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Industrial and Biotechnological Applications of Algae: A Review

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Abstract:

Algae are a class of photosynthetic organisms found in both marine and freshwaters habitats. As these organisms have a short doubling time, they are considered among fastest growing creatures. They have different pathways to fix atmospheric carbon dioxide and to efficiently utilize the nutrients to convert it into biomass. In few years, a focus has been shifted towards these organisms due to their food and fuel production capability. In fuel industry algae biofuels have been emerged as a clean, nature friendly, cost effective solution to other fuels. Algae fuels are categorized into bio-ethanol, biogas, bio-hydrogen, biodiesel and bio-oil. Algae as a food have been explored for different applications as in production of single cell proteins, pigments, bioactive substances, pharmaceuticals and cosmetics. The present review has been prepared to throw a light on enormous applications of algae as food and fuel and also to provide some information about different commercially available algae products.

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Introduction

Algae are being used from a long period of time due to their high biomass production rate in different extreme habitats as compared to cereal based crops. Algae are categorized as third generation biofuels due to their many advantages over different agricultural based crops. The concept of using algae for energy production is not new. Till now the cost of production of algae biofuels is very high due to its limited cultivation systems. But with passage of time, new technologies are being developed for cultivation of algae over a large scale all over year, under different climatic zones varying from tropical to moderate climate.

Algae have a potential to fix atmospheric carbon rich gases, due to which they act as quenchers of carbon dioxide and nitrogen oxides released from different sources [1,2]. About 1 kg of algae biomass is capable to fix approximately 1.8 kg of carbon dioxide. Algae can use wastewater containing high amount of nitrogen and phosphorus for their growth with benefits of providing biofuels and also helping to get rid from excess nitrogen and phosphorus [4,5,6].

A wide range of metabolites from algae containing various bioactive compounds are yet to be exploited. *Haematococcus pluvialis*, a freshwater algae is a source for producing commercially available astaxanthin pigment, whereas *Chlorella vulgaris* as a food supplement and algae *Dunaliella* species for β-carotene production. Marine biomass could also be used as a feedstock to produce different fuels as bioelectricity by co-firing, bioethanol, biodiesel, bio-oil by pyrolysis and biomethane via fermentation. The market potential of algal biofuels is vast due to their sustainable technology to replace fossil fuels. Algae mainly contain over 50% starch which can be converted into ethanol. The cell walls of algae are mainly composed of different carbohydrates due to which they can be used as a raw material in similar manner as in cellulosic ethanol. By the process of pyrolysis, algal biomass can be converted into organic liquids, acetic acid, acetone, and methanol, various clean and cost effective gaseous products [7]. The different criteria for algae to fit as a candidate for bioenergy production includes: high biomass productivity, easy harvesting by mechanical techniques, cost effective production than other biomass present.

In present era, the cultivation cost of algal biomass is very high for production of biofuels only. Therefore, the need of hour is to compensate the cost of biofuel production from other byproducts that can be produced from algae. Currently various outputs from agriculture and food produced by different sustainable strategies are in market. The production of various co-products along with biofuels will make the process more feasible, cheap and expected to provide new opportunities due to its positive effect on sustainability [8].

Different Algae based Fuels:

In modern era, fossil fuel depletion and global warming has led to the world's eyes on production of bioenergy from algal biomass. Therefore the key plans to reduce poverty are increased access and energy security. Currently, the only alternative to replace the fossil fuel consumption and dependency is the production of biofuels from algal biomass. (Figure 1)

Biofuels

The term biofuel refers to any type of solid, liquid, or gaseous fuels which can be derived from renewable raw materials. The key points for any conversion process are form and quantity of biomass, kind of energy and economic return from the product [9]. Agricultural crops are classified as first generation biofuels due to their use for food or feed, but there is always a race between food and fuel to produce enough biofuel to contribute a large portion towards total fuel consumption. In comparison to biofuels produced from agricultural feedstock, algae cultivation does not occupy agricultural land to compete with agriculture. With the combined benefits of large biomass productivity, wastewater treatment, all year production, chemical composition of algae, oil content of algae can be controlled by change of algae cultivation techniques.

Bio-Oil

Bio-oils are produced by a process called thermo-chemical conversion which in absence of oxygen converts biomass into oil along with char and gas at very high temperature. Bio-oils are quite similar to petroleum oils due to which they can be used as a substitute [11]. The bio-oil formation process is categorized into two steps: pyrolysis and thermo-chemical liquefaction [12]. Pyrolysis is performed at a very high temperature

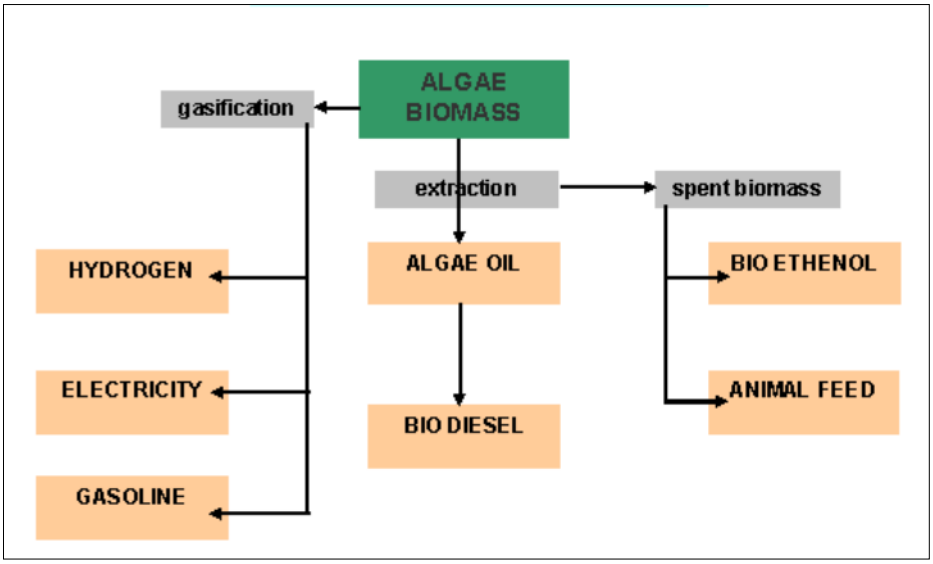

Fig. 1 Energy production pathway [10]

(350-530°C) for production of a liquid, a gaseous and solid part. The liquid part is made up of an aqueous and a non-aqueous phase called bio-oil or tar and biomass is dried. During thermo-chemical liquefaction, wet biomass is hold upon lower temperature and high pressure of about 300°C and 10 MPa respectively.

The bio-oil contains various organic compounds accumulated as lipids, proteins, carbohydrates in algae and as compare to lipids present in algae, and amount of yield is high. A number of microalgae have been investigated to produce bio-oil via pyrolysis or thermal liquefaction [13. 14, 15, 16, 17]; for example: formation of different hydrocarbons by pyrolysis of *Dunaliella* sp. biomass. Bio-oil yields from microalgae have been reported up to 41% for *Spirulina* [18], about 24%–45% for microalgae *Scenedesmus* [19], about 37% for *Dunaliella* [20] and up to 49% for *Desmodesmus* [21]. Bio-oil yield from macroalgal biomass has been reported up to 23% after liquefaction process [22, 23] while in macrolagal biomass *Laminaria saccharina* it accounts for 63% energy restoration[24] and *Laminaria saccharina* yielded 79% oil after hydrothermal liquefaction [25], Whereas freshwater macroalgae, *Oedogonium* and *Cladophora* yielded only 26% and 20%, respectively [26].

