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Microalgae: A potential alternative to health supplementation for humans

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ABSTRACT

Microalgae has been consumed in human diet for thousands of years. It is an under-exploited crop for production of dietary foods. Microalgae cultivation does not compete with land and resources required for traditional crops and has a superior yield compared to terrestrial crops. Its high protein content has exhibited a huge potential to meet the dietary requirements of growing population. Apart from being a source of protein, presence of various bio-active components in microalgae provide an added health benefit. This review describes various microalgal sources of proteins and other bio-active components. One of the heavily studied group of bio-active components are pigments due to their anticarcenogenic, antioxidative and antihypertensive properties. Compared to various plant and floral species, microalgae contain higher amounts of pigments. Microalgal derived proteins have complete Essential Amino Acids (EAA) profiles and their protein content is higher than conventional sources such as meat, poultry and dairy products. However, microalgal based functional foods have not flooded the market. The lack of awareness coupled with scarce incentives for producers result in under-exploitation of microalgal potential. Application of microalgal derived components as dietary and nutraceutical supplements is discussed comprehensively.

1. Introduction

The Hunger Project, in November 2017, reported that out of 7.6 billion of the population in the world, 815 million do not have enough food to sustain themselves. Amongst them, almost three quarters of the population is directly dependent on agriculture and similar activities [1]. The exponential population spurt threatens to reduce levels of food security as time progresses. According to *The Future of Food and Agriculture*, a report by UN's Food and Agriculture Organization, "expanding food production and economic growth have often come at a heavy cost to the natural environment". It also stated that the Earth is capable of fulfilling the demands of food security, however, the agricultural sector will require 'major transformations' to reach its full potential [2].

Microalgae has been utilized as food by humans for thousands of years and supplementation with help of microalgae will release the stress on intense resource demanding terrestrial food crops [3]. Algae, are considered to be one of the oldest plants in the world. Their first appearance dates back about 3.5 billion years ago. These photosynthetic species constitute of multi-cellular structure (Macroalgae) of length up to 60 m and uni-cellular organisms (Microalgae) with size as small as 0.2 um [4]. Microalgae are extremely diverse group with estimated number of species ranging from 200,000 to 800,000 [5]. Some of these species are cultivated at industrial scale to extract bio-active compounds for human & animal consumption, cosmetics and bio-fuel industry [6]. Fig. 1

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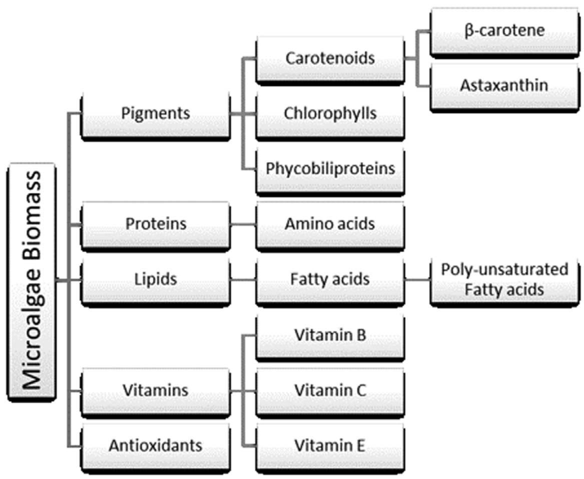

Fig. 1. Bio-refinery of component extraction from micro-algal biomass.

demonstrates the biorefinery approach for extraction of various bio-active components from microalgal biomass.

