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Potential Applications of Algae for High Value-Added Products

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Abstract

Due to their broad application possibilities in the renewable energy, biopharmaceutical, and nutraceutical industries, microalgae have recently gained significant interest on a global scale. Biofuels, bioactive pharmaceuticals, and food additives can all be produced from microalgae in an environmentally friendly, economically feasible manner. Several microalgae species have been looked into for their potential to become high-value products with exceptional pharmacological and biological properties. They are an ideal biofuel alternative to liquid fossil fuels in terms of price, renewability, and environmental issues. A large amount of atmospheric CO2 can be converted by microalgae into beneficial byproducts including carbohydrates, lipids, and other bioactive compounds. Even though microalgae are viable sources of bioenergy and bioactive value chemicals, there are still several obstacles to be addressed on an industrial scale. This review covered a variety of bioactive substances derived from microalgae that are mostly used in agriculture, animal feed, medicine, pigments, human food, and cosmetics industries.

Index Terms- Algae, Biofuels, bioactive compounds, High Value-added products.

1. Introduction

Microalgae have recently attracted a lot of attention around the world because of their vast range of applications in the renewable energy, biopharmaceutical, and nutraceutical industries. A variety of microalgae species have been studied for their potential as value-added products with outstanding pharmacological and biological properties. In terms of affordability, renewability, and environmental issues, biofuels are a great substitute for liquid fossil fuels. Microalgae can convert atmospheric CO2 into valuable products like carbohydrates, lipids, and other bioactive compounds. Algae are photosynthetic organisms that flourish in a variety of aquatic habitats such as lakes, ponds, rivers, oceans, and even wastewater. They can grow alone or mutually and can survive in a wide range of temperatures, salinities, and pH values, as well as varying light intensities and environments in reservoirs and deserts. Algae are categorized into three groups i.e., Rhodophyta (red algae), Phaeophyta (brown algae), and Chlorophyta (green algae), and based on the size of macroalgae and microalgae. Microalgae are microscopic single cells that can be prokaryotic, like cyanobacteria, or eukaryotic, like green algae. Macroalgae (seaweed) are multicellular, large-size algae that can be seen with the naked eye.

They can also be used to clean wastewater and reduce CO_2 levels in the atmosphere. Microalgae have brought a renewed interest in biorefinery as a renewable and sustainable feedstock for biofuel generation. To improve their potential as a future source of renewable bioproducts, growth enhancement techniques and genetic engineering may be applied. Algae and cyanobacteria have several advantages that make them suitable candidates for the manufacture of biomaterials and value-added products such as (1) the use of water as an electron donor in oxygenic photosynthesis, (2) very high per-acre biomass productivity compared to oily seed crops, (3) ability to resolve food vs. fuels debates as a nonfood feedstock, (4) no need for arable and productive agricultural land for cultivation, (5) adaptation to growth in brackish water, seawater, and wastewater, and (6) production of a broad range of products.

Materials, chemicals, and energies derived from renewable biological resources are known as bioproducts or bio-based products. Microalgae have been recommended as a sustainable alternative for high-value bioproducts such as lipids (particularly triacylglycerides), polyunsaturated fatty acids (PUFAs), sterols, carbohydrates, proteins, polysaccharides, and terpenoids, including carotenoids. Microalgae bioproducts can be employed in a variety of applications, including pharmaceuticals, nutraceuticals, food colouring, animal feed, and biofuel. Oleaginous microalgae, such as *Chlorella sp., Nannochloropsis sp., Scenedesmus sp.,* and *Dunaliella tertiolecta* can accumulate a large number of neutral lipids, which can be up to 20 ~ 80% of the dry cell weight (DCW) [28]. Microalgal lipids (mostly neutral lipids, such as TAGs) have been considered as possible biodiesel sources. Some microalgal species, such as *Crypthecodinium cohnii* [44], *Nannochloropsis oceanic* [48], and *Phaeodactylum tricornutum* [3], can produce high-value long-chain PUFAs (LC-PUFAs), such as ω-3 PUFAs docosahexaenoic acid (DHA, 22:6Δ4,7,10,13,16,19), eicosapentaenoic acid (EPA, 20:5Δ5,8,11,14,17), and α-linolenic acid (ALA, 18:3Δ9,12,15) as well as ω-6 PUFA arachidonic acid (ARA, 20:4Δ5,8,11,14). These essential fatty acids are good for human health. In light of the preceding discussion, the purpose of this review is to establish a framework for the future use of microalgae as a source of biofuel and value-added products.