Biodiesel

In Recent years study of biodiesel has been widely recognized and it is mostly produced from oil seed crops like soybean oil, palm oil and rapeseed oil [27]. The production cost of biodiesel mainly depends upon type of raw material used, as it is a critical factor accounting for 50-85 % of total fuel price. For production of cost effective biodiesel, assessment of feedstock is important in terms of productivity, quality and exploitation of by-products which should be taken into consideration [28, 29]. The process of conversion of raw material lipids mainly triacyleglycerols/free fatty acids into non-toxic and ecofriendly biodiesel is called transesterification. The crude algal oil having high viscosity is converted into low molecular weight compounds in form of fatty acid alkyl esters. During the process of transesterification, crude oil in presence of a catalyst reacts with an alcohol usually methanol and fatty acid methyl esters (FAME) are formed as final product along with glycerol. The application of acid catalyst has been regarded as advantageous [30], but alkali catalyst is used commercially due to its fast nature up to 400 times as compared to acid catalyst [31].

Chlorella vulgaris and *Chlorella protothecoides* are two main species; containing high oil content has been studied by many workers for production of biodiesel. Gülyurt et al., [32] evaluated the potential of *Chlorella protothecoides* for Biodiesel Production Microwave-Assisted Transesterification. Transesterification was performed with *Chlorella protothecoides* oil methanol, and potassium hydroxide as the catalyst. Methanol:oil ratio, reaction time and catalyst:oil ratio

were investigated as process parameters affected methyl ester yield. 9:1 methanol/oil molar ratio, 1.5% KOH catalyst/oil ratio and 10 min were optimum conditions for production of highest biodiesel yield.

Microalgal biodiesel is mainly composed of unsaturated fatty acids [33]. The algal biomass from wastewater contains a mixture of various algae and hence different fatty acid profiles can be obtained. Using a mixture of different systems, Bjerk [43] had produced biodiesel from algae *Chlorella* sp., *Euglena* sp., *Spirogyra* sp., *Scenedesmus* sp., *Desmodesmus* sp., *Pseudokirchneriella* sp., *Phormidium* sp. and *Nitzschia* sp..

Biohydrogen

The diversity of biofuel sources has become an urgent energy issue. In current years, a much attention has been paid towards the bio-hydrogen production. But still, production of bio-hydrogen on large scale is not feasible due to costly process and low biomass concentration. In some studies it has been reported that exposing some algae species to various environmental stress like depriving light in algae, could trigger appreciable amount of hydrogen gas. But this technology is still in its beginning stage and process can be developed or improved till higher level [35]. To overview the current scenario of hydrogen production from algae, we refer to the work of many researchers [36, 37]. The three pathways suggested for the production of hydrogen are: 1. Direct photolysis 2. Indirect photolysis 2. ATP driven pathway. Direct photolysis is made feasible only when produced hydrogen and oxygen are continuously removed. In this process, photosynthesis and water splitting are linked, leading to production of hydrogen and oxygen together, which results in bigger security risks, also increasing the cost for separation of hydrogen and oxygen. Furthermore, the hydrogenase enzyme used in process are very oxygen sensitize. Due to these reasons, indirect processes are favored mostly. Under anaerobic and sulfur limited environment, starch contained in cell walls of algae converted into hydrogen up to some extent. In most of the studies it has been found that cyanobacteria are main producers of biohydrogen through biological approach, hydrogenase and nitrogenase enzymes act as catalyst in this process [38].

Biomethane Production

In these days, worldwide production of biogas from biomass is gaining importance. An anaerobic digester contains synergistic microbial populations, which convert algal organic compounds (lipid, protein, carbohydrate) to methane and carbon dioxide. Methane is widely used both as a fuel and chemical feedstock. Chynoweth et al. [40] investigated the potential of different feedstocks such as algae, wood, grass, soild waste for biomethane production and found algae biomass as potential candidate for production of biomethane. The biomass productivity of algae is generally higher than land plants, but its growth is influenced by limiting of different nutrients. Wang et al., [41] examined the thermal pretreatment of microalgae for enhancement of biomethane production by using *Chlorella* sp.. Methane yields from untreated algae were 155 mL g^{-1} VS_{add}, while thermal pretreatment at 70 °C and 90 °C for 0.5 h increased the methane yield by 37% and 48%, respectively. Thermal pretreatment at 121 °C for 0.3 h resulted in the highest methane yield (322 mL g^{-1} VS_{add}), which was 108% higher than the untreated algae.

Bioethanol

Bioethanol production from algae has gained unusual importance due to its high biomass productivity, diversity, variable chemical composition, high photosynthetic rates of these organisms. Algae are the optimal source for production of bioethanol due to large amount of carbohydrates/polysaccharides and thin cellulose walls. Commonly two processes are used for production of bioethanol from algae, Fermentation and gasification [42]. In various countries, commercial ethanol is produced from sugary and starchy crops on a large scale by fermentation. The biomass is grinded, and the starch is converted to sugars by different means. The starch of microalgae is released from the cells with the aid of enzyme, acid, alkali and yeast, *Saccharomycess cerevisiae* is added to initiate fermentation and sugar is converted to ethanol [43]. The final product from fermentation i.e. ethanol is then drained and pumped to holding tank attached to a distillation unit.

Ueno et al., [44] has examined the potential of marine green alga *Chlorococcum littorale* to produce ethanol under dark fermentation and about 27% of starch contained in algal cells was used within 24 hrs at 25 ^{0}C. John et al., [45] assessed the feedstock potential of algal biomass to produce bioethanol and to encourage

its use as renewable biofuel for providing tenable option. Examples of green algae employed for bioethanol are: *Dunaliella, Chlorella, Chlamydomonas, Arthrospira, Sargassum, Spirulina*, *Gracilaria, Prymnesium parvum, Euglena gracilis* and *Scenedesmus.* El-Sayed et al., [46] assessed the bioethanol potential from seaweed *Ulva lactua* by fermentation with yeast. The optimization of bioethanol process was done by Plackett-Burman experimental design followed by immobilization technique on supported solid materials. The results of the experiment showed that the sugar concentration, pH level and the inoculums size have a significant effect on the bioethanol production by *S. cerevisiae* with conversion efficiency of 47.1% while immobilized yeast showed conversion efficiency of 52%. .

