Marine Algae and Their Pharmacological Potential Review on The Medicinal Properties of Various Marine Algae

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Abstract: **Marine algae is a highly potent source of bioactive compounds which have various therapeutic and commercial applications. This review comprises of diversity, chemical composition and pharmacological properties of marine algae. This review is specifically focused on marine algal compounds which include polysaccharides, polyphenols, pigments, and other types of secondary metabolites. These compounds exhibit biological activities which include anti-inflammatory, antioxidative, antiviral, antibacterial and anticancer properties. Primarily through modulation of key biochemical pathways related to oxidative stress and cytokines regulation. Additionally, marine algal polysaccharides have increased attention in terms of their use in immunomodulation and functional food applications, especially in nutraceuticals, aquaculture, and pharmaceutical formulations. There are certain challenges such as high production costs, variability in composition, and the need for advanced extraction and characterization techniques hamper their large-scale utilization. This review also emphasizes about the recent advancements in biotechnological approaches, extraction technologies and potential commercial applications while highlighting gaps for future research. Hence, marine algae is valuable and underexploited resource to support the development of new bioactive compounds and functional products, requiring further scientific exploration and industrial investment.**

Keywords: Marine Algae, bioactive compounds, pharmacological activities, antioxidant activity, anti-inflammatory activity, antidiabetic potential, therapeutic applications.

I. INTRODUCTION

Marine algae are aquatic organisms which are primarily found in ocean also called as seaweed, kelp, algae, marine plants, oceanic algae and macroalgae having photosynthetic and eukaryotic characteristics that play a crucial role in marine ecosystems. Marine algae can grow even in saline and blackish water and carry out photosynthesis and utilize sunlight and some other elements (N, P, K) for energy and release oxygen as the by product. They are also a good source of bioactive compounds such as proteins, antioxidants, polyunsaturated fatty acids (PUFAs), fatty acids, carbohydrates, amides, amines, and pigments. [1]

Marine algae are also used in dermatological products, food preservatives and cosmetic products, etc. Marine algae are crucial for aquatic system as their one of the primary functions is to convert the sunlight to energy which forms the basis of the marine food web. Brown algae form underwater forests that supply shelter and habitat to various marine species, it also stabilizes sediments and protect shoreline from erosion. [2]

Red algae help to maintain coral reef health by secreting calcium carbonate which is important for reef structure and biodiversity. Green algae play a vital role in nutrient cycling by absorbing excess nutrients; therefore, it maintains water quality and supports herbivorous marine life. Marine algae have a vast history in traditional medicine, it was used to treat various illnesses, conditions such as burns, scurvy and inflammation. In ancient China (from2953 BCE) people used medicines which were made from fish including marine algae. Hippocrates was a well-known physician who recognized that marine organisms had antibiotic properties. Dioscorides (in Materia Medica 65 CE) wrote about using brown algae to treat inflammation. Galen a prominent Greek physician (2nd century AD) acknowledged the therapeutic properties of marine algae. Marine algae have vast number of bioactive compounds which are used in pharmaceutical, cosmeceutical and nutraceutical industries. [3]

II. DIVERSITY OF MARINE ALGAE

Marine algae are biodiverse species generally categorized into macroalgae and microalgae. Macroalgae are commonly called as seaweeds (Multicellular Sea habitats), which are mainly divided into three divisions (based on their pigmentation): Rhodophyta, Chlorophyta, and Phaeophyta. Microalgae are single-celled photosynthetic organisms, eg, Phytoplankton. Marine algae are the base of the food chain, which contributes 70% of total living biomass. Scientists have found a total of 3,00,000 distinct algal species. Globally there are 11,000 species, including red seaweed having 7,200 species, brown seaweed having 2,000 species, and green seaweed consisting of 1,800 species. Unicellular algae are motile or non-motile, whereas multicellular algae are relatively complex tissues and organ-like structures.