2. Bioenergy and Microalgae

The world's rapidly rising population continues to raise the global demand for fuel energy. Because of their unsustainable and nonrenewable nature, the intensive use of fossil fuels around the world causes depletion and will bring them close to exhaustion. Consequently, now biofuels are becoming a more viable alternative to fossil fuels around the world. Biofuels are already being produced commercially in several developed countries. Biofuels like biodiesel and bioethanol are proven to be good alternative fuels, and they can be made from a variety of biomass sources, like food crops, crop wastes or fruits, woody plant parts, rubbish, and algae. Biofuels made from biomass have the advantages of being renewable and contributing much less to environmental damage and global warming. Fossil fuels are responsible for 29 gigatons/ year of release of CO_2 with a total of 35.3 billion tons of CO_2 till now [40]. Biofuels, such as algae fuels, have oxygen levels ranging from 10 to 45 per cent and very low sulphur emissions, whereas petroleum-based fuels have nil oxygen levels and substantial sulphur emissions. Biofuels are a non-polluting, locally available, accessible, sustainable, and reliable source of energy. Microalgae-based fuels are environmentally safe, non-toxic, and have a significant potential for CO_2 sequestration. It has been reported that 1 kg of algal biomass is can fix 1.83 kg of CO_2 furthermore some species use SOx and NOx as nutrient flow along with CO_2 [19]. Microalgae as a feedstock for bioenergy production is currently being hailed as the most promising raw material for compensating and balancing the ever-increasing demands for biofuels, food, feed, and important chemical production.

3. Biosynthetic Precursors of some High-Value Bioproducts from Microalgae

Microalgae can absorb CO_2 as a carbon source and trap light energy as an energy source. The CO_2 enter in Calvin cycle in the chloroplast and generate glyceraldehyde 3-phosphate (GAP). GAP could be available for pyruvate production through the glycolytic pathway. Pyruvate is a precursor that can be utilised to produce glucose, starch, fatty acids, and terpenoids. Polyketide derivatives are the most common sources of lipids. Lipids are hydrocarbons with a long chain of C6 to C32 that have a hydrophilic carboxyl group at one end and a methyl group at the other. In naturally occurring fatty acids, these hydrocarbon chains have an even number of carbon atoms. Depending on the presence and number of double bonds, the hydrocarbon chain might be saturated, monounsaturated, or polyunsaturated. Polyunsaturated fatty acids (PUFAs) are more physiologically important than other fatty acid types due to their therapeutic qualities. PUFAs (polyunsaturated fatty acids) involve omega-3 and omega-6 fatty acids. These omega-3 and omega-6 fatty acids are deemed important for human health and must be consumed through diet. The parent fatty acids of the omega-3 and omega-6 fatty acid series are -linoleic acid (ALA, 18:3n-3) and linoleic acid (LA, 18:2n-6), respectively. Omega-3 fatty acids are deemed necessary because they cannot be produced by humans or animals due to a lack of Δ-12 and Δ-15 desaturase enzymes. Because humans and animals are unable to synthesise de novo omega-3 fatty acids, they must obtain them from their diet. Microbial oils can be found in microalgae. These organisms are recognised to be natural producers of omega-3 PUFAs and their sources.

Microalgae can produce C_5 isoprenoid precursors, such as isopentenyl diphosphate (IPP) and its isomer dimethylallyl diphosphate (DMAPP), via the mevalonic acid (MVA) pathway in the cytosol or the 2 C-methyl-D-erythritol 4-phosphate (MEP) pathway in the plastids. Farnesyl pyrophosphate (FPP) (C_{15}) is an important precursor in the biosynthesis of sesquiterpenes, triterpenes, and sterols. Furthermore, geranylgeranyl pyrophosphate (GGPP, C20) is a necessary precursor for several compounds, including gibberellins, chlorophylls, diterpenes, tetraterpenes, and carotenoids.

