, leading to its potential application in drug delivery systems (Baier *et al*., 2000; Rao & Alving, 2000) [9, 108]. The unique structure of lipopeptides and amphipathic behaviour make them capable of disrupting the function of channel systems (Carter *et al*., 1984) [17]. Among cyanobacteria, almost 85% of the total identified lipopeptides (Fig. 7) are bioactive as anticancer, cytotoxic, antibiotic, enzyme inhibitor, antiviral, antifungal and the remaining having activity like tumour promotor, herbicide, antimycotic, antimitotic, antimalaria, antimicroalgal, cardioactive compound etc (Burja *et al*., 2001) [14]. .

13. *Mycosporine-like amino acids (MAAs)*

MAAs are a collection of molecules comprising an amino acid bound to a chromophore molecule and defending the organism against UV radiation. In *Chlamydomonas nivalis*, a highly UV-tolerant snow alga, this MAA produced in a significant amount under UV irradiance stress conditions. Nevertheless, its biosynthesis directly related to the nitrogen concentration within the cells (Karsten *et al*., 2007) [67]. MAAs, isolated from algae used commercially for skin-care products for UV protection (Schmid *et al*., 2006) [116] and photo-stabilising additives in varnish, paint, and plastics (Bandaranayake, 1998). *Ankistrodesmus spiralis*, *Chlorella minutissima*, *Scenedesm us sp*., and *Scotiella nivalis* (Xiong *et al*., 1999) [133], rhodophyta, and cyanobacteria (Rastogi & Madamwar, 2016) [109] are some examples of it. Typically, these MAAs are colorless, small, and hydrophilic intracellular compounds and have an inordinate potential to disperse extra energy as a heat and protect cells to toxic oxygen radicals (Singh *et al*., 2017) [124]. The biosynthetic pathway of MAAs is still has to be explored, however, some studies have explained it is synthesized from the shikimic acid pathway.

14. *Antioxidents*

Microalgal antioxidants have a number of advantages over synthetic or even plant-derived antioxidants: they are produced without pesticides, occur in natural stereoisomeric forms with superior bioavailability, frequently co-occur with synergistic compounds (omega-3 fatty acids, vitamins, and polysaccharides), and microalgae biomass is scalable without arable land. This makes them a pillar of pharmaceutical and nutraceutical development, particularly in the areas of metabolic health, cancer support, and anti-aging. The microalgae *scillatoria* sp., *Lyngbya* sp., *Microcystis* sp., *Spirulina* sp., and *Nostoc* sp.) (Hossain *et al*., 2016) [58] often face potential oxidative stress when exposed to high oxygen concentration and irradiance environments. Therefore, these organisms developed a strong defence mechanism through the production of various important antioxidants. These antioxidants prevent DNA, proteins, and lipids from injury. Like algae, humans and animals also suffer severe health problems cause by oxidative stress (Fig. 8). When taken as a diet, the isolated

algal antioxidants have the capability to limit or prevent certain health issues. Some examples of important antioxidants from algae have turn into very popular supplements for human nutrition: carotenoids, vitamins C and E, butylated hydroxytoluene (BHT), and astaxanthine (Skjånes *et al*., 2013) [125]. Table 6 represents some examples of microalgae and the type of antioxidant substance that they produce.