Early taxonomic records show that the collections were mainly from islands visited by science expeditions, initially identified by taxonomic specialists in Europe. The first real records were six species described by Endlicher and Diesing (1845) considering 2 red algae and 4 brown algae. Borgesen published the first comprehensive account of seaweeds (Benthic algae) from the Gulf based on specimens collected from Kharg Island, Near Bushire (Iran) and Near Manama (Bahrain). Marine algal diversity in the Arabian Gulf has been documented with important contributions from Iran where Nizamuddin and Gessner (1970) recorded 68 species and Sohrabipour and Rablei (1996-2007) added 115 new taxa. They found 4 new green algae and 45 red algae by the Gulf of Oman and more than 60 were found to the Gulf. Silva et al's list (1996) had many more. That list had 214 types. [4]

Dinoflagellates contain 3,000 described species with 500-8,000 more expected. Euglenophytes comprises 900 described species and perhaps up to 1,000 yet to be described. Cryptophytes including 200 described species and 1,000 saliently missing and glaucophytes are represented only by 13 recognized species rest are undiscovered. The pace of algal biodiversity acquisition is gradual due to dependence on time and resource consuming methods, e.g, clonal culture, electron microscopy, molecular sequencing, etc.

Marine algae have rich bioactive compounds consisting of carbohydrates, proteins, minerals, fatty acids, antioxidants and pigments. Biotic factors (plants, microorganisms) and abiotic factors (temperature, pH, salinity, light intensity) are mainly responsible to produce primary and secondary metabolites in algae. Algal bioactive compounds are used in nutraceutical, therapeutic, and nanotechnological applications) e.g, nanotheranostics, nanoparticle synthesis). Marine algae are abundant in bioactive components including carbohydrates, proteins, minerals, polyunsaturated fatty acids (PUFAs), fatty acids (FAs), amines, amides, antioxidants (e.g., polyphenols, tocopherols), and pigments such as carotenoids, chlorophylls, carotene, xanthophylls, and phycobilins (phycocyanin (PC), phycoerythrin (PE)) which function as stabilizing/capping and reducing agents for the biosynthesis of thermodynamically stable NPs. Physiologically active substances present in marine algae are classified into two (based on mechanistic differences): i) Non-absorbed high molecular materials ii) absorbed low-molecular materials. Various algal groups such as (Phaeophyceae, Rhodophyceae, Chlorophyceae, Microalgae) show distinct profiles, such as red algae rich in carrageenan's and phycobiliproteins, brown algae produce fucoidans and phlorotannin's and green algae producing ulvans and specific amino acids. Some compounds of algae are functionally diverse, they perform a wide range of physiological functions e.g., antioxidant, antiviral, anti-inflammatory, anticancer, neuroprotective, UV-protective. [5]

III. PHYTOCHEMICAL CONSTITUENTS

Marine algae are an excellent source of plant compounds with nutritional and medicinal benefits. Their main metabolites include polysaccharides like alginate, fucoidan, carrageenan, and ulvan. They also contain proteins, amino acids, dietary fiber, minerals, trace elements, vitamins and sterols which vary by species for e.g, ucocholestrol, cholesterol, β-sitosterol, fucosterol, brassicasterol, desmosterol and Chalina sterol. Algae also produce many secondary metabolites such as phlorotannins, polyphenols, phytosterols, halogenated compounds, alcohols, aldehydes, terpenoids, and phenolic compounds. Many secondary metabolites show strong antioxidant,

anticancer, anti-cholesterol, anti-diabetic, anti-bacterial, anti-algal and antifungal effects. Pigments like fucoxanthin, chlorophylls, carotenoids and phycobillins give unique colors and add bioactivity, antioxidant and anti-obesity benefits. Algal extracts are rich in natural plant growth regulators such as auxins, cytokinins, and gibberlins which expand their use in agriculture. Within polysaccharides, alginate and fucoidans are particularly significant as they are linked to various biological activities such as anticancer, antiviral effects and anit- inflammatory effects. Due to these plant compounds marine algae are positioned as valuable resources for nutritional, medicinal and functional food uses.