4. Biofuel from Microalgae

Biofuel is made from organic matter like any other hydrocarbon fuel, which undergoes photosynthesis by photosynthetic bacteria, vascular land plants, and microalgae. Research and development have been ongoing for quite a while since biofuels can be recognized as a viable alternative to traditional fossil fuels like diesel and gasoline. Microalgae biomass can be processed using a variety of technologies, including thermochemical, biochemical, or biological methods.

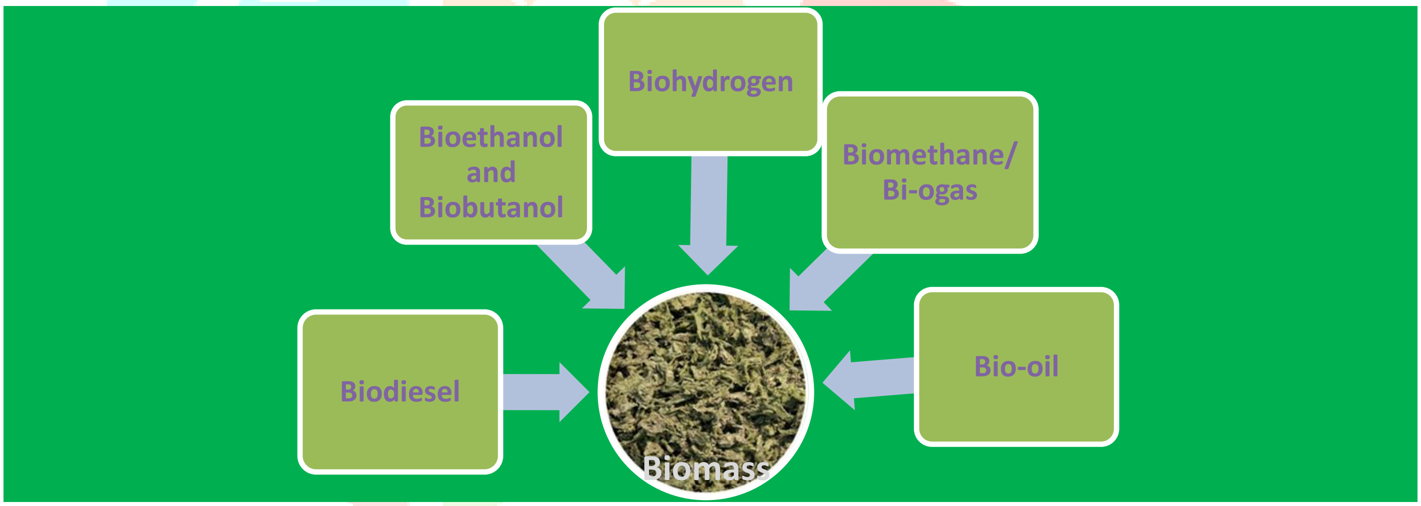

Fig.1. Various Biofuel products from Algal Biomass.

4.1.Microalgae as a Biodiesel Source

Biodiesel is one of the most widely utilised biofuels since it has a high demand and may be used to replace non-renewable fuels in industry and transportation. Biodiesel is a non-toxic, biodegradable, and reusable liquid fuel that may be used in diesel or conventional engines without modification. Transesterification is the most common method for producing biodiesel. Transesterification is the chemical interaction of oil/fat with alcohol to form glycerol and methyl esters, which are frequently facilitated by a catalyst. Because the purification and manufacture of biodiesel from microalgae, as well as esterification and transesterification, need a lot of energy, research has concentrated on how to use energy more efficiently in these processes.