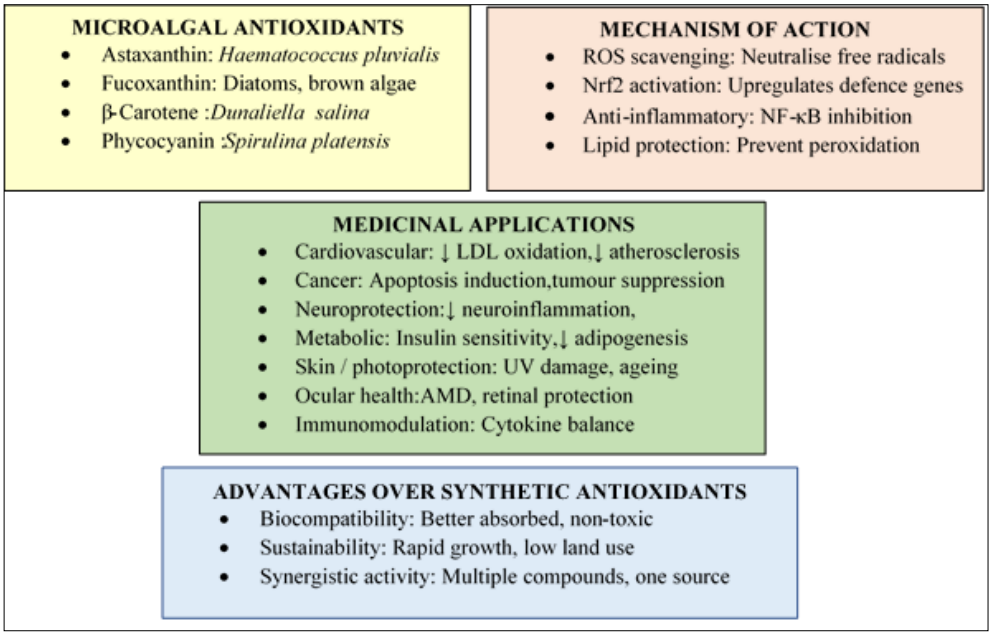

Fig 8: Some antioxidant and its action mechanisms & advantage

15. *Antibiotics*

In the last decade, researchers have emphasised to explore microalgae as well as bioassays for medicinal active compounds and identified a huge number of antibiotic compounds with unique and innovative structures (Senhorinho *et al*., 2015) [118]. There are abundant review articles that have published about microalgal antiviral, and antineoplastic compounds, showed structurally complex, which makes a challenge to produce it by chemical synthesis (Borowitzka, 1995). These isolated molecules are designated as antibacterial compounds (Fig. 9), having diverse chemical classes such as alkaloids, fatty acids, indoles, macrolides, peptides, phenols, pigments, and terpenes (Table 5). Furthermore, in addition to human applications, it is now involved in veterinary and agricultural applications. Others can be use, for instance, as research tools or as structural models for the development of new drugs (Senhorinho *et al*., 2015) [118].

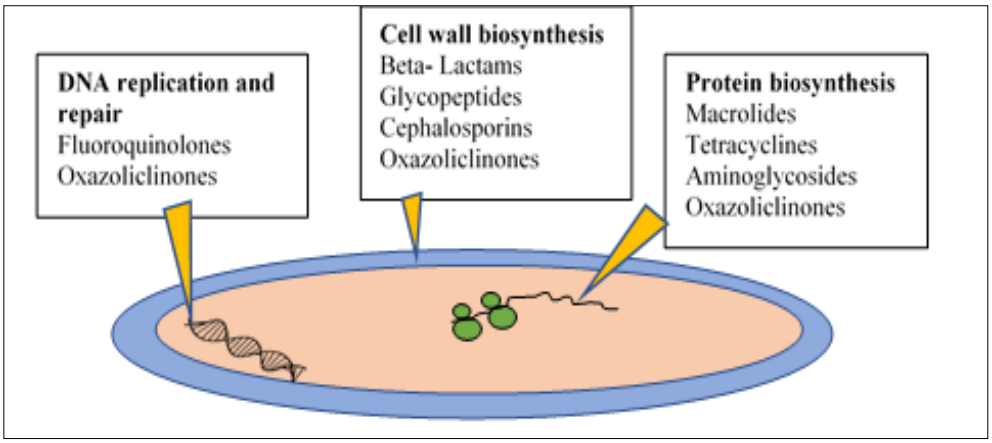

Fig 9: Showing different site of antibiotics action that available currently in market

16. *Carotenoids*

Human metabolism recognizes and uses natural microalgal carotenoids more readily than manufactured ones because they are stereoisomeric combinations. For instance, the 3S,3'S stereoisomer of astaxanthin from *H. pluvialis*, which is also present in salmon, exhibits significantly more antioxidant activity than the racemic synthetic counterpart. Microalgae are becoming a more viable feedstock for pharmaceuticals and nutraceuticals since they can be grown in closed photobioreactors with controlled purity, scaled without agricultural land or pesticides, and harvested year-round.