3.1 Primary Metabolites: Polysaccharides, amino acids, fiber, vitamins, minerals and sterols are primary metabolites of seaweed. Polysaccharides (alginate, fucoidan, carrageenan, and ulvan) are structural constituents and significant to the nutraceutical, pharmaceutical and biotechnological industries. Fucoidans are sulfated polysaccharides obtained from brown algae and possess important antitumor, antiviral and anti-inflammatory effects. The amino acids and proteins have important nutritional value and dietary fiber helps in digestion. Algae is an outstanding dietary supplement as it contains vitamins such as tocopherols, caretinoids and some of the B vitamins and variety of minerals and trace elements. To some extent, sterols are specific characteristics of the species. Chlorophyceae (Green algae) have ococholestrol, and β-Sitosterol, Phaeophyceae (Brown Algae) have fucosterol, brassicasterol and cholesterol and Rhodophyceae (Red Algae) have desmosterol, chalinasterol, and fucosterol. These sterols have cholesterol-lowering, antioxidant and anti-diabetic properties.

3.2 Secondary Metabolites: The importance of algae as a source of bioactive compounds is being recognized. Phaeophyceae (Brown Algae) are known for their diversity of bioactive compounds, cinsisting oof phlorotannins, phytosterols, polyphenols, halogenated compounds, terpenoids, aldehydes, alcohols, and phrnols. Phlorotannins are unique to brown algae, they are produced through the acetate-malonate (polyketide) pathway, particularly through the polymerization of phloroglucinol as phlorotannins are highly hydrophilic, they possess a wide range of molecular sizes. Individual phlorotannins such as eckol, dieckol, bieckol, and phlorofucofuroeckols possess a diversity of beta activities that are bioactive including anti-diabetic, anti-proliferative, antioxidative, anti-HIV, anti-allergic, skin protective and radioprotective. Members of Laminaria and Sargassaceae families are particularly considered rich sources of phlorotannins. Especially, brown algae mainly contain phytosterols such as fucosterol and its derivatives along with ither sterols including stigmasterol, brassicasterol, campesterol, β-Sitosterol and cholesterol. All are bioactive and show significant cytotoxic, antioxidative, cholesterol ameliorative, anti-diabetic and anti-proliferative activites.

Brown algae or Phaeophyceae are valuable for their high concentration of fucoxanthin. A notable xanthophyll carotenoid pigment recognized for its anti-inflammatory properties. They are also an important source of sodium alginate, which has considerable value in various industrial applications. Brown algae have low-protein content but comparatively have good amount of carbohydrates and minerals. Additionally they offer substantial amounts of beta-carotene and vitamins and they do not contain anti-nutrients. Red algae or Rhodophyta are known by the presence of Phycocyanin and phycoerythrin pigments that impart characteristic coloration. Primarily, their cell walls are composed of carrageenan and agar which are long-chain polysaccharides whith significant industrial uses. Some groups within red algae such as coralline algae, further distinguish themselves by depositing calcium carbonate in their cell walls, that provides as specific structural element. Green algae or Chlorophyta consist of chlorophyll-a and chlorophyll-b, the pigments responsible for their green coloration. Nutritionally, green algae are valuable for a high protein content (more than 15%), low energy value and an high amount of dietary fiber including both soluble and insoluble glucans. Seaweeds are also a source of bioactive amino acids such as valine, taurine, leucine and isoleucine which show antioxidant activity. Aspartic acid and glutamic acid are present in most species of seaweed. Seaweeds proteins also contain essential amino acids including tryptophan, threonine, cysteine, lysine, methionine, and hisitidine. Sulfated and non-sulfated polysaccharides consist of an important category of a bioactive phytoconstituents

with significant therapeutic potential. Sulfated polysaccharides (SPs) from Spirulina platensis comprise galactose, glucose, arabinose, rhamnose and glucuronic acid. Red Algae comprise 3,6-anhydro-L-galactose and D-galactose show strong antitumor and antiviral activity. Within these fucoidans are identified as the main sulfated polysaccharides of brown algae such as Ascophyllum nodosum, Fucus vesiculosus, Laminaria japonica, Fucus evanescens, Laminaria cichorioides and Sargassum thunbergia which are known for possessing a wide range of biological properties, cholesterol-lowering, and protection against metabolic syndrome, antipeptic, antioxidant, antiproliferative, anticancer, anti-inflammatory, antithrombotic, anticoagulant, and antiadhesive properties. Reports indicate that metastasis via the inhibition of matrix metalloproteinases (MMP) and VEGF work in synergy with traditional anticancer drugs to limit lung cancer. Furthermore, soluble dietary fibers are found from sources like Euchema cottonii, Chondrus ocellatus, Caullerpa lentilifera, Ahnfeltiopsis concinna, Sargassum polycystum, Gayralia oxysperma, Sargassum obtusifolium, and Ulva fasciata promote metabolic health by lowering levels of cholesterol and providing protection against metabolic syndrome.