4.2. Microalgae as a Source of Bioethanol and Biobutanol

One of the most common biofuels is bioethanol, which is divided into three categories: sugar and starch bioethanol, lignocellulosic bioethanol, and microalgal bioethanol. Sugarcane is often employed as a raw material for the production of bioethanol due to its abundance and ease. Although biomass and lignocellulosic starch are less expensive, they must be hydrolyzed to yield fermentable sugars. Because of their high carbon content, macroalgal bioethanol can be fermented utilising a variety of microalgae by forming essential or fundamental sugars from polysaccharides. In the manufacture of alcohol, microalgae polysaccharides such as cellulose, agar, starch, laminarin, and mannitol are employed. Microalgae with a lot of starch, like *Chlorella*, *Dunaliella*, *Chlamydomonas*, and *Scenedesmus*, are great for making bioethanol [26]. Brown algae are often used as the main feedstock in modern agriculture due to their high carbohydrate content [27]. Drying, cell rupture, saccharification, and fermentation are all processes in the production of bio alcohol. Although it is conceivable to use directly harvested wet biomass in the generation of bio alcohol, it is thought that dried biomass will perform much better.

4.3. Microalgae as a Source of Biohydrogen

Hydrogen is a clean energy source that is abundant, long-lasting, and cost-effective. Hydrogen could become a sustainable bioenergy source shortly as a result of innovative studies on hydrogen production, processing, and technical advancement. A photobiological reaction involving water and sunlight produces biohydrogen. Water electrolysis, methane (CH_4) reformation by steams; coal gasification, oil and natural gas oxidations, and thermal processes, as well as indirect and direct bio photolysis, are all examples of hydrogen production methods. Organic molecules are converted to hydrogen through photo-fermentation and dark fermentation. To make hydrogen gas, photo fermentation uses the most abundant ingredients, light and water. Unfortunately, this form of hydrogen generation fails because the oxygen released at the same time inhibits the hydrogenase enzyme, halting the hydrogen production mechanism. Fructose, xylose, stringent anaerobes, and oxygen emit hydrogen gas during the dark fermentation process.

4.4. Microalgae as a Source of Biomethane/Biogas

Biomethane/biogas is a biofuel that may be generated from a variety of feedstocks, such as biomass and organic waste, using an anaerobic digestion process. Microalgae biomass, both pre-treated and untreated, as well as leftovers after lipid extraction, can be employed as a methane-producing substrate. Anaerobic digestion of defatted microalgae produces carbon dioxide, methane, and digestate (fertilizer). Before microalgae may start producing methane, they must be pre-treated. Even though using enzymes increases methane productivity significantly, the cost of doing so prohibits it from being used in real-world situations. Crude enzymes can be employed to pretreat microalgae biomass to get around this problem.

4.5. Microalgae as a Source of Bio-oil

Producing crude bio-oil, a black, viscous, and energy-dense fuel, is one common technique to harness algal energy. The pyrolysis and hydrothermal liquefaction processes can be used to make bio-oil from microalgae. It has been reported that the bio-oil yields from several microalgae were 5–25 wt.% higher than their lipid content [8]. Aquatic processing of microalgae biomass is interesting because it minimizes the energy costs of drying. Aldehydes, cresols, and acids are present in the bio-oils chemically. Bio-oils made from lignocellulose biomass by pyrolysis are high in oxygen, but it is also complicated and viscous. As a result, hydrogenation and cracking are required to improve bio-oils.

5. Fine Chemicals and Bioactive Compounds Production from Microalgae

When it comes to non-fuel materials, microalgae play a significant role in industrial product formation. Algal biomass can be used for the production of lipids, proteins, carbohydrates, PUFAs, cellulose, starch, vitamins, food, cosmetics, pesticides, organic fertiliser, livestock feed, animal feed, natural dyes, nutraceuticals, pigments, and even combustion-based electricity generation, are just a few of the industrially significant co-products or value-added products. [16, 47]