Carotenoids (also called tetraterpenoids) are accessory pigments of photosynthesis. It protects (antioxidative role) the photosynthetic machinery from excess light by scavenging reactive oxygen species (ROS) with singlet oxygen and other free radicals. Their physiochemical properties decide their molecular bioactivities and are

involved in the treatment of cancer (Baeza-Morales *et al*., 2024) [8], macular degeneration (Nguyen *et al*., 2023) [94], and precursors of vitamin A (Grune *et al*., 2010) [47]. It has significant contributions as feed for aquaculture and animal farming and has nutraceutical potential for human use (Del Campo *et al*., 2007) [38]. Some algae accumulate carotenoids as part of their biomass (Ben-Amotz & Avron, 1990) [12] and are good natural sources of β-carotene, e.g., *Dunaliella salina (Guerin et al., 2003)* [49]. One of the richest natural sources of astaxanthin is *Haematococcus pluvialis* (Fig. 16), and it used for large-scale production (Guerin *et al*., 2003) [49]. Another important carotenoid, "leutein", mostly found in foods, has used as an additive in aquaculture and poultry operations. The microalga *Muriellopsis* is the most auspicious source of leucine, used for the treatment of cataracts, macular degeneration, and early stages of atherosclerosis (Del Campo *et al*., 2007) [38]. The rate of carotenoids production by algae depends on high cell densities and efficient growth under minimum illumination, although further research and growth studies are required for its large-scale production.

Molecular Mechanism of Biomolecules Action

Based on their chemical behavior, the isolated microalgal biomolecules act on specific molecular targets (Table 6). Carotenoids like fucoxanthin and astaxanthin reduce oxidative damage and pro-inflammatory cytokine production by suppressing NF-κB-driven inflammation and activating the Nrf2 antioxidant pathway (Davinelli *et al*., 2022) [31]. Microalgae like Nannochloropsis and Phaeodactylum tricornutum produce large amounts of omega-3 fatty acids, EPA and DHA, which are incorporated into cell membrane phospholipids and shift eicosanoid making toward anti-inflammatory resolvins and protectins. They also function as ligands for PPARγ, further suppressing NF-κB transcriptional activity (Bodur *et al*., 2025) [13]. Toll-like receptors on macrophages and dendritic cells are activated by sulfated polysaccharides and exopolysaccharides, resulting in innate immune signaling cascades that boost phagocytic activity, cytokine production, and antiviral responses (Hwang *et al*., 2022) [61]. In addition to downregulating anti-apoptotic Bcl-2 proteins and initiating caspase cascades to cause cancer cell death via the intrinsic mitochondrial apoptosis pathway, phycobiliproteins like phycocyanin directly scavenge peroxynitrite and hydroxyl radicals (Wang *et al*., 2025) [59]. Carotenoids like astaxanthin have been demonstrated to influence lipid metabolism and LDL profiles in part through interactions with the PCSK9–LDL receptor axis, and microalgal phytosterols decrease intestinal cholesterol absorption by competing with dietary cholesterol for micellar incorporation (Medoro *et al*., 2024) [88]. The antioxidant, anti-inflammatory, immunomodulatory, anticancer, and cardioprotective qualities ascribed to microalgal biomolecules are collectively supported by these pathways (Oladipo *et al*., 2025) [97].

Discussion: Microalgae as Therapeutics

Microalgae have become very promising therapeutic candidates for their abundant production of bioactive metabolites such as carotenoids, phycobiliproteins, PUFAs, and sulfated polysaccharides, with evidence for their anti-inflammatory, antioxidant, immunomodulatory, anticancer, and neuroprotective properties (IntechOpen, 2025) [13]. Their biomasses have antibacterial, antifungal, antiviral and chemo-preventive activities, indicating potential for the management of neurological conditions such as Alzheimer's disease, AIDS and COVID-19. Their carotenoids, polyphenols and tocopherols are important players at the antioxidant front, scavenging free radicals and reducing oxidative stress important players in aging and chronic disease. Moreover, several studies have shown their ability in improving insulin sensitivity by antioxidant, anti-inflammatory and pancreatic β-cell protective mechanisms, supporting their use as nutraceuticals in the management of diabetes mellitus. Due to their biocompatible cell walls, engineered nanoparticles and antioxidant carotenoids, they can serve as a combined drug delivery platform to improve controlled release, bioavailability and stability of pharmaceutical compounds. However, the field is still in its infancy and requires significantly more rigorous research before microalgae can be considered a fully established domain of therapeutics, with important barriers such as regulatory complexity, lack of standardized protocols, limited clinical trials and insufficient pharmacokinetic data currently hindering progress. The field, however, remains beset by significant and well-documented limitations. There are still major challenges to be faced such as regulatory hurdles, development of standardized protocols for cultivation and extraction, safety assessment and scalable production systems. The number and extent of human clinical trials are still limited and robust data on pharmacokinetics, bioavailability and long-term effects are essential before regulatory approval can be realistically pursued. At the delivery systems level, microalgae have excellent biocompatibility and readily modifiable surface properties. However, traditional drug delivery systems are limited by problems such as low drug-loading efficiency, immunogenicity, and simple functionalization. These problems need to be solved before microalgae-based delivery systems can meet the needs of complex pathological conditions.