IV. PHARMACOLOGICAL ACTIVITIES

Marine Algae are presently considered as highly important reservoirs of bioactive compounds with excellent pharmacological potential in drug development and other therapies. Reported bioactivities of marine algae include antioxidants, hepatoprotective, antidiabetic, anticancer, antimicrobial, neuroprotective, hypolipidemic, anti-allergic, anti-inflammatory, anti-coagulant, cytotoxic and anticholinesterase activities.

4.1 Antidiabetic activity: Marine algae have bioactive constituents such as polyphenols, phytosterols, polysaccharides, carotenoids and flavonoids which have antidiabetic potential and has been demonstrated through synergistic interaction among the bioactive constituents of marine algae. Various algal species, especially brown, red, and green algae from the Indian coast and from the other parts of the world have been researched and enhancement in blood sugar control, lipid metabolism and insulin function has been reported. In brown algae, Padina boergesenii was studied, the extract recovered insulin and lipoprotein levels, glycogen ability of the liver and total protein, reduced fasting blood sugar and stabilized the functioning of streptozotocin (STZ)-induced diabetic rats. The extract activated glycolytic pathways and suppressed gluconeogenic regulation, indicating significant hypoglycemic potential and synergistic effects. Methanolic extract of Gracilaria edulis (red algae) and Sargassum polycystum (brown algae) help in controlling hyperglycemia, the lipotropic action normalized the altered lipid profile (high cholesterol, triglycerides, LDL) in diabetic patients and restores pancreatic beta cells which lead to normal insulin secretion. Cystoseira moniliformis and Caulerpa lentillifera have been reported to promote the secretion of insulin from pancreatic beta cells, enhance glucose homeostasis, and stimulate glucose uptake in adipose tissues indicating their antidiabetic effects. Acarbose and miglitol (clinically prescribed antidiabetic medications) have similar mechanisms to those of brown algae polyphenols, especially those derived from Ecklonia stolonifera and Ecklonia Cava. This reduces postprandial hyperglycaemia, lowers diabetic-associated lipid peroxidation and enhances glucose controlled in the plasma in diabetic animal model. Dieckol and other polyphenolics exhibit anti-inflammation and lipid-lowering demonstrating their potential in managing diabetes. This research suggests that marine algae are a new and well-founded source of potential antidiabetics. The mechanisms by which these marine algae improve or promote insulin secretion, regeneration of the pancreatic β-cells, lipid and oxidative metabolism, carbohydrate homeostasis, suppression of hyperglycemia, diabetes and inhibition of the carbohydrate digesting-enzymes and various associated complications highlight the potential for innovative antidiabetic medications.

4.2 Antioxidant Activity: Marine algae consist of a wide range of natural antioxidants mainly due to the presence of flavonoids, sulfated polysaccharides, phenolics and carotenoids. These compounds save cells from oxidative damage by neutralizing free radicals, by lipid peroxidation (oxidation of cell membranes that damage cell membranes, and sequester metal ions like iron, copper as these ions work as catalyst in oxidative reactions. Gracilaria corticate, Turbinaria conoides and Halimeda tuna

contain phenolic compounds which contain antioxidant compounds which have strong ability to neutralize free radicals. These compounds donate their hydrogen atoms and neutralize reactive oxygen species. Also, Acanthophora specifera has demonstrated radical scavenging of DPPH, hydroxyl radicals, nitric oxide and Fe^{2+} and indicates strong antioxidant activity, which illustrates the complex antioxidative interplay between radical scavenging and metal chelation. Additionally, Enteromorpha compressa and Ulva fasciata showed considerable in vivo and in vitro oxidative stress mitigation, supporting their involvement in cellular redox balance. Antioxidant activity in marine algae tissues is ascribed to carotenoids (fucoxanthin, β-carotene), tocopherols, carotenoids, and ascorbic acid which are secondary metabolites. The combination of these compounds enhances the redox potential of algal tissues. They also stimulate the activity of catalase (CAT), glutathione peroxidase (GPx), and superoxide dismutase. All vital intracellular antioxidants and strengthen the cellular defense system against active reactive oxidative species. In oxidative stress-related disorders (inflammation, neurodegenerative diseases, diabetes and cancer) the therapeutic potential of marine algae is apparent in their antioxidant activities. Antioxidant molecules in marine algae show synergistic effect also coupled with their natural origin and bioavailability make them appropriate for nutraceutical, pharmaceutical and cosmeceutical formulations. [7] [8]