Obata et al., [47] studied the feasibility of producing bioethanol from brown seaweeds (*Ascophylum nodosum* and *Laminaria digitata*) pretreated and hydrolyzed by dilute sulphuric acid and commercially available enzymes. Large amount of fermentable sugars were obtained with glucose and rhamnose being the predominant sugars, respectively. Fermentation of the resultant seaweed sugars was performed using two non-conventional yeast strains: *Scheffersomyces (Pichia) stipitis* and *Kluyveromyces marxianu* Although the yields of ethanol were quite low (at around 6 g/L), macroalgal ethanol production was slightly higher using *K. marxianus* compared with *S. stipitis.*

Yoza and Masutani, [48] have studied that, acid pretreatment can release up to 49% of sugars from algal biomass, whereas enzymatic hydrolysis can release up to only 20% of sugars based on its dry weight. For *Ulva lactuca*, ethanol yields was reduced even after release of sugars after hydrothermal pretreatment, but the yield was enhanced by the mechanical pressing up to 0.14 gg^{-1} dry matter due to removal of inhibitors formed during fermentation [49]. Among all algae (brown, green, red algae) which can be converted into ethanol by fermentation, brown algae is considered as a potential feedstock for ethanol production due to high carbohydrate content and ease of cultivation [50]. *Laminaria hyperborean* contains Laminarin and mannitol which underwent fermentation to produce large amount of ethanol by yeast, *Pichia angophorae* [51]. The fermentation of red algae has also been reported, using acid hydrolysis agar was converted into sugars, but ethanol yield was low as up to 45% theoretical yield maximum. The fermentation of seaweed produces ethanol yield between 0.08 and 0.12 $kgkg^{-1}$ dry seaweed, depending upon the genera of algae and different methods for pretreatment and hydrolysis [52].

Wargacki et al., [53] investigated the ethanol yield of a dry sea weed which was found up to 0.281 gg^{-1} with 80% efficiency higher than previous experimental yields, another worker Aizawa et al., [54] have proposed an ethanol yield of 0.296 gg^{-1} dry seaweed for commercial purpose. Still, a conversion efficiency of 50% for ethanol from seaweed is a challenging task and has not been seen at scale. A current investigation has achieved a potential ethanol yield of approximately 90 litres $tone^{-1}$ of dried macroalgae, but this is low in comparison to land based crops for biofuel production [55].

Horn et al. [56] from their study have come to a point that production of ethanol from brown seaweed needs higher ethanol yields for industrial process and application of all ingredients of seaweed for non fuel based products also. In Brazil, bioethanol is commercial-ly used as ethanol or mixture of ethanol and petroleum in 86% of sold cars [57]. But still, there are many limitations of bioethanol as low vapor pressure, low energy density and low flame luminosity [58].

Biobutanol Production

In Asia, Europe and South America, algae cultivation is mainly accomplished for bioethanol and biogas production, whereas in USA, algae are gaining attention for biobutanol production. Since 100 years, butanol has been used as a fuel in transportation and has been recommended as a potential candidate for biofuel, not only to improvise, but to take place of ethanol as petroleum additive due to its low vapor pressure and high energy density [59]. The bacteria used in butanol production not only digest starch and sugars but also utilize cellulose present in algal biomass; therefore butanol production could be as economic as ethanol [60]. By anaerobic fermentation many *Clostridium* sp. are capable of yielding acetone, butanol and ethanol (ABE) by utilizing both hexoses and pentoses sugars by a process called as ABE fermentation [61], but limitation of butanol is inhibition of fermentation leading to less yield and productivity. Butanol has been produced from fermentation of algae *Ulva Lactuca* by *Clostridium* strains, but butanol yield is

lower up to 0.16 g butanol g^{-1} than ethanol yield under similar conditions [49]. *Ulva lactuca* used as a feedstock for fermentation by *Clostridium,* was pretreated with hot water followed by enzymatic hydrolysis by commercial cellulases for production of acetone, butanol and ethanol (ABE) with a yield of 0.35 g ABE g^{-1} sugar [61]. However these results determined the potential of seaweed, *Ulva lactuca*, as a feedstock for ABE fermentation, but this was projected for consecutive production of 1, 2 propanediol (propylene glycol) in a seaweed biorefinery as a replacement to fossil fuel derived products rather than just a root for butanol as fuel. Macrolagae *Ulva* extracted from Jamaica Bay, New York City, was used for production of butanol on a pilot scale from saccharification of sugars [59]. In a study on Brown algae, *Saccharina* butanol fermentation from acid treated organic matter was determined, but the yields were low as up to 0.12 g g^{-1} extracted soluble solids. The main fermentation products derived from laminarin were mannitol and glucose but a major portion of alginates was obstinate and did not undergo fermentation process. Gao et al., [60] studied butanol fermentation from microalgae-derived carbohydrates after ionic liquid extraction to compare between ionic liquid extracted algae (ILEA) and hexane extracted algae (HEA) for acetone, butanol, and ethanol (ABE) fermentation. Direct ABE fermentation of ILEA and HEA showed a butanol titer of 4.99 and 6.63 g L1, respectively, with a feasibility of producing biodiesel and butanol from a single feedstock for reducing the feedstock cost of each process.

Algae-based Non-Energy Options

The application of algae is practically infinite for number of products, due to its large diversity and changes in chemical composition influenced by different cultivation systems. Till now, the field of algae based products is very narrow due to untappment of this natural resource. There are many factors for this: economic limit, approval of new products by regulating authorities [63], non awareness about products [62], lack of knowledge for algae cultivation, and lack of investments for establishing large scale facilities. From bulk of commercial products available from algae, most products as food, alginates are derivatives of seaweed and moderately derived from natural populations than cultivated. (Table 1)

Pharmaceuticals

Algae are rich sources of peculiar biologically active compounds including primary and secondary metabolites, which could be used as a potential candidate of interest for pharmaceutical sector [65]. The presence of various bioactive compounds in algae is anticipated due to inhabitation of these organisms in natural aquatic communities, where an inhibitory competition occurs between producers and consumers in same niche. Microalgae are source of immense bioactive compounds that can be exploited for commercial applications. Algae provide a wide range of pharmacy products, proteins, vaccines, nutrients that otherwise are not available or are very costly to produce from animal and plant sources [66, 67]. Various pharmaceutical products from microalgae has high value but its commercialization is still in its infancy and but in near future can be seen as a gateway to multibillion dollar industry. Microalgae have a great genetic potential for various bioactive agents. This proven ability of microalgae to produce these compounds places these microorganisms in the biotechnological spotlight for

Table 1. Useful substances present in algae [64].

S.No.	Natural substances present in algae	Different compounds derived from algae
1.	Pigments	Astaxanthin, lutein, zeaxanthin, canthaxanthin, chlorophyll, phycocyanin, phycoerythrin, fucoxanthin
2.	Carotenoids	β-carotene
3.	Polyunsaturated fatty acids (PUFAs)	DHA, EPA, ARA, GAL
4.	Vitamins	Biotin, riboflavin, nicotinic acid, pantothenate, folic acid
5.	Antioxidants	Catalases, polyphenols, superoxide dismutase, tocopherols
6.	Other	Antimicrobial compounds, toxic products, aminoacids, proteins

applications and commercialization as in the pharmaceutical industry [68]. Algae have also been examined as vitamin and vitamin precursor sources such as ascorbic acid, riboflavin and tocopherol. Yet only few micro-algal species have been examined for various pharmaceuticals and nutraceuticals [69]. But large diversity of micro-algae makes it a potential candidate for discovery of various new metabolites and high value compounds.