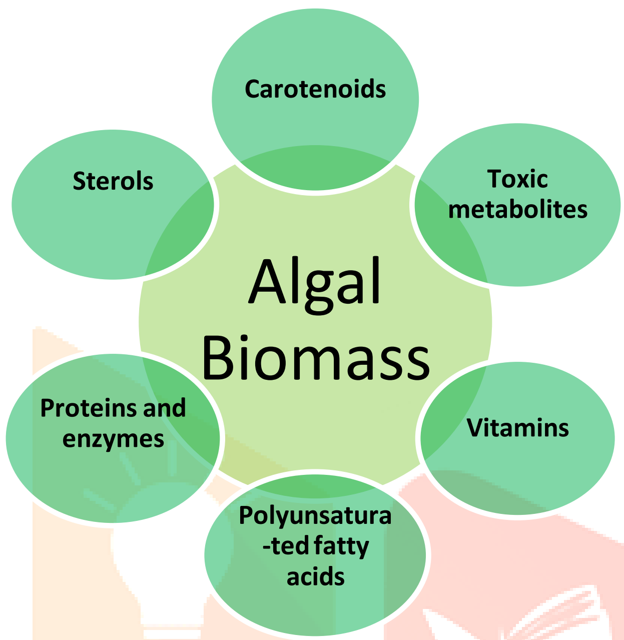

Fig.2. Algal biomass and their various value-added products.

5.1. Microalgae in Agriculture

Microalgae can be employed as biofertilizers, soil modifiers, and feed additives in modern agriculture, making them an environmentally safe alternative to chemical fertilisers. Cultivation of rice inoculated with marine or aquatic microalgae like *Spirulina platensis* and *Chlorella vulgaris* as biofertilizers increased rice yield by 7–20.9 per cent [18]. Microalgae as a soil additive increase root capacity, chlorophyll development, sprout dry weight, and plant height significantly [37,1]. Microalgae boost soil health as a soil supplement by fixing CO_2 and N_2 and secreting extracellular polysaccharides, minimising the cost of macro and micronutrients required for good yields. Auxin, cytokinin, and jasmonic acid are plant growth hormones produced by microalgae that act as biostimulants [21]. Microalgal species have been discovered to boost the plant immune system by producing antimicrobial chemicals that inhibit or kill pathogenic bacteria, fungi, or nematodes, and so could be utilised as a substitute for toxic chemical fungicides.

5.2. Microalgae as a Source of Animal Feed

Microalgae include a wide range of high-quality substances, such as carbohydrates, lipids, and proteins, as well as vitamins, antioxidants, and minerals, demonstrating their utility as aquaculture or animal feed food sources. In general, the microalgae must be of a size acceptable for consumption, have a digestible cell wall, be toxic-free, and have a sufficient number of biological components. Proteins, a major source of human and animal nourishment, constitute 50–70% of microalgae structure [16]. Microalgae are used as commercial feed for many aquatic animals, both marine and freshwater, such as larvae, molluscs, finfish, and adolescent shellfish [40]. Microalgae are also employed to produce the zooplankton that young crustaceans and finfish require as live food. *Spirulina, Isochrysis, Chaetoceros, Chlorella, Nannochloropsis, Tetraselmis, Thalassiosira, and Skeletonema* is the most often employed microalgae species in aquaculture. *Spirulina, Isochrysis, Chaetoceros, Chlorella, Nannochloropsis, Tetraselmis, Thalassiosira, and Skeletonema* have high pigment content and are commonly utilised in aquaculture feed, particularly for tropical fish. Fish fed on Spirulina were found to develop quicker, have better palatability, have more flesh and less fat, and had brighter skin. Small amounts of microalgae biomass added to the feed improve physiological aspects such as gastrointestinal function, illness tolerance, and antiviral and antibacterial action, which improves the animal's development, feed conversion ratio, weight, and overall reproductive performance. Microalgal biomass, which is high in bioactive chemicals and proteins like polyunsaturated fatty acids (PUFAs), especially EPA and DHA, has been demonstrated to improve meat quality in pigs, broilers, and lambs.