Table 5: Identified antibacterial compounds from microalgae (Shannon & Abu-Ghannam, 2016) [119]

Organism	Compound(s)	Chemical nature
Chlorella	**Chlorellin**	**Fatty Acids**
Haematococcus pluvialis	Butanoic acid and Methyl lactate	
Phaeodactylum tricornutum	Eicosapentaenoic acid	
Oscillatoria redekei	Coriolic acid and α-dimorphecolic acid	
Spirulina platensis, Nostoc CCC537	γ- linolenic acid	
Fischerella sp.	Ambiguine H & I isonitriles)	Alkaloids
Nostoc sp.	Carbamidocyclophanes A-E	
Fischerella ambigua	Fischambiguine B	
Nostoc insulare	Norharmane	
Nostoc spongiaeforme	Nostocine A	

Nostoc sp.	Nostocycline A	
Nostoc muscorum	Muscoride A	
Anabaena basta	Bastadin	Terpenoids
Nostoc commune	Diterpenoid	
Navicula delognei	Ester	
Nostoc commune	Noscomin	
Scytonema sp.	Scytoscalarol	
Tolypothrix nodosa	Tolyporphin	
Anabena variabilis	Belamide A	Peptides
Hormothamnion enteromorphoides	Hormothamnins	
Stichochrysis imobilis	Peptide	
Microcystis aeruginosa	Kawaguchipeptin B	
Schizothrix sp.	Schizotrin A	
Nostoc pongiaeforme	Tenuecyclamides	
Lyngbya majuscula	Malyngolide	δ-lactone
Fischerella ambigua	Parsiguine	Oxygenated polyethylene
Fischerella ambigua	Ambigol A, B	Polyphenols
Phaeocystis sp.	Phaeocystis sp. acrylic acid	Unsaturated acids

Table 6: Molecular mechanism of some isolated biomolecules action from microalgae

Biomolecule	Key signaling pathways	Molecular targets	Biological effects	References
Astaxanthin Carotenoid *Haematococcus pluvialis*	NF-κB ↓ MAPK ↓ Nrf2 ↑ PI3K/AKT ↓ SIRT1/PGC-1α ↑	Cyclin D1, p21 Bcl-2/Bax iNOS, NO bioavailability Antioxidant enzymes	· Anti-inflammatory · Antioxidant · Anticancer (cell cycle arrest, apoptosis) · Cardioprotective Neuroprotective (Alzheimer's)	Davinelli *et al*., 2022; Pepeira *et al*., 2021; Liu *et al*., 2023[31, 80, 101]
Fucoxanthin Xanthophyll *Phaeodactylum tricornutum*	NF-κB ↓ NLRP3 ↓ Nrf2 ↑ PI3K/AKT ↑ Caspase cascade	TNF-α, IL-6, VEGF TGF-β, IL-1β Caspase-3 Bcl-2/Bax	· Anti-inflammatory · Anticancer (apoptosis, autophagy, angiogenesis inhibition) · Anti-obesity Antioxidant	Kim *et al*., 2021; Mohibbullah *et al*., 2022; Ávila-Román *et al*., 2021[69, 73]
C-Phycocyanin Phycobiliprotein *Spirulina* sp.	COX-2 ↓ Nrf2/HO-1↑ PI3K/AKT/mTOR ↓ PKCα/βII ↑	p70S6K PARP-1, Caspase-3 COX-2 (IC_{50} = 180 nM) HO-1 expression	· Anti-inflammatory (selective COX-2 inhibition) · Antioxidant · Anticancer (G0/G1 arrest, apoptosis) Photoprotective (UV-induced apoptosis)	Reddy *et al*., 2003; Romay *et al*., 2003; Patel *et al*., 2006[100, 110]
EPA & DHA ω-3 PUFAs *Nannochloropsis* sp.	PPARα ↑ NF-κB ↓ Nrf2–ARE ↑ Resolvin synthesis ↑	COX-2, iNOS IL-1β, IL-6, TNF-α Arachidonic acid cascade Eicosanoid synthesis	· Anti-inflammatory · Cardioprotective · Neuroprotective · Anti-diabetic (insulin sensitivity)	Jesionowska *et al*., 2023; Wang *et al*., 2010; Lupette & Benning, 2020[63, 82, 132]
Bioactive Peptides Hydrolysates *Chlorella* sp.	ACE inhibition DPP-IV inhibition Bcl-2/Bax Caspase cascade	Angiotensin II Glucagon-like peptides Caspase-3/-9 ROS, SOD, CAT	· Antihypertensive · Anti-diabetic · Anticancer · Antimicrobial · Antioxidant	Li *et al*., 2021; Sedighi *et al*., 2025; Chakrabarti *et al*., 2018[7, 18, 117]
olysaccharides EPS/IPS *Porphyridium* sp.	Iron chelation TLR modulation Gut microbiome ↑ Immunomodulation	Fe^{2+}/Fe^{3+} ions Bacterial membrane Gut epithelium –OH, –COOH functional groups	· Antimicrobial (iron sequestration) · Immunomodulatory · Prebiotic (gut eubiosis) · Antioxidant	Zhao *et al*., 2023; Fan *et al*., 2025; Teixeira-Santos *et al*., 2021[41, 128, 136]
*↑: up regulation; ↓ down regulation				