Various unicellular algae like *Chlorella vulgaris, Chlamydomonas pyrenoidosa* have shown antibacterial activity against many pathogens including gram positive and gram negative bacteria from its cell extract and extracts of growth media. Few reports of *in vitro* antifungal activities from extracts of green algae and diatoms have also been attained. Some blue green algae and microalgae such as *Ochromonas sp.*, *Prymnesium parvum* are capable of producing toxic substances having immense potential in pharmaceutical [70, 71]. Many Cyanobacteria sp. are admitted to outcome intracellular and extracellular metabolites with a wide array of biological activities like antibacterial, antifungal and antiviral activity [72]. (Table 2)

Antiviral Activity of Microalgal Compounds

There is an urgent need to investigate the antiviral compounds which can be derived from microalgae. For example, Out of 600 cultures of Cyanobacteria, different extracts were screened for inhibition of cellular infections like HIV-1 and HSV-2, but showed only success rate of 10%. Patterson *et al.,* [74] isolated a new compound from cynaobacteria named cyanovirin-N, which was demonstrated as a powerful virucidal agent against HIV, by blocking the interaction of viral glycoprotein gp120 with CD4 [75]. There is latent of developing a relevant vaginal microbicide against HIV based on this compound [76].

Spirulina platensis showed antiviral activity against various viruses as Human cytomegalo viruses, Herpes simplex and measles virus by blocking their entry due to the presence of sulphur containing polysaccharide [77, 78]. Moreover the enhanced antiviral activity due to sulphur containing polysaccharides has also been shown by a red alga *Porphyridium* by blocking the adsorption of virions against HSV-1, HSV-2 [79].

Anticancer Activity of Microalgal Compounds

One of the compounds which are intended to focus from microalgae is various bioactive compounds having anticancer activities. About 1000 extracts were screened from cyanobacteria for antineoplastic activity isolated from surroundings. This activity was shown due to presence of inhibitors on differentiation of human leukemic cells and a success rate of 7% was recorded [80]. In other reports, a marine microalga containing various extracts was studied using mechanism based assays like various enzymes such as ptotein kinase C and protein tyrosine kinase [81]. A algae named as *Poteriochromonas malhamensis* has shown inhibition of enzyme activity, protein tyrosine kinase due to presence of a novel compound chlorosulfolipid. There are many cyanobacteria which are promising producers of bioactive compounds and capable of destroying cancer cells by process of apoptosis, affecting cell signaling by activation of signaling enzymes of protein kinase C family [82]. These compounds are more effective against implanted lymphocytic leukaemia and lung carcinoma [83]. A metabolite named cryptophycin with higher anticancer activity was screened from *Nostoc* ATCC 53789 [84] whereas a protein serine inhibitor named scytonemin isolated from *Stigonema*, may

Table 2: Biotechnological applications of bioactive compounds from algae [64]

S.No.	Algae Specis	Different compounds	uses
1.	*Spirulina platensis*	Phycocyanins	Nutraceuticals, cosmetics
2.	*Chlorella vulgaris*	Ascorbic acid	Health food, food supplement, food surrogate
3.	*Haematococcus pluvialis*	Carotenoids, astaxanthin	Nutraceuticals,, pharmaceuticals, additives
4.	*Odontella aurita*	Fatty acids	Pharmaceuticals, cosmetics, baby food
5.	*Porphyridium cruentum*	Polysaccharides	Pharmaceuticals, cosmetics,
6.	*Dunaliella salina*	Carotenoids	Nutraceuticals,, food supplement, feed

provide an admirable drug with antiproliferative and antiinflammatory activities [85].

Cosmetics

Microalgal species like *Arthrospira* and *Chlorella* are well established players in the skin care market and some companies like LVMH, Paris, France and Daniel Jouvance, Carnac, France have landed in their own microalgal cultivation systems. Microalgal extracts are part of various cosmetics such as anti-aging cream, rejuvenating care products, sun protectants and hair care products [86]. Due to awareness about skin cancer and photoaging process due to sun exposure, an increased consumption of various sunscreen products has been seen in the last decades.

The use of amino acids like mycosporine, due to their efficient and natural UV blocker in sunscreen is attracting commercial attention. Many microalgae produce metabolites such as amino acids sporopollenin, , scytonemin and mycosporine to guard them from UV radiations, but allowing passage to visible radiations involved in photosynthesis [87].Various algae components are generally used as thickening agents, water-binding agents and antioxidants [88]. Microalgae extracts are present in various face and skin care products. Generally species like *Chondrus crispus*, *Ascophyllum nodosum*, *Alaria esculenta*, *Spirulina platensis*, *Nannochloropsis oculata*, *Chlorella vulgaris* and *Dunaliella salina* are used in cosmetics. Various beauty products from *Spirulina* includes: *Spirulina* firming algae mask by Optimum Derma Aciditate for improving moisture balance and to increase skin's immunity; *Spirulina* Whitening Facial Mask by Ferenes Cosmetics containing proteins and herbal extracts for improving skin complexion and reducing wrinkles without any side-effect; *Spirulina* Facial Scrub by Ferenes Cosmetics containing quality ingredients and herbs for removal of dead skin cells and as a cleanser to energize the face. Codif Recherche & Nature (Paris, France) has marketed a *Phormidium persicinum* product Phormiskin Bioprotech G, which has unique photo-protective property [89]. (Table 3)

Pigments

A large number of pigments associated with light occurrence are found in microalgae. Expect chlorophyll as primary photosynthetic compound, the important ones are phycobiliproteins and carotenoids. Carotenoids extracted from microalgae have various applications in market: β-carotene from *Dunaliella* as vitamin supplement in health foods, Lutein, zeaxanthin and canthaxanthin for pharmaceutical uses and chicken skin colouration and Astaxanthin for aquaculture to provide naturally red colour for some fishes like salmon, extracted from *Haematococcus.*The phycobiliproteins like phycocyanin and phycoerythrin which are unique in algae are already in use as food and cosmetics applications [90, 91].

The antioxidant activity of carotenoids is of high importance for human use. Antioxidants show anti-cancer effects due to their role as free radicals scavengers. Among different natural anti-oxidants, astaxanthin is of high potential. Due to its antioxidant effect and role as vitamin A precursor, nowadays β-carotene in used in health foods. Pigments extracted from microalgae have commercial uses as natural food

Table 3: Sources of UV-screening compounds from different algae [64]

S.No.	UV screening compound	Algae
1.	**Sporopollenin**	Characium terrestre, Coelastrum microporum, Enallax coelastroides, Scenedesmus sp., Scotiellopsis rubescens, Dunaliella salina, Chlorella fusca
2.	**Scytonemin**	Chlorogloeopsis sp., Calothrix sp., Scytonema sp., Nostoc commune , Nostoc punctiforme
3.	**Mycosporines**	Ankistrodesmus spiralis, Chlorella minutissima, Chlorella sorokiniana, Dunaliella tertiolecta, Isochrysis sp., Corethron cri-ophilum, Stellarima microtrias, Alexandrium catenella

colorants and cosmetic ingredients. There are number of algae which contain appreciable amount of carotene except β-carotene. β-carotene is commonly known as a food colorant or colour enhancer in fish flesh, yolk of eggs to improve the health and fertility of grain fed cattle [92].