Numerous species of microalgae are reported to contain similar amount of protein compared to the traditional protein sources like milk, soybean, egg and meat. However, extraction of protein from microalgae has various benefits in terms of nutritional value, efficiency and productivity. The protein yield from microalgae is reported at 4–15 tons/Ha/year compared to terrestrial crops production of 1.1 tons/Ha/year, 1–2 tons/Ha/year and 0.6–1.2 tons/Ha/year for wheat, pulse legumes and soybean respectively [7]. The production of terrestrial crops via agriculture accounts for roughly 75% of total global freshwater [8]. Meanwhile, animal protein sources consume 100 times more water compared to plant sources for equivalent protein extraction [9]. Additionally, marine microalgae can be cultivated without freshwater and arable land further maximizing the resources required for additional terrestrial food crops production [7]. Moreover, due to the severe extreme environmental conditions and phototrophic mode of growth, microalgae are exposed to free-radical and high oxidative stresses. This has evolved the microalgae in developing natural protective system such as production of antioxidants and pigments (for example chlorophylls, carotenes and phycobiliproteins). These components are useful for human supplementation as they are not synthesized internally by individuals [10].

This review emphasises on importance of microalgae in food and nutraceutical industry and how it can assist in improving the health and well-being of humans. It focuses on current status of micro-algal human supplementation and future prospective.

2. Food and supplementation from microalgae

In some developed nations, the local population consumes high calorific foods due to their busy and modern lifestyle. This results in various health issues such as obesity, high blood pressure, diabetes and other heart related problems. For a healthy lifestyle, a balanced diet constituting of antioxidants, vitamins, PUFAs, etc is required. Numerous species of microalgae are reported to be rich in proteins, carbohydrates, lipids and other bio-active compounds [11]. According to Becker et al., microalgae are excellent sources of vitamins such as vitamin A, B1, B2, B6, B12, C and E and minerals such as potassium, iron, magnesium, calcium and iodine [12]. The Chinese people consumed *Nostoc* species of Microalgae around 2000 years ago as food and later Chlorella and Spirulina species were consumed as functional healthy foods in Taiwan, Japan and Mexico [11]. Currently the microalgae derived foods are marketed as healthy foods and are available in industry as capsules, tablets, powders and liquids [13]. They are also mixed with candies, gums, snacks, pastes, noodles, breakfast cereals, wine and other beverages [14]. The microalgae species widely used include *Spirulina plantesis*, *Chlorella* sp., *Dunaliella terticola*, *Dunaliela saline* and *Aphanizomenon flos-aquae* due to their high protein content and nutritional value [15]. However, in recent years, Chlorella and Spirulina species are dominating the global microalgae market as they are gaining popularity in the health-food supermarkets and stores. This is attributed to the nutrient-rich profiles of these species [11,16]. Similar to human supplementation, microalgae is also a source of food for many aquatic species, ruminants, pigs, poultry and other animals. The microalgal species of *Spirulina, Chlorella, Tetraselmis, Nannochloropsis, Nitzchia, Navicula, Scenedesmus, Crypthecodinium,* and *Chaetoceros* are reported to be used as feed for terrestrial as well as aquatic animals [17]. Table 1 depicts the composition of major microalgal species.

Table 1
Composition of microalgal species in percentage of dry biomass matter

Microalgae Species	Composition (%dry matter)			References
	Protein	Lipids	Carbohydrates	
Anabena cylindrica	43–56	4-7	25–30	[1]
Aphanizomenon flos-aquae	62	3	23	[2]
Chaetoceros calcitrans	36	15	27	[3]
Chlamydomonas rheinhardii	48	21	17	[4]
Chlorella vulgaris	51–58	14–22	12–17	[5]
Chlorella pyrenoidosa	57	2	26	[3]
Diacronema vlkianum	57	6	32	[6]
Dunaliela salina	57	6	32	[3]
Dunaliela bioculata	49	8	4	[7]
Euglena gracilis	39–61	22–38	14–18	[3,7]
Haematococcus pluvialis	48	15	27	[6]
Isochrysis galbana	50–56	12–14	10–17	[3]
Porphyridium cruentum	28–39	9–14	40–57	[3,7]
Prymnesium parvum	28–45	22–38	25–33	[7]
Scenedesmus obliquus	50–56	12–14	10–17	[4,8]
Scenedesmus dimorphus	8–18	16–40	21–52	[3,7]
Scenedesmus quadricauda	47	1.9	21–52	[7]
Spirogyra sp.	6–20	11–21	33–64	[7]
Spirulina maxima	60–71	6–7	13–16	[3]
Spirulina platensis	46–63	4–9	8–14	[3]
Synechococcus sp.	63	11	15	[4]
Tetraselmis maculata	52	3	15	[7]