5.3. Microalgae as a Source of Medicine

The therapeutic effects of microalgae are incorporated in a variety of human medicinal products, including anticancer, antiviral, antibacterial, antifungal, cardiovascular health, anti-inflammatory, and others [5]. Microalgal bioactive components can be found in medicines that inhibit sickness and encourage well-being, such as pills, tablets, powders, beverages, and gels. Carotenoids are organic pigments found in plants and photosynthetic organisms' chromoplasts and chloroplasts. Over 600 carotenoids are produced naturally by photosynthetic bacteria, plants, and algae, some of which have found commercial applications, such as astaxanthin, lutein, β-carotene, zeaxanthin, lycopene, and bixin. Various microalgae were used to produce commercially viable pigments, such as β-carotene originating from *Dunaliella salina* and *astaxanthin* from *Haematococcus pluvialis* [45]. *Dunaliella salina*, a type of algae, is said to be the best source of β-carotene. One form of the carotenoid present in both freshwater and saltwater algae is astaxanthin. Astaxanthin is a powerful antioxidant with anti-inflammatory, sun protection, anti-ageing, anticancer, and immune system enhancing properties, making it suitable for use in nutraceutical products, food sources, and feed [15]. Astaxanthin prevents UV-induced photo-oxidation occurring in the skin and oxidative degradation in the retina and is used to treat nerve damage correlated with age-related macular degeneration. It also lowers the risk of neurodegenerative disorders like Alzheimer's and Parkinson's disease [51, 17]. It is also known as a natural superfood that can increase stamina and speed up muscle recovery and ultimately boost athletic performance [11]. *Chlorella zofingiensis* and *Haematococcus pluvialis* are commonly used for astaxanthin processing [22,50]. Lutein is a type of carotenoid found in the pigmentation of animal tissues. It is a major nutraceutical that is used as a colourant in pharmaceuticals, cosmetics, and foods. Natural producers of high lutein content, such as *Chlorella protothecoides, Muriellopsis sp., Chlorella zofingiensis,* and *Scenedesmus almeriensis*, have been identified, potentially are making them a good substitute for marigold. Microalgal components have been shown to boost the immune system and lower blood cholesterol levels, making them useful in the treatment of hypercholesterolemia. Taurine, a non-proteinaceous amino acid found in marine red algae, lowers blood cholesterol levels [48]. Several species of microalgae contain 70% protein that can fulfil all essential amino acids for human health [48]. Microalgae consist of long-chain polyunsaturated fatty acids essential for neurological and cardiac function, as well as helping the body combat heart disease, hypertension, cancer, and cholesterol issues [45,47,29]. Microalgae contain a variety of critical fatty acids that can be processed to generate efficient nutritional supplements. *Odontella*, *Porphyridium cruentum*, *Cryptothecodinium cohni*, *Isochrysis galbana*, and *A. platensis* are examples of PUFA-producing microalgae [37]. According to studies, consuming DHA and EPA promotes health by controlling inflammation and lowering the occurrence of cardiovascular diseases, as well as aiding in the growth of the nervous system in children and improving brain function [49,32]. Regulated EPA/AA absorption might be beneficial in the treatment of several diseases and metabolic disorders [37]. Gamma-linolenic acid (GLA) decreases LDL cholesterol in people with hypercholesterolemia, reduces premenstrual syndrome, and cures atopic dermatitis and rheumatoid arthritis. Studies of humans and animals have shown that GLA dietary supplementation suppresses inflammation [49].