β-Carotene

Carotenoids are generally employed as natural food colouring agents, additives for cattle feeds and in various cosmetics. In terms of nutritional important, various carotenoids such as β-carotene act as provitamin A [68]. Many physical properties of natural β-carotene make it a superior candidate than synthetic compounds. β-Carotene is specifically a fat soluble. Recently National Cancer Institute declared β-carotene as anticarcinogenic; various other investigations have also found the effective nature of β-carotene for controlling cholesterol and preventing the risks of heart disease. Such new studies make β-carotene as a potential candidate to hopefully boost the order of product in commercial sector.

The application of microalgae as food colorants is restricted, because of non-photo stability of food colorants and bleaching of colour with heating. In exception to all these disadvantages, the promising market for microalgae derived food colorants is boundless. Microalgae *Dunaliella salina* is cultivated for β-carotene, a photosynthetic pigment. The uses of β-Carotene are: as orange dye and vitamin C supplement. Many countries like Australia, Israel, USA and China hve established various commercial plants for cultivating this microalgae [93, 94]. β -carotene derived from *Dunaliella* has more antioxidant property in comparison to synthetic β-carotene because the latter is comprised of only trans-isomers while algae products have both cis and trans isomers [95].

Astaxanthin

A different carotenoid from microalgae is astaxanthin which has industrial applications. This pigment is a keto-carotenoid, mainly derived from alga *Haematococcus pluvialis* and produced during unfavorable conditions, when thin flagellated algae cell walls changes to red thick walled resting stages due to 4 -5% dry weight [96]. This pigment is generally used as food colorant, feed additive for poultry industry and as feed additive for fishes like salmon, trout and shrimp [96]. The aquaculture market of this pigment is net US$200 million annually along with average price of US$2,500/kg [97]. Currently, astaxanthin in form of encapsulated nutraceutical has been sold for human use [98]. Due to its antioxidant activity, this product has many health benefits about 100 times greater than tocopherol [99].Various reports have shown the positive effects of astaxanthin against various diseases e.g. cancer, metabolic disorders, diabetes, eyes diseases and neurogenerative disorders [100].

Phycobiliproteins

The water soluble accessory photosynthetic pigments found in different types of algae such as cyanobacteria, rhodophytes cryptophytes, glaucophytes and commonly known as phycobiliproteins. These are divided into three main categories, 1. phycocyanin 2. allophycocyanin 3. phycoerythrin, differing only in their spectral properties.

The amount of various elements like phycobiliproteins in algae; alter with environmental parameters like intensity of light and spectral quality of light. For example, *Spirulina platensis* when grown at various light intensities, the amount of phycocyanin varies from 11 to 12.7% dry weight [101]. *Spirulina* and *Porphyridium* are two common microalgae, which are commercially exploited for production of phycobiliproteins. These pigments have main potential in food as natural dyes, cosmetic products and diagnostic tools in biomedical research as fluorescent markers [102]. For example, pigment phycocyanin is advertised under a brand name called Lina blue by Dainippon Ink and Chemicals for use in popsicles, candies, cold drinks, dairy products and chewing gum. The price of phycobiliproteins vary from US$ 3 to US$ 1500/ mg for some cross linked pigments [103].

High-Value Molecules

Out of 30,000 known species of microalgae, only a few are harnessed for production of high value compounds such as pigments or proteins. Currently microalgae represent itself as a hidden source of various new bioactive compounds. Due to their large biodiversity, studies related to exploration of various novel bioactive compounds can be viewed as an endless ground. The important sources of various bioactive lipid compounds are marine microalgae with percentage of polyunsaturated fatty acids (PUFA), effective against

numerous diseases. The prevention of several diseases including cardiovascular disorders, cancer, asthma, arthritis, kidney and skin disorders, depression and schizophrenia has also been shown by polyunsaturated fatty acids (PUFA) like linolenic acid, eicosapentaenoic acid (EPA), docosapentaenoic acid (DPA) and docosahexaenoic acid (DHA). Among various algae species, *Dunaliella* sp., *Chlorella* sp. and *Spirulina* sp. are major producers of high value compounds such as proteins, lipids and pigments [104, 105, 106]. (Table 4)

Algae-derived compounds for human usage

The use of algae as a food has been dated back to 2500 year ago in Chinese literature [108]. Many macroalgae (seaweeds) are consumed in various parts of Asia as food directly and edible in small amount by native people of countries like Africa, South America and Mexico due to their vitamins and nutritional value [109]. They can also be added into different foods like pastas, snacks, gums, beverages, noodles, cookies [110, 111]. A blue green alga named *Spirulina platensis* is acquiring worldwide attention as food additive due to its high nutritional value as a food to human. It has been demonstrated as a rich source of proteins [112], polyunsaturated fatty acids [113], pigments [114, 115], vitamins and phenolics [112, 116]. These days *Chlorella* is also being majorly sold out in food store and as a fish feed, like *Spirulina* [117]. Currently, the microalgal market is ruled by *Chlorella* and *Spirulina* [118, 68], due to their high protein value, nutritional value and ease of growing. Their biomass is sold as tablets, capsules and liquids, to be used as nutritional supplement [118]. The biomass of microalgae composed of three major portions: proteins, carbohydrates, and lipids [119]. In the table 5, compositional analysis of various microalgal biomass in terms of main components is given.

Table 4. Various high-value compounds derived from microalgae [107]

S.No.	Product group	Applications	Examples (producer)
1.	Phycobiliproteins	Pigments, cosmetics, vitamins	Phycocyanin (Spirulina platensis) β carotene (Dunaliella salina) astaxanthin (Haematococcus pluvialis)
2.	Polyunsaturated fatty acids (PUFAs)	Nutraceuticals, food supplements	EPA-(Chlorella minutissima) DHA-(Schizochytrium sp.)
3.	Vitamins	Nutrition	Biotin -(Euglena gracilis) α-tocopherol) -(Euglena gracilisa Vitamin C- (Prototheca moriformis)

Table 5. Commercialization of important microalgae for nutrition (Adapted from 68, 111, 120]

S.No.	Algae	Algae based companies	Different algae products
1.	*Spirulina* (*Arthrosphira*)	Hainan Simai Pharmacy Co. (China) Earthrise Nutritionals (California, USA) Cyanotech Corp. (Hawaii, USA)	powders, tablets, powders, tablets, powders, beverages, tablets, chips, pasta
2.	*Chlorella*	Taiwan Chlorella Manufacturing Co. (Taiwan)	tablets, powders, nectar, noodles, powders
3.	*Dunaliella salina*	Cognis Nutrition and Health (Australia)	powders b-carotene

Fertilizer

Both macro- and microalgae contain numerous compounds to promote germination, leaf or stem growth, flowering and can also be used as a biological protectants agent against plant diseases [68] and are used in various coastal areas. After the recovery of oil and carbohydrates from macroalgae and microalgae, still many nutrients are left in spent biomass. One potential application for this leftover biomass is to use as a biofertilizer and will increase economic potential of algae for reuse in cultivation after extraction of nutrients. The left-over biomass will be used as fertilizer. Most of the cyanobacteria are able to fix atmospheric nitrogen and can be used as effective biofertilizers. They play a major role in conserving and building soil fertility for increasing rice growth and yield as natural biofertilizer [121]. After water, nitrogen is second important factor for growth of plants in fields and its requirement met by fertilizers [122].With the help of Blue green algae (BGA), various physical, chemical properties of soil are improved along with increasing yield and saving of fertilizer nitrogen. Blue green algae like *Nostoc*, *Anabaena* and *Tolypothrix* are capable of fixing atmospheric nitrogen and are used as inoculants for growing paddy crops in both upland and low land conditions [123]. (Table 6)

Fibres for Paper

Various sulphur containing polysaccharides provide structural stability to most of the algae [124]. As a potential feedstock, cellulose-containing algae can be owned for production of paper and but there are few examples of algae as a non-wood fibre source. A mixture of algae was taken from municipal waste water treatment plant. Ververis *et al.* [125] used it as 10% of pulp mix, resulting in appreciable increase in mechanical paper strength with 45% lower material cost due to decrease in brightness leading to 0.9-4.5 % reduction in total cost. But this concept is limited till research gate and an immediate attention is needed for commercialization.