4.3 Anticancer and Cytotoxic Activity: Marine algae are recognized as promising sources of anticancer agents for their diverse bioactive compounds. They contain various bioactive compounds such as terpenoids, fatty acids, polyphenols, sterols and sulfated polysaccharides having exhibited various levels of antiproliferative and cytotoxic activity against multiple cancers. Extracts of Laurencia brandenii demonstrated strong cytotoxic and bioactive fatty acids like linoleic acids, as fractions possessed an LD50 of 93ug/ml against Arthemia salina. Equally, methanolic extracts of Gracilaria corticata supressed the proliferation of human leukimeia cell lines (Jurkat and Molt-4) in MTT assays signifying anti-tumor activity connects its high flavonoid and phenolic content. Additionally, polyphenolic compounds isolated from Gracilaria tenuistipitata and Callophyllis japonica showed suppression in cellular proliferation, reduced DNA damage, induced aptosis in cancer cells, illustrating their capability to regulate key molecular pathways involed in carcinogenesis. This evidence collectively suggests that marine algae show potent cytotoxic and anticancer properties making them a supportive and valuable natural source for the development of therapeutic and chemo preventive agents against cancer. Marine algae are a good natural option for anticancer medicine due to various bioactive compounds.

Algae compounds work against cancer through various connected pathways like apoptosis. Apoptosis is basically programmed cell death by turning on caspases and messing with signals from mitochondria or death receptors. Sphlorotannins and fucoxanhthins from brown algae help elevate the proteins that push the cells to die. Some of the metabollites inhibit the cell cycle from going forward, blocking the cell cycle at different phases, thus inhibiting uncontrolled cell growth. For example, Bioactive constituents from Chlorella species suppress inhibit the AKT/mTOR pathway, responsible for cancer cell survival and proliferation, thereby enhancing apoptosis. Specific phlorotannin's, including phlorofucofuroeckol A, act on the ATF3 pathway, which is involved in cellular metabolism and is closely linked to cancer metastasis. Green Algae has a unique property that contributes in a certain way to anticancer mechanisms based on chlorophyll, magnesium liganded chloro[hyll pigments a and b consists antigenotoxic, antimitotic and antitumor activities including protective effects against aflatoxin B1–induced hepatocarcinogenesis, reduced DNA adduct formation, and inhibition of DNA damage resulting from chemical carcinogens. Apart from native chlorophyll, chlorophyll-derived compounds show notable demonstrate pronounced anticancer activity with tetraprenyltoluene and siphonaxanthin n exhibit strong cytotoxic effects toward human colon cancer cells. Lutein and zeaxanthin from green algae have demonstrated chemopreventive effects against oral and liver cancers resulting in reduced tumor formation fewer preneoplastic lesions. Furthermore, (3S 3'S) β-carotene form green algae supports in preventing cancer through an indirect mechanism that is absorbed at the intestine wall and converts to retinol which stimulates retinol-binding protein a pathway

associated to lower levels of carcinogens. Anticancer activity in red algae has been demonstrated for sulfated polysaccharides (agarans and carageenans) causing an immunomodulatory capacity inhibiting with tumoral growth and metastasis. [9]