Future Perspectives

Microalgae have developed into enormous, nearly untapped natural product reserves. Fortunately, as human desires continue to rise, so do the scientific and technological possibilities in the field of bioactive microbial products research. Only one-third of cancer patients are currently receiving treatment using currently available medications. Prokaryotic and eukaryotic microalgae's advantageous and detrimental characteristics may make them suitable for use in biotechnology to address such issues. Researchers should think about examining species from neglected microbial sources, like cyanobacteria, bacteroidetes, proteobacteria, and other microalgae. In coming future, bioactive microalgae molecules will be the most promising chemicals with higher recovery and fewer side effects, and will be a natural alternative. Today, culture techniques for the production of microbial biomass have bioengineered for their various practical uses in health and society. Advanced and rapid screening methods are evolving to identify new and cheap sources of bioactive molecules, cosmetics, healthy foods, pet foods, and many more. For most of these applications, the market is still developing and the use of microalgae biotechnology will expand very soon into new areas. Moreover, in the face of the challenge of population growth, only microbial diversity and biotechnology can meet the needs of the food, feed, pharmaceutical, fuel, and

bio fertilizer etc. and many more sustainable potent molecules.

Conclusions

In conclusion, despite the health benefits highlighted throughout the literature, there is consensus that the field of microalgae is still in its infancy and much more research is required before it can be considered a fully established therapeutic domain. The pharmaceutical potential of microalgae deserves more scientific attention and interdisciplinary research. Because the nature of secondary metabolites depends on their adaptation to the environment, these microscopic classes need to be examined more closely to find new compounds, especially in extreme habitats. Algae (prokaryotes and eukaryotes) are organisms with a wide range of biological activities, including antibiotics, antiviral agents, antitumor agents, antioxidants, and anti-inflammatory evidence from phytochemical and pharmacological studies. It has great appeal as a natural source of active molecules. They produce most of the chemical metabolites for the environment. While challenges remain in large-scale isolation, structural elucidation, and toxicity profiling, advances in genomic mining, synthetic biology, and heterologous expression systems are increasingly enabling the harnessing of microalgal biosynthetic pathways, underscoring their immense untapped potential as scaffolds for novel therapeutic agents across oncology, neurology, infectious disease etc. Some of the bioactive ingredients obtained from this strain are amino acids, terpenoids, polysaccharides, steroids, phenolic compounds, halogenated ketones, alkenes, cyclic polysulfides, and peptides. Secreted toxins contain a variety of nitrogen-rich alkaloids and peptides that humans fear, but they also have great potential for the development of pharmaceutical and agricultural applications.

Search Engine and Software Used

Google Scholar, ResearchGate and PubMed used search engine for the published articles. ChemSketch and Mendeley used to draw chemical structures of biomolecules and arrangement of references respectively.

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