As Processed Food Ingredients

The products like agar, alginates and carrageenans are among most valuable products that can be derived from algae due to their gelling and thickening properties. In past years, a considerable growth has been observed in area of algae research and development in fields like protoplast fusion, macroalgal cell cultures, transgenic algae [68].

Agar

Agar derived from macroalgae has many applications in food products such as frozen food, deserts, candies, fruit juices along with industrial uses like paper sizing, textile printing, and molecular biology as agarose and in various biomedical fields to produce capsules, tablets, anticoagulants [125].

Carragenans

Carrageenan derived from algae are water soluble polysaccharides and most commonly used than agar for application as emulsifying and stabilizing agents in various foods. κ- and ι-carrageenans are commonly used in various foods like jellies, jams, deserts, meat products due to their thickening action. Various pharmaceutical applications of carragenans like antiviral, antitumor, anticoagulant have also been investigated.

Table 6: crop growth enhancing compounds derived from several Cyanobacteria[64]

S.No.	Cyanobacteria	Growth enhancers
1.	Cylindrospermum sp.	Vitamin B12
2.	Tolypothrix tenuis	Vitamin B12
3.	Nostoc muscorum, Hapalosiphon fontinalis	Vitamin B12
4.	Nostoc, Hapalosiphon	Auxin like Indole-3-acetic acid indole-3-propionic acid or 3-methyl indole

Alginate

Alginate, a brown alga derived compound is used in textile industry for sizing cotton yarn and is of high importance due to its gelling properties. Alginate has chelating property and ability to make highly viscous solution which makes it a potential candidate for food and pharmacy sectors [125].

Aquaculture Feed

Presently, various algae feeds are used for culture of various fish like larvae, juvenile fish and finfish [126]. The most commonly used algae for aquaculture feed are *Chlorella*, *Tetraselmis*, *Pavlova*, *Phaeodactylum*, *Nannochloropsis*, *Skeletonema* and *Thalassiosira.* By using *Chlorella* and *Spirulina*, or their mixture many companies are making aquaculture feed. *Hypneacervi-cornis* and *Cryptonemia crenulata* microalgae, rich in protein were tested as shrimp diet [127]. Hundreds of microalgae have been examined as food over last few decades, but still a less than twenty have gained importance in context of aquaculture.

Algae based Companies in World

From a long time, researchers have an eye on algae as a potential candidate for converting biomass to biofuel. Nowadays algal biofuels is an expanding sector, having many high profile start-ups like Craig Venter's Synthetic Genomics, along with interest of big time investors like Bill Gates. But still there are many difficulties for making it a competitive fuel. Algal biofuels costs much to yield-over $8 per gallon. Moreover the presently existing species of algae do not produce appreciable amount of oil, which could be quickly scaled up to produce commercial biofuels. Another reason of concern for companies is contamination of local environment and need of water for cultivation of large batches. Although these inroad challenges, algal biofuels have appeared as a promising sector [128].

Major Algae based Companies in World:

1. Algenol: Algenol, a Florida based company with head office in Fort Myers founded in 2006. Algenol is an industrial biotechnology company, commercializing its patented technology for ethanol production from algae and other fuels. Their technology includes production of four major fuels such as ethanol, gasoline, jet and diesel using a recovery process with involvement of algae, sunlight, carbon dioxide and salty water to produce ethanol and to produce other biofuels from spent algal biomass [129]. They have the only process which can convert more than 85% of its CO_2 feedstock into the four fuels. Algenol have tested their algae for non-invasiveness, non-toxicity in natural habitats [10]. Over one wet acre of algae, company could yield approximately 8,000 gallons of liquid fuel. Their production of biethanol mainly contains 500 gallons diesel, 380 gallons of gasoline, and 315 gallons of jet fuel [129, 130, 131, 132]. Algenol has established its new unit in Southwest Florida. This new unit is trying to develop a commercially viable fuel from algae [133].

2. Solix Algredients: Solix Algredients is Colorado based company with headquarter in Fort Collins where it has an array of algae-specific technical, R&D and analytical resources. The company is a well known player in algae cultivation and has displayed its technology at scale. Solix is using its experience and expertise of algal cultivation to bring products like Solasta ® Astaxanthin, Solmega® DHA omega-3 and other natural algal ingredients to market.

Solasta® Astaxanthin- natural astaxanthin extract (*Haematococcus pluvialis)*. The product is a rich source of astaxanthin as dietary supplements and personal care. This is a non-GMO, vegetarian, and extracted in the USA [134]

3. Sapphire Energy: Sapphire Energy offers the most advanced facility for algae production in desert scrub outside of Columbus, New Mexico. The company has world's first commercial demonstrated algae farm, with integration of total value chain starting from cultivation to production, to extraction. Sapphire Energy produces "Green Crude" from algae, providing a crude oil with many properties of fossil fuel oil. Green Crude is a low carbon, 100% renewable crude oil with reduced carbon emissions as compared to petroleum products [135].

4. TerraVia Holdings, Inc. (formerly Solazyme): is a biotechnology based public company in United States. This company uses its patented technology to convert low cost plant sugars into high value oils and whole algae ingredients. TerraVia supplies a variety of sustainable algae-based food ingredients to a number of brands, which included Hormel Food Corporation, Utz Quality Foods Inc., and Enjoy Life Foods [136]. TerraVia also sells its own culinary algae oil under the Thrive Algae Oil brand. Solazyme began development of a food ingredient line known as AlgaVia. AlgaVia was launched in 2014 and received GRAS certification the same year

[137]. With the company's change in March 2016, TerraVia acquired AlgaVia as well as AlgaWise, another food ingredient brand. The AlgaVia brand provides food manufacturers with two whole algae powders that offer sustainable, non-allergenic, vegan protein and lipids. As the name suggests, the entire algae cell is used as whole algae powders, grounded into a fine powder. AlgaVia's Lipid-Rich Whole Algae powder is intended to add texture and reduce the need for dairy, eggs, and oils in recipes. The Protein-Rich Whole Algae powder is intended to offer an allergen- and gluten-free source of vegan protein. AlgaWise Ultra Omega-9 Algae Oil offers over 90 percent mono-unsaturated fat and less than 4 percent saturated fat. TerraVia boasts that the oil has an extremely high smoke point and a neutral taste, making it good for frying and searing. AlgaWise High Stability Algae Oil is intended to resist oxidation and reduce the need for preservatives and extra stabilizing ingredients. TerraVia is also responsible for the Thrive Algae Oil brand. Thrive is marketed as "The Best Oil For Your Heart" due to its high levels of monounsaturated fats, which are known to reduce the level of bad cholesterol and reduce the risk of stroke. TerraVia supplies aquaculture feed producer BioMar with an algae-based feed ingredient known as AlgaPrime DHA [138]. AlgaPrime DHA is a source of omega-3-fatty acids, which reduces the aquaculture industry's dependence on wild fish as a source of DHA. TerraVia currently manufacturing the brand 'Algenist' along with Sephora and QVC for marketing and distribution arrangements for luxury skin care market It is sold in Canada, France, and the United Kingdom.