Chlorella species are often marketed as 'healthy foods' and are being promoted as a functional foods to prevent, cure or help common diseases or acute diseases like Alzheimer's disease, cancer, etc. [23]. Due to the rising concern about healthy and nutritionally balanced diet, *Chlorella* sales has been growing and the global chlorella market stood at US$ 138 million in 2016 and is expected to reach US$ 164 million by 2021 [24]. Additionally, chlorella species are good sources of nutrient rich foods for aquatic species, poultry and ruminants. Currently, there are more than 70 industrial companies producing about 2000 tonnes of Chlorella products every year [11,25]. The largest individual producer of Chlorella is situated in Taiwan which produces 400 tons/year followed by a German firm with 130–150 tons/year. A study conducted in 1940s by two researchers namely Jorgenson and Convit on 80 leprosy patients in Venezuela, who were provided plankton soup consisting of *Chlorella* sp. as dietary supplement, showed increased energy, health and weight of the patients. This is the first documented evidence of microalgae as a potential health supplement [26]. According to Barrow and Shahidie, the Chlorella sp. extract exhibited numerous health benefits [27]. For example, chlorella sp. are excellent heptatoprotective and hypocholesterolaemic agents during malnutrition and ethionine intoxication, they lower blood sugar concentration and increase haemoglobin concentration. Chlorella also contains an active immunostimulator-β-1,3-glucan, which reduces blood lipids and acts as a free radical scavenger.

Spirulina sp., also known as "superfood", a label given by World Health organization (WHO), belongs to the blue-green photoautotrophic genus of unicellular microalgae. Its cells are protein rich with protein content reaching up to 70% of dry weight. It has been used by indigenous people of Mexico and Africa since 1950s [15]. It is also an excellent natural source of vitamin A, B1, B2 and B12, essential fatty acids and useful pigments such as xanthophyll and carotenoids. These bio-active components cannot be synthesized by humans, therefore, importance is given on production of Spirulina or Arthrospira [11]. A spoonful (7 g) dried biomass of Spirulina contains almost 4 g of protein, 1 g of fat including PUFAs like omega-3 and omega-6 fatty acids and 11%, 15% and 4% of Required Daily Allowance (RDA) of Vitamin B1, B2 and B3, respectively. It also constitutes for 21% and 11% of RDA corresponding to copper and iron, respectively. Additionally, various other minerals such as magnesium, manganese and potassium are reported in small amounts [28]. Spirulina is reported to lower LDL cholesterol and triglyceride levels [29,30], lower blood pressure [30,31] and control blood sugar [29]. Supplementation with spirulina is also reported to increase haemoglobin levels of red blood cells in older people and improve their immune system [32]. The WHO recommended Spirulina spp. to be added in diet of National Aeronautics and Space Administration (NASA) astronauts in space as it is an ideal and compact food for space travel. It contains wide range of nutrients even when consumed in small amount [33]. Spirulina is reported to contain protein as high as 670% compared to tofu, calcium as high as 180% compared to milk, iron as high as 5100% compared to spinach and β-carotene as high as 3100% compared to carrots [34].