5.4. Microalgae as a Source of Pigment

Microalgae contain a wide variety of naturally coloured pigments. They can be used to make food colourants sustainably. Microalgal cultivation is a cost-effective alternative to chemical colourants as a source of natural food colours, as well as being environmentally friendly and safe. Natural algal pigments such as carotenoids, chlorophylls, and phycobiliproteins are precursors to vitamins found in food and animal products, as well as colouring agents in biomaterials, cosmetics, and medications. The majority of microalgae species contain 0.5–1% chlorophyll and 0.1–0.2% carotenoid. Chlorophyll, a pigment essential for photosynthesis, is found in all microalgae. Carotenoids are essential components of oxygenic photosynthesis, acting as light-harvesting pigments or protein folding structural molecules in the photosynthetic apparatus, keeping it stable and playing a key part in commercial microalgal pigment production. Carotenoids derived from economically viable algae are utilised in animal and fish feed, culinary colouring, and cosmetics. Phycobiliproteins are a form of hydrophilic protein that resembles photosynthetic pigments known as phycobilins, which are found mostly in red algae and cyanobacteria. In the health sector, phycobiliproteins are used as anti-inflammatory, anti-allergenic, antioxidant, antiviral, anticancer, and neuroprotective substances, and in other pharmaceutical applications [14]. Phycocyanin, a form of phycobiliprotein produced by *Arthrospira platensis*, is used to colour fermented milk products, carbonated beverages, alcoholic beverages, sweets, ice cream, chewing gum, milkshakes, and fish feed, among other things. The US Food and Drug Administration (FDA) regulate phycocyanin pigment extracted from *Spirulina platensis* used as a colouring pigment in gum, toffee, and other foods [23]. Salmon pigment is made from *Chlorella zofingiensis* [40]. At present, there are two carotenoids (*Dunaliellasalina* producing β-carotene and astaxanthin from *Haematococcus Pluvialis*), one phycobiliprotein (*Arthrospira platensis* producing phycocyanin), and chlorophyll (from *Chlorella Vulgaris*) which are commercially cultivated [36].

5.5. Microalgae as Source of Human Food

Some of the most common microalgal species utilised as supplements to popular food products such as pasta, noodles, cookies, ice cream, bean curd candies, and bread to enhance the nutritive value and health aspects of these foods are Spirulina, Chlorella, and Dunaliella. In several places throughout the world, the chlorella strain is commonly utilised as a food alternative. Alginates are a form of polysaccharide found in brown algae that have been employed as a human food source because of their capacity to absorb contamination, generate short-chain fatty acids, change the properties of bacterial colonies, and inhibit cholesterol absorption. Microalgae such as *Thalassiosira*, *Isochrysis*, *Tetraselmis*, *Chaetoceros*, and *Nannochloropsis*, contain beneficial health additives such as DHA and EPA [16]. DHA is an ingredient in a variety of foods, including infant meals, baby formula, eggs, dairy, bread, and non-alcoholic drinks, because it has been found to have cardioprotective effects in various studies. Cardioprotective effects of DHA extracted from Schizochytrium sp. and *Crypthecodinium cohnii* have been reported. Microalgae have certain properties such as their green colour, which negatively affects consumers' perceptions of taste and consistency and limits their use in everyday goods [12].

5.6. Microalgae as a Source of Cosmetics

Components obtained from microalgae may be of interest to the cosmetics industry for use in personal care products. Cosmetic products use active substances that are particularly suited for different skin types to improve the structure and look of the skin. Antioxidant enzymes present in algal products can help reduce the negative effects of reactive oxygen species, one of the primary causes of ageing. Extracts from microalgae organisms are widely used in the cosmetics industry in various sectors: anti-ageing agents (*Colpomenia*, *Halymenia*, *Padina*, *Polysiphonia*, *Spirulina*), moisturizing and skin softening agents (*Ulva Lactuca*, *Codium tomentosum, Postelsia palmaeformis*), wound healing agents (*Kappaphycus alvarezii)*, and hair growth promoters (*Ecklonia cava*) [45,20]. Microalgae extracts offer potential as antimicrobials in addition to anti-ageing skin care products, broadening the already extensive range of applications in the cosmetics area. It has been reported that eye shadow can be produced from thermophilic blue-green microorganism's pigments as well as pink and purple colours from colourants of red microalgae natural pigments [6,2]. Extracts from *Chlorella vulgaris* have been shown to enhance collagen repair pathways in anti-ageing supplements and cosmeceuticals [43]. Extracts from these microalgae are also used in products to stimulate tissue regeneration and wrinkle reduction. The extracts from *Arthrospira, Nannochloropsis oculata* and *D. salina* microalgae can repair the indications of skin ageing, tighten the skin, and prevent the development of striae [7,9]. Additionally, *Dunaliella tertiolecta* and *Tetraselmis suecica* microalgae may be used to produce vitamin E which is a powerful antioxidant that is commonly utilised in cosmetics [13,10]. Because of the potential application of extracts from microalgae as cosmetics, recently, different industries (Codif, France; Greentech, USA; Pentapharm, Switzerland) have begun to invest in the use of microalgae extract in producing a variety of cosmetic products [34]. Companies have recently filed new patents for innovative topical administrations using exopolysaccharide particles from microorganisms. Solazyme Inc. (San Francisco, CA, USA), for example, has filed new patents for the production of exopolysaccharides by green microalgae (Parachlorella) for the improvement of skin health and beauty. Terravia Holdings, Inc. (San Francisco, CA, USA) just released Golden ChlorellaTM and AlgaPürTM Algae Oils, which it claims will deliver considerable cosmetic benefits to skin and hair.