TerraVia also markets its AlgaPūr Algae Oil brand to personal care producers. Unilever, a leading consumer goods company, is one of TerraVia's biggest partners. In 2010, Solazyme and Unilever started its partnership to develop renewable algae oils for use in soaps and other personal care products [139] in 2011. Solazyme started a brand of industrial drilling lubricant known as Encapso. Scientists were able to harness the prolific oil-producing capabilities of microalgae to create a first of its kind product, microencapsulated oil cells that burst only under sufficient pressure, friction, and shear.

5. Aurora biofuels: Aurora biofuels is a California based energy Company providing new sources of feedstock for production of biofuels. This company as a leading producer provides highly accomplished and excellent algae derived products with application in pharmaceutical, nutrition and fuel market.

Different products Manufactured by Aurora algae:

- A2 Omega-3™—a family of Omega-3 oils which provides natural and cost effective alternate to fish oil and fermented products for nutraceuticals and pharmacy sectors.
- A2 Feed™— composed of protein rich algae grains as a feed for animal and aquaculture market for raising healthy animals.
- A2 Fuel™— provides biomass and biodiesel as renewable energy alternatives for transportation.
- A2 Protein™— protein-rich powder products for the food and beverage industry. [140] (Figure 2)

6. Major Algae based Non-Fuel Companies in World: (Figure 3)

Earthwise Spirulina natural powder is a very high-quality *Spirulina* produced in California. Earthwise has the world's largest *Spirulina* farm, which is located in Sonoran Desert of southeastern California. Their *Spirulina* is cultivated in protected environment without the use of pesticides, with an effort to be environmentally friendly [142].

Nutrex-Hawaii Hawaiian *Spirulina pacifica* is among one of the most popular brands of spirulina and for good reason [143]

Bulk Supplements Pure Spirulina is a quality *Spirulina* harvested in China but tested and packaged in the US.

Healthfoce Spirulina Azteca is a wonderful spirulina made in Chile. HealthForce Nutritionals is a hard-core, vegan, therapeutic superfoods company. They've created pure, quality standards for sourcing and production which they claim is significantly beyond organic called Truganic [144].

Taiwan Chlorella Manufacturing Company (TCMC) was first company to produce *Chlorella* in Taiwan and was established in 1964. TCMC is the world's oldest and largest Chlorella producer. Their goal is to be "The Best Chlorella Manufacturer in the World." Chlorella can be added to foods like pasta, cookies and can be taken as tablets or capsules. Chlorella improves the nutritional quality of diet and can be taken in any form [145].

Fig. 2 The finished products. Protien pellets on the left, bio-diesel in the middle and omega 3 oil on the right.(Aurora algae) [141]

Fig. 3Different Spirulina brands by Companies [142, 144, 143]

Far East Bio-Tec Co., Ltd. (ALGAPHARMA BIOTECH CORP.) is a Taiwan supplier and manufacturer of organic spirulina, organic chlorella and biotech microalgae research market. FEBICO has been offering customers various high value spirulina, chlorella, organic chlorella, bio chlorella and blue green algae since 1976.

FEBICO SOROKINA® is a range of diiferent products derived from an efficient strain of thermophilic *Chlorella* known as *Chlorella Sorokiniana*. Sorokina products encompasses various other PPAR dietary supplements in form of quality, availability and effectiveness.

Biophyto® Premium Spirulina – This is another product of the company. FEBICO have been supplying quality organic microalgae and nutraceuticals for 40 years. As a specialist producer of microalgae, they have formulated finished products based on microalgae.

Apogen® is extracted from natural microalgae with special extraction method providing protections against viral infections.

Apomivir® was approved to precede the clinical trial by US FDA and Taiwan FDA respectively on treatment and alleviation of Influenza associated syndrome. Apomivir® could directly enter phase II trial to evaluate

the efficacy in human with no bio-safety concern. In preclinical study, Apomivir® had been proven to show excellent broad-spectrum anti-flu ability, and also include the Oseltamivir-resistant, resistant to new pandemic and H7N9 influenza viruses.

Flogen® is FEBICO's brand name for selling phycobiliprotein, includes:

1. Flogen® Phycobiliprotien
2. LyoFlogen® Phycobiliprotein
3. LyoFlogen® Recombinent Protein
4. Flogen® Conjugate
5. Flogen® Conjugate Service

Apogina® Phyco-radiance Powder: boosts the metabolic rate of skin, excess ketain elimination, provides white complexion with shiny skin.

Narogen® Energy Collagen Mask: extracted from microalgae and provides moisture, rejuvintation and renewal to skin cell.

Apogen® Children Granule: is a patented microalgae extraction containing (sulfated polysaccharide, nucleic acid, peptide, amino acids, minerals), Lactose, Tomato extract powder (Lycopene), DHA, Gamma-Linolenic acid, milk powder [146]. (Figure 4)

Nutress : has emerged as a biggest algae food company of Europe and was founded in 2012 with headquarters in Ochten, The Netherlands. The company provides several value added products to feed, pharmacy and food sector. It works towards providing innovative solutions for nutritional products. Nutress is an ISO 22000:2005 and nature certified company.

Essentials™ Food: provides world's most natural food which holds a significant amount of algae. Worldwide it is sold in four flavours - sweet, salty, sour and bitter but also has a fifth taste of algae called 'umami'. This food has more shelf life upto 50%, non-GMO, no synthetic nutrients, upto 30% less salt content. This product provides combined benefits of algae, food grains and 100% vegetarian.

Essentials™ Health: Essentials™ products replenish the most essential nutrients in the body. The natural power of Essentials™ is in the benefit of algae: the origin of all aquatic life, the source of the food chain and full of energy rich proteins, antioxidants, unsaturated fatty acids and other valuable components such as fibers and vitamins [147].

Essentials™ Pet food: selects the right algae containing the essential nutrients needed for pets. This food provides synergistic effects to animal's immune system and helps in their well being. **Fishfeed:** containing essential nutrients as proteins, antioxidants and omega-3 fatty acids [148].

Source Naturals®: was founded in 1982 with a goal to provide each individual a healthy life by C.E.O. Ira Goldberg. They came with an idea to provide benefits of various nutrients, herbs and pharmaceuticals into one product which is very common today, but was rare in those early days.

Source Naturals concept with Wellness Formula®, is now the industry's no. 1 immune support product.

Astaxanthin (AstaReal®): *Haemotococcus pluvialis* Microalgae Extract.