2.1. Pigments (carotenoids, chlorophyll)

Pigments are essentially molecules that absorb light from the visible spectrum. The wavelength which is not absorbed by these molecules is caught by human eye and therefore exhibit the corresponding colour. Pigments are used for variety of products including food additives/colorants, aquaculture, pharmaceutical and nutraceutical products [35]. These pigments are currently produced on industrial scale via non-renewable synthetic sources such as petrochemicals, inorganic chemicals and organic acids. The raw materials and cost of production is cheaper with synthetic sources. However, there is rising demand for naturally produced pigments due to the safety and environmental concerns associated with synthetically produced pigments [35–37]. The food industry is very keen on utilizing natural pigments as food colorants owing to the harmful elements present in the synthetic sources [37].

The natural sources of pigment production include fruits, flowers, vegetables, insects and photosynthetic micro-organisms like microalgae and cyanobacteria [38]. Microalgae are photosynthetic species that produce various pigments depending on the species and their corresponding colours. For example, green microalgae contains chlorophyll, red and blue microalgae possess phycobiliproteins and yellow, orange and red microalgae synthesize carotenoids. Among the various sources, microalgae are superior source of pigments due to their ability to synthesize natural pigments in higher concentration compared to others [39]. Additionally, microalgae can be cultivated in brackish or wastewater with high concentration of heavy metals. The microalgae consumes nutrients present in the wastewater while reducing the dependence on chemicals and freshwater [40]. Furthermore, microalgae are 10 to 50 times more efficient in capturing CO_2 and sunlight for photosynthesis compared to terrestrial plants [41]. Several studies have reported that *Scenedesmus* sp. and *Clorella* sp. have the ability to tolerate 10–30% atmospheric CO_2 and hence have the ability to sequester large amounts of flue gas from nearby power plant [40,42]. The microalgal growth rates and productivity are higher compared to any plant systems [41]. Fig. 2 depicts the production of carotenoids content in numerous natural sources.

Carotenoids are isoprenoid structured lipophilic pigments which are found in non-photosynthetic organisms, microalgae and higher plants [44]. These pigments have a therapeutic effect on humans and animals due to their strong anti-oxidant properties therefore protecting the organisms from oxidative and free-radical stresses [11]. Carotenoids act as provitamin A in human body and are usually present in the range of 0.1–0.2% of total dry matter of microalgae [4]. The global carotenoids market is estimated to be valued at USD 1.24 Billion in 2016 and is projected to reach USD 1.53 Billion by 2021, however most of the production incorporates chemical raw materials [36]. The carotenoids are classified with their functional groups. The carotenoids with only hydrocarbon groups is known as carotenes. The ones with epoxy, hydroxyl and oxo groups are known as xanthophylls. With more than 400 identified carotenoids, only β-carotene and astaxanthin are industrially commercialized [18].

B-carotene is an important carotenoid pigment due to the presence of provitamin-A, an additive in multivitamin supplement and tablets. β-carotene is also applied as food colour on cheese, butter and margarine [18]. D. Salina is reported to contain up to 10–14% of its dry matter as β-carotene [45]. Rodrigues et al., identified 24 types of carotenoids in *Phordium autumnale*.

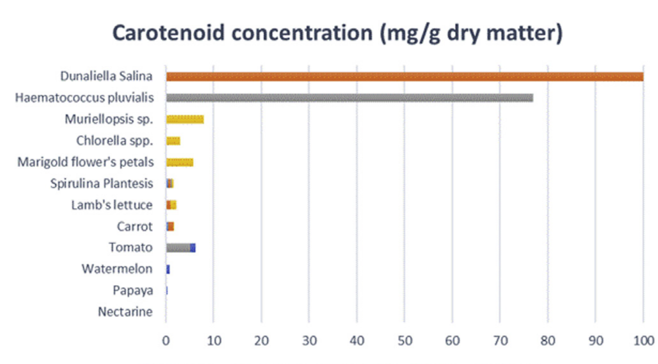

Fig. 2. Carotenoid content of different sources including flowers, vegetables and microalgae.
Adapted from Refs. [39,43].