4.4 Antibacterial and Antifungal Activity: A marine habitat supports a highly diverse range of organisms that are exposed to high levels of pathogenic and surface-attaching microorganisms. To survive these conditions algae highly have evolved highly advanced chemical defense mechanisms. Microalgae (e.g., seaweeds) and macroalgae (e.g., diatoms) are rich sources of bioactive secondary metabolites including fatty acids, peptides, phlorotannin's, sulfated polysaccharides and terpenoids which play an active role in protection against pathogenic bacteria infection. Compounds isolated from marine algae show antimicrobial activity against Gram-positive bacteria and Gram-negative bacteria. Brown algae polyphenols such as phlorotannin's show potent antibacterial effects by impairing bacteria cell walls and membranes inhibiting metabolic enzyme activity by obstructing nucleic acid and protein biosynthesis. Fatty acids and their derivatives show bactericidal activity by destabilizing bacterial membranes resulting in cellular lysis and leakage by impairing membrane stability and permeability. Sulfated polysaccharides such as carrageenan, ulvan and fucoidan demonstrate antibacterial effects by antibacterial and biofilm development which reduces bacterial colonization and virulence. Moreover, terpenes and algal peptides have shown potent inhibitory activity against numerous and medically important pathogens. From a pharmacological approach, antibacterial compound derived from algae are particularly appealing due to their unique mechanism of actions, natural sources and relatively lower toxicity. These compounds have demonstrated potential applications in therapeutic antibiotics, surface disinfectants, food products, and antifouling agents, thereby responding to industrial and clinical challenges. [10]

4.5 Anti-Inflammatory Activity: Inflammation is the body's natural defense mechanism that helps it fight harmful factors such as toxins, infections and physical injuries. Anti-inflammatory drugs help by reducing inflammation by blocking key molecules in the body, consisting of cytokines, enzymes such as e COX-2, and nitric oxide produced by iNOS. While acute inflammation is important to maintain tissue health, chronic or uncontrolled information may lead to various disorders such as cardiovascular diseases, rheumatoid arthritis, and neurodegenerative conditions. Non-Steroidal Anti-Inflammatory Drugs (NSAID's) are majorly used in the treatment of inflammation, but their prolonged use is linked with significant side effects highlighting the need for safer therapeutic options. The anti-inflammatory properties of marine algal metabolites mainly come from the regulatory action on significant inflammatory pathways. These compounds also help to reduce production of pro-inflammatory cytokines such as TNF-α, IL-1β, and IL-6 and also block key inflammatory enzymes like iNOS and COX-2. As well as lower oxidative stress through decreasing Reactive Oxygen species (ROS). Moreover, they modulate significant signaling pathways such as AKT, ERK, and NF-κB which play a major role in controlling the inflammatory response. [11]

The brown marine algae contain various bioactive substances consisting of phlorotannins and fucoidans that have exhibited outstanding anti-inflammatory effects on anti-inflammatory conditions linked to the skin. As fucoidans are sulfated polysaccharides, they show their anti-inflammatory effects by interfering with the pro-inflammatory cytokines IL-6, IL-1β and TNF-α inhibiting immune cell migration and preventing sone of the significant signaling pathways for e.g. NF-κB. On the other side, phlorotannins work as anti-inflammatory antioxidants from the elimination of free radicals, inhibiting enzyme actions like COX-2, regulating signal transduction pathways, consisting of MAPK and NF-κB. Furthermore, their activity depends on sulfate content and molecular weight with higher levels of sulfation enhancing their effectiveness. Phlorotannins have anti-inflammatory and antioxidant properties as they have free radical scavenging abilities, and control pathways such as NF-κB and mitogen-activated protein kinase. These two substances help in increasing the levels of anti-inflammatory cytokines, hence balancing the immune system response. Brown seaweed contributes to skincare by moisturizing and hydrating the skin, improving wound repair and showing antimicrobial properties against microbes such as Staphylococcus aureus. Delivery systems that enhances skin

penetration consist of nanoformualtion systems. Overall extracts from marine algae give a more natural approach for managing inflammation-related diseases, especially skin diseases like psoriasis, eczema, and atopic dermatitis. [12]