Fig. 4 Different commercial products from algae by FEBICO Ltd. [146]

Source Natural's Blue-Green Algae is cultivated in upper regions of Upper Klamath Lake, Oregon and is of great quality. The name of these algae has been derived from two colour pigments present in it as: phycocyanin (blue), chlorophyll (green)

Organic Blue-Green Algae: This algae contains mixture of two algae named *Aphanizomenon flos-aquae* and *Arthrospira platensis*.

Source Natural's Spirulina: is of the high quality. Many early investigations have suggested the role of spirulina, to supports the immune system and providing health benefits. This superior quality protein is composed of all nine essential amino acids [149].

Status of algae based products in India: (Figure 5)

Herbal Hills: Herbal Hills cultivates manufactures and exports various ayurvedic herbal products and various algae products as spirulina tablets in India [150].

Shibin Exports started its operations in the year 2012 as a merchant exporter of nutraceuticals and right from its inception, the firm is been well-renowned for its matchless nutritional supplement products that are highly synonymous with optimum quality, reliability and cost-affordability which you can hardly avail from any other branded health supplements.

Spirulina Powder, tablets, Capsules: helps in nutrient adsorption in body, improving immune response and boosting of health in different ways.

Shibin Chlorella: became the first company in India to start commercial production of Chlorella as a nutritional supplement from July 2015 [151].

Parry Nutraceuticals: The company is one the best providing microalgal health supplements, with headquarters in Chennai, are a division of E.I.D. Parry (I) Ltd.

Spiruzan™: The latest offering from Parry, contains the potential combination of Spirulina and Astaxanthin. A powerful composite with nutritional benefits of Spirulina and the antioxidant properties of Astaxanthin, Spiruzan™ is procured from the world's richest, natural micro-algal source.

Parry's Natural Astaxanthin: The source of Parry's Astaxanthin (ZanthinTM) is the world's richest natural source *Haematococcus Pluvialis*, a green, fresh water algae that has commercial importance due to presence of Keto-carotenoid and Astaxanthin up to 2-3% (w/w) of dry weight of cells.

Parry's Natural Mixed Carotenoids: display effective anti-oxidant properties that help in protecting the body against cell and tissue damage by scavenging free radicals. It is a mixture of best antioxidants, generally called natural mixed carotenoid, which include β-carotene, α-carotene and Xanthophylls like Zeaxanthin, Cryptoxanthin and Lutein, derived from the microalga *Dunaliella saline*, the richest source [152]. (Figure 6)

Pondicherry Spirulina Farms (PyFarms): were established in May 2008, having a license to commercially grow the algae Spirulina as health food in the Union Territory of Pondicherry, India. This is a South

Fig 5. Commercialized Spirulina tablets of different companies [150, 154]

Fig. 6 Commercialized *Chlorella* tablets from different companies [152]

-India based food company with specialization in harvesting, production and marketing of *Spirulina*.

1. Pondicherry Spirulina Capsules

2. Pondicherry Spirulina Powder [153]

The Algae Company: is the first company in India to have a dedicated focus on algae as nutraceuticals. The main products of company are:

Chlorella Factor: provides a potential food candidate due to its high protein content and other nutrients, it contains up to 20% carbohydrate, 5% fiber, 10% minerals and vitamins and up to 45% protein in its dried form.

Organic Spirulina: contains up to 60% protein with over 100 times more protein content as found in fruits and nuts [154].

Zenith Nutrition: This company provides a wide range of products like vitamins, probiotics, herbal formulations and amino acids. This is a leading company involved in high quality research for providing formulations to benefit health.

Zenith Nutrition's Astaxanthin: Zenith Nutrition's astaxanthin, extracted from microalgae *Haematococcus pluvialis*, act as a natural antioxidant carotenoid. Various analytical studies have shown its potential to promote healthy inflammatory response, to promote joint and eye health, support skin during exposure to skin. A study on astaxanthin research has been conducted with daily dose between 4 and 12 mg.

Zenith nutrition's Spirulina: comes with a tag line: Eat your Spirulina greens for good health. This product provides better immune health with antioxidant benefits. This supplements intake of fruits and vegetables with 1 serving of spirulina a day [155].

Major Challenges to Algae Production:

There is no terminology like perfect energy source. Each and every source has its own benefits and compromises [156]. Algal biofuels carry on their possession as sustainable and carbon neutral source of transportation fuel. The various possibilities of algal as biofuels have been displayed [157, 158] but the economics and energy demands of production require substantial improvement. The changes can be attained only by increasing productivity, cost reduction and meeting energy demand and the application of the biorefinery concept (production of algal co-products). The main goal of current work is achieve this by combining both biological and engineering methods.The major challenges currently being addressed are as:

☐To increase productivity in large scale outdoor location cultures

☐ Maintaining the purity of algal culture by avoiding contamination from predators and other algal species

☐ To control the changes in temperature and reduce water loss due to evaporation

☐Optimization of light and CO_2 supply

☐To develop efficient and cost effective designs

☐ To improve utilization of resources and increasing productivity in biorefinery approach

☐ Producing valuable co-products

☐ Decreasing environmental footprint through recycling of water, energy and nutrients.

Cons of Algal products:

Despite all benefits of algae being as fuel, food or feed and other products, there are some disadvantages of algal products which are enlisted here:

1. The algal biofuels are too costly. The present cost of fuel production algae cultivated from open raceway ponds is too high to make a economically viable process. There is need to do lot of work on it.

2. Algae fuel on burning emits carbon dioxide. Basically, using algae to filter coal and then burning it will emit captured carbon dioxide. According to Low-tech Magazine, "Algal fuel can even be considered a worse idea than "clean" coal [159].

2. Some studies have shown that Blue-green algae and spirulina are more harmful than beneficial to human health as they contain many toxins such as neurotoxins, hepatotoxins as well as BMAA(beta-N-methylamino-L-alanine). Contaminated blue-green algae can cause liver damage, stomach pain, nausea, vomiting, weakness, thirst, rapid heartbeat, shock, and death.

4. Some people who take sun chlorella may suffer from gastrointestinal problems including gas, abdominal pain, nausea, diarrhea and/or constipation. Additional side effects may include fatigue, irritability and increased sensitivity to sun exposure.

5. As high quality microalgae is free of many adverse side effects, but it does contain iodine, so people who are allergic or sensitive to iodine could developed different types of problem and also avoided by people with hyperparathyroidism.

6. Astaxanthin could lower the blood pressure and in women it can reduce the level of calcium which is a serious health issue.

7. Chlorella or Spirulina harvested from a polluted source, contain toxic heavy metals. Spirulina may also contain microsystins or potentially deadly bacteria that can affect liver and central nervous system function, according to the State of Washington Department of Ecology [160]

Conclusion

In field of algae, there is a need to boost the various research and development activities to overcome various technological barriers, as the algae have potential to provide novel chemicals and bioactive compounds. Except this the applications of algae are limitless in biotechnology sector. There is a great need to harness the rich algal diversity for various futile applications. In terms of their applicability in market, algae are promising sources of biofuels, high-value molecules, nutraceuticals, and various bioactive metabolites for digging out new drugs. In their exploitation, there is a need of total algal biomass utilization and need of exploration for various potential applications.

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