Table 2
Protein content in various food sources including microalgae. Adapted from [4]

Food origin	Protein content (% dry matter)
Beef	17.4
Fish	19.2–20.6
Chicken	19-24
Peanut	26
Wheat Germ	27
Parmesan Cheese	36
Skimmed Milk powder	36
Soybean flour	36
Beer Yeast	45
Whole egg	47
Chlorella sp.	50–60
Spirulina sp.	60–70

Amongst them, all-*trans*-β-carotene, all-*trans*-lutein and all-*trans*-zeaxanthin were the major contributors with concentration of 225.44 μg/g, 117.56 μg/g and 88.46 μg/g of biomass respectively [46]. Recently, studies have shown that β-carotene production can be enhanced via manipulating the culture conditions to high salinity, high light intensity, lower nutrient content and extreme temperature [47,48]. Optimizing the culture medium conditions results in production efficiency of B-carotene, further production of 9-*cis* isomers [49]. The 9-cis isomer of B-carotene have shown positive results on plasma lipids and thus have a possibility of preventing advancement of atherosclerosis in humans [50]. A Manfredonia Study conducted on 640 individuals to evaluate the effects of B-carotene in cardiovascular health concluded that atherosclerosis diseases can be prevented with adequate addition of B-carotene and other antioxidants in diet, given that other external factors such as smoking, hypertension, dyslipidemia and diabetes are under control [51].

Astaxanthin is a natural pigment and possesses powerful antioxidant properties compared to Vitamin C, E or any other carotenoids like β-carotene, lutein, lycopene and zeaxanthin [52]. Astaxanthin is the second most important carotenoid pigment and is mostly extracted from Haematococcus pluvialis, a freshwater green microalgae [53]. Haematococcus pluvialis is reported to contain astaxanthin about 4–5% of their dry weight [11]. Apart from H. pluvalis, Chlorella zofingiensis also produces Astaxanthin, however, its production rate is lower. Under nitrogen limiting conditions, C. zofingiensis produces hydroxyl radicals which are responsible for astaxanthin generation [54,55]. It is commercially marketed as a feed for salmon fishing industry [52]. Consumption of food rich in astaxanthin is promoted as a beneficial dietary supplement as its antioxidant strength is 100 times that of α-tocopherol [53,56]. Recently several studies have been conducted to prove that addition of astaxanthin in diet of humans reduce inflammation, oxidative stress and further improving the immune system of patients suffering from cardiovascular problems [57–59]. Kim et al., also reported that consumption of Haematococcus astaxanthin resulted in prevention of oxidative damage in heavy smokers by suppressing lipid peroxidation [58]. Yoshida et al., also reported an increase in serum HDL and adiponectin in 61 non-obese subjects with daily dose of 12–18 mg of natural astaxanthin [60]. Table 4 illustrates phenolic and carotenoid activity with respect to different microalgae strains.

Chlorophyll, a natural source of green pigments, is synthesized by all the photoautotrophic microalgal species and constitutes for about 0.5–1.5% of the dry cell matter. The microalgae *Phordium autumnale* was also reported with two chlorophyll pigments namely chlorophyll-a (2.7 μg/g) and chlorophyll-b (0.7 μg/g) [46]. Chlorophyll consumption has shown a potential to increase bile secretion and further stimulate the recovery of liver [61]. It also possesses antioxidant, anticarcenogenic, antigenotoxic and antimutagenic properties [16]. Chlorophyll is a well-known detoxifying agent and a phyconutrient. It has a positive effects in human reporoduction and improves metabolism of proteins, carbohydrates and lipids in humans [62]. Chlorophyll contains chlorophyllin (CHL), a sodium-copper-salt water-soluble derivative, which is readily absorbed by human body. Nagini et al., reported that addition of CHL in diet, has a potential to inhibit the progression of cancer as it targets multiple pathways of carcinogens and invades their cell cycle [63]. A study conducted by Das et al., successfully reported that introduction of CHL aided in slow progression of lung cancer in mice. The study further concluded that due to the ability of CHL to cross the blood-brain-barrier in mice, it will potentially be successful in human application [64].