V. BIOTECHNOLOGICAL AND PHARMACEUTICAL APPLICATIONS

The Microalgae are single-cell plants that are photosynthetic, they are one of the initial forms of living things on earth. They can develop in various conditions, which include salt water and waste water also they do not interfere with agriculture at all. The microalgae consist of many significant substances such as lipids, fatty acids, pigments, vitamins, proteins and antioxidants. That's why there are many industrial utilizations for them, including food, medicines, energy sources, health foods and cosmetics. The manufacturing of microalgae is associated with some obstacles which consist of low biomass output, expensive production, rigid regulations and small market share. The market is rapidly growing due to the increasing need for products from microalgae in the global market environment. Microalgae consist of bioactive elements such as polysaccharides, proteins, polyunsaturated fatty acids, antioxidants and vitamins that are capable to play an important role in the treatment of disease such as cardiovascular, diabetes, and neurodegenerative diseases. Technological innovations in biotechnology and synthetic biology have helped make the production process even more efficient and inexpensive. Microalgae such as Nostoc, Chlorella and Spirulina serve as food products and supplements in various communities. At present, they are used in various industries such as pharmaceuticals, food, cosmetics, aquaculture, bio-fertilizers and biofuel. One of the main challenges is related to the inefficiency in large-scale production and product recovery from microalgae. However, researchers are working towards achieving this objective.

5.1 Pharmaceuticals: Microalgae are a rich source of bioactive compounds such as carotenoids, phycocyanin, vitamins, polysaccharides and fatty acids which possess various medicinal properties such as anti-inflammatory, antiviral, anticancer, antioxidants, antibacterial and cardioprotective activity. Spirulina microalgae helps boost immunity and decrease the level of cholesterol, whereas Chlorella decreases blood glucose, and acts as a natural detoxifier, also speeds up wound healing processes and boosts the functionality of liver. Certain bioactive compounds such as phycobilliproteins, can be helpful in treatment of cancer, whereas carotenoids (astaxanthin, β-carotene), have shown protection against oxidative stress, inflammation and degenerative diseases. Moreover, the omega-3 fatty acids present in the microalgae are effective in decreasing blood lipid and cholesterol levels and therefore are responsible for maintaining cardiovascular health.

5.2 Nutraceuticals: The idea of functional foods was developed in Japan During1980's. The term functional foods mean foods that have extra health benefits and help in improving people's overall health status while decreasing their chances of being ill. Such foods include bioactive ingredients such as phytosterols, vitamins, omega-3 fatty acids, probiotics and polyphenols. Microalgae are traditional source of nutrients that have high nutritional value. Microalgal protein is affordable as compared to proteins obtained from animals, this makes microalgae a highly valued food supplement source. Microalgae have beneficial composition hence, they are extensively used to produce supplements in a form of pills, soft gel capsules and liquid preparations. Microalgae are also included in various food products such as Snacks, pastas and beverages. Currently, microalgae such as Chlorella, Dunalella and spirulina contribute to global nutrition industry and products derived from microalgae account for multi-billion-dollar market.

5.3 Cosmeceuticals: Cosmetic industry uses microalgae as it has presence of biologically active compounds that stimulate anti-aging properties, antioxidant properties, moisturization and UV protection. Common microalgae species used in cosmetics consist of Spirulina (Arthrospira), Dunalelia, Nannochloropsis, Chlorella and Haematococcus. These are added in products such as cream, shampoo, lotions, face masks and sunscreen. Microalgae extracts play an important role in cosmetology by improving skin health and appearance such as Chlorella stimulates production of collagen, clears pores, reduces wrinkles and regenerates skin cells. Extracts of Spirulina are filled with protein

which delay skin aging, Nannochloropsis provides elasticity to skin, also carotenoids such as astaxanthin give protection to the skin against UV damage and photo-oxidation. Microalgae based compounds assist in maintaining the structural integrity of skin through regulation of proteins, such as collagen, elastin and glycoaminoglycanes. Such compounds can stimulate the production of protein or inhibit their breakdown process.

5.4 Microalgae as Prebiotics: Microalgae contain rich amounts of carbohydrates and polysaccharides that can be produced into prebiotic oligosaccharides that have many health benefits. They do not break down in the upper part of the gastrointestinal system rather they ferment within the intestine, hence fostering healthy bacteria while restricting detrimental organisms from proliferating. Thus contribute to a healthier gastrointestinal tract, better immune function, increased nutrient absorption, and decreases the chances of developing infectious diseases, obesity and colon cancer. Furthermore, prebiotics that are obtained from microalgae for eg., β-glucans, oligosaccharides and galactans derived from alginate have diverse biological activities such as antioxidant, immune-modulatory, antimicrobial, anti-inflammatory and hypoglycemic effects. Microalgae species like Chlorella, Spirulina and Porphyridium promote the growth of friendly bacteria such as Bifidobacteria and lactobacilli while inhibiting pathogenic microorganisms. Polysaccharides isolated from microalgae are recognized for their immune enhancing as well as antiviral and anticancer properties. They are widely used in functional foods, especially dairy products, also serve as feed supplements and as immunostimulants in aquaculture and animal systems. However, their production remains costly and the need for more research still limit their full utilization. [13]