6. Significant Compounds produced by Microalgae

Source Algae	Compounds	Applications	References
Spirulina Platensis Chlorella Vulgaris	extracellular polysaccharides	used as biofertilizers	[18]
Spirulina Platensis Chlorella Vulgaris	plant growth hormones	used as biostimulants	[21]
Haematococcus pluvialis	Astaxanthin (Natural superfood)	antioxidant, anti-inflammatory, anti-ageing, anticancer,	[45] [15]
Chlorella protothecoides, Muriellopsis* sp., *Chlorella zofingiensis, Scenedesmus almeriensis	Lutein	as a colourant in pharmaceuticals, cosmetics, and foods,	[41]
Dunaliella salina	β-carotene	an ingredient for multivitamins supplements, as an additive in cosmetic formulations, as a colouring agent in animal feed	[35] [30]
Red algae, cyanobacteria	Phycobiliproteins	anti-inflammatory, anti-allergenic, antioxidant, antiviral, anticancer, and neuroprotective substances	[31] [14]
Arthrospira platensis,	Phycocyanin	colouring pigment	[44].

Brown algae	Alginates	used as a human food	[33]
Schizochytrium* sp., *Crypthecodinium cohnii	DHA	cardioprotective effect	[4]
***Phaeodactylum tricornatum Nannochloropsis* sp.**	EPA	food supplements and nutrition	[41]
***Colpomenia* sp., *Halymenia* sp., *Padina* sp., *Polysiphonia* sp., *Spirulina* sp.**	Biomass extract	Anti-ageing agents	[45] [20]
Ulva lactuca Codium tomentosum Postelsia palmaeformis	Biomass extract	moisturizing and skin softening agents	[45] [20]
Kappaphycus alvarezii	Biomass extract	wound healing agents	[45] [20]
Ecklonia cava	Biomass extract	hair growth promoters	[45] [20]
Dunaliella tertiolecta Tetraselmis suecica	vitamin E	powerful antioxidant	[13] [10]

7. Limitations and Challenges in production of High-Value Bioproducts from Microalgae

The majority of microalgae-based bioproduct production systems are achievable at the laboratory scale. However, full implementation of microalgae-based processes is difficult, especially on a large scale and in terms of economic feasibility. Microalgae-based systems must address the difficulties of lowering biomass harvesting and extraction costs through advances in engineering and culture management, reducing waste emissions, and screening strains for high productivity. Microalgal biomass harvesting from growing systems accounts for 20 to 30% of total production costs. Selecting appropriate species with a high growth rate, high productivity of specific bioproducts, and environmental resistance will help optimise microalgae farming even more. However, while molecular techniques have shown considerable promise in increasing the accumulation of bioproducts from microalgae, there is still a long way to go. The major concerns of genetically modified (GM) microalgae relating to human health and environmental consequences are considered restricted. The release of GM microalgae into the environment could have negative ecological consequences such as displacing native microalgae, breaking food chains, changing microalgal diversity in the ecosystem, forming dangerous algal blooms, and producing toxins and allergies, among other things. Microalgae are used as a human food supplement or animal feed in some cases. As a result, the release of GM microalgae may endanger human health.

8. Conclusions

Microalgae can generate biofuels and a wide range of high-value bioproducts. Microalgae-based technologies for bioproduct production from the laboratory to the commercial-scale will be developed and fine-tuned shortly by overcoming the associated hurdles and limits.

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