VI. CONCLUSION

Marine algae are a promising and flexible raw material that offers a wide variety of potentially valuable bioactive compounds. This review discusses the various pharmacological actions including antidiabetic, anti-inflammatory, antioxidant, antimicrobial, and anticancer activities that have been observed due to the presence of polyphenols, polysaccharides, carotenoids, sterols, and flavonoids. The synergistic interactions among these constituents increase their significant biological efficacy and help in in disease prevention and management. Despite, ot of progress has been made in understanding the bioactivities of marine algae, there are still several challenges to overcome. This include variability in chemical composition between species, limited clinical validation and and difficulties in large-scale production and standardization. Addressing these gaps through advanced extraction techniques, conducting detailed molecular studies, and carrying out well-designed clinical trials. Overall, marine possess great potential for the development of novel therapeutic agent and functional products. To fully realize their potential and bring these benefits into practical healthcare applications, more collaborative research across different fields and stronger industry support are essential.

REFERENCES

[1] Ferdouse F, Holdt SL, Smith R, Murúa P, Yang Z. Marine algae-derived bioactive compounds. *Mar Drugs*. 2021;19(9):499. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC8469996/

[2] Wang HMD, Li XC, Lee DJ, Chang JS. Potential biomedical applications of marine algae. *Bioresour Technol*. 2017;244:1407–1415. Available from: https://doi.org/10.1016/j.biortech.2017.05.198

[3] Zhang X. The ecological role of marine algae in coastal ecosystems. *J Aquac Eng Fish Res*. 2024;10(8):80. Available from: https://doi.org/10.3153/JAEFR.10.08.80

[4] Ecological significance of marine algae. *Mar Biol Ecol*. 2023;12(3):45–67.

[5] Dioscorides P. *De Materia Medica*. Osbourn TA, translator. 2000.

[6] Galen. *On the Natural Faculties*. Translated by Brock AJ. 1916.

[7] Priyanka KR, Rajaram R, Sivakumar SR. A critical review on pharmacological properties of marine macroalgae. *Biomass Conv Bioref*. 2022. Available from: https://doi.org/10.1007/s13399-022-03134-4

[8] Ahmed N, Sheikh MA, Ubaid M, Chauhan P, Kumar K, Choudhary S. Comprehensive exploration of marine algae diversity, bioactive

compounds, health benefits, regulatory issues, and food and drug applications. *Meat Food*. 2024;100163. Available from: https://doi.org/10.1016/j.meafoo.2024.100163

[9] Frazzini S, Rossi L. Anticancer properties of macroalgae: a comprehensive review. *Mar Drugs*. 2022;20(3):182. Available from: https://doi.org/10.3390/md20030182

[10] Shannon E, Abu-Ghannam N. Antibacterial derivatives of marine algae: an overview of pharmacological mechanisms and applications. *Mar Drugs*. 2016;14(4):81. Available from: https://doi.org/10.3390/md14040081

[11] Ghallab DS, Ibrahim RS, Mohyeldin MM, Shawky E. Marine algae: a treasure trove of bioactive anti-inflammatory compounds. *J Ethnopharmacol*. 2022;290:115066. Available from: https://doi.org/10.1016/j.jep.2022.115066

[12] Ersoydan S, Rustemeyer T. Investigating the anti-inflammatory activity of various brown algae species. *Mar Drugs*. 2024;22(10):457. Available from: https://doi.org/10.3390/md22100457

[13] Gamal R, Shreadah MA. Marine microalgae and their industrial biotechnological applications: a review. *J Environ Sci Health A*. 2015;50(13):1235–1247. https://pmc.ncbi.nlm.nih.gov/articles/PMC11387356/