Phycobiliproteins are water-soluble or hydrophilic protein complexes that capture light energy and thus assist in photosynthesis of cyanobacteria and other red microalgae [65]. The major producers of this pigment are *Porphydium* sp., *Spirulia* sp. *and A. flosaquae* [17]. Phycocynin, a fluorescent blue-coloured phycobiliprotein, is extracted from Spirulina sp. as a natural dye. It is also used in popsicles, chewing gum, confectionery, wasabi, dairy products and soft drinks [18]. However, in nutraceutical industry, these pigments are marketed as anti-inflammatory, anti-oxidative, anti-viral, hepatoprotective and neuroprotective agents [6,16,66].

2.2. Proteins and amino acids

Proteins, also known as building blocks of human body are essential macro-nutrients responsible for overall growth of an individual. According to ACSM, American Dietetic Association and Dieticians of Canada, individuals who exercise with moderate to intense activity, require 1.3–1.7 g protein per kg of bodyweight per day to repair and add muscles tissue to the body [67]. Proteins are made of long chains of amino acids; essential and non-essential, linked by peptide bonds [68]. The essential amino acids (EAAs) are not synthesized de-novo in human body and need to be consumed externally as food items. The common sources of these EAAs are eggs, poultry meat, red meat, dairy, soy/tofu, and fish. The above food items have complete profile of EAAs. However, for population following a vegetarian and vegan diet, there are very few options as most of the plant derived proteins do not have complete EAA profile. Microalgae on the other hand is an excellent source of EAAs. Chlorella and Spirulina species are reported to constitute around 70% protein with respect to its mass [6]. According to WHO/FAO/UNU recommendations, microalgae such as Chlorella sp. and Spirulina sp. contain well balanced EAA content required for human consumption [69]. Table 2 summarizes the protein content percent of the total dry matter.

The above table clearly demonstrates the high protein extraction potential of microalgae. Microalgae is identified as an alternative high-protein source which can meet the requirements of malnourished population [4]. The consumption of microalgae as a dietary supplement is via pills, tablets, powder or paste [13]. Although, in recent years, microalgae derived proteins have been incorporated in biscuits, sweets, bread, noodles, drinks and beer [14]. Due to its high protein content and added nutritional properties, Spirulina spp. are widely consumed across the world. The amino acid content in some microalgae are also found to be comparable to that of high protein content sources. Amino acids such as isoleucine, valine, lysine, tryptophan, methionine, threonine and histidine were found to be present in microalgae in quantities that are comparable or larger compared to protein-rich sources such as eggs and soybean [4]. Table 3 compares the amino acid profiles of conventional meat sources with microalgal proteins.

Table 3
Amino acids profile of conventional protein sources and microalgae (g/100g of dry matter). Adapted from [2,9–11]

Source	Egg	Chicken Breast	Soybean	*Chlorella sp.*	*Chlorella Vulgaris*	*Nannochloropsis sp.*	*Scenedesmus sp.*	*Scenedesmus obliquus*	*Dunaliella sp.*	*Dunaliella bardawil*	*Spirulina sp.*	*Spirulina Platensis*	*Arthrospira maxima*	*Aphanizomenon sp.*
ESSENTIAL AMINO ACIDS														
Histidine	2.4	4.5	2.6	2.4	2.0	2.6	2.5	2.1	2.6	1.8	2.0	2.2	1.8	0.9
Isoleucine	6.6	3.24	5.3	4.4	3.8	4.7	4.7	3.6	4.5	4.2	5.8	6.7	6.0	2.9
Leucine	8.8	6.4	7.7	9.2	8.8	9.4	9.3	7.3	9.4	11.0	9.0	9.8	8.0	5.2
Lysine	5.3	7.9	6.4	8.9	8.4	6.8	6.2	5.6	6.8	7.0	5.1	4.8	4.6	3.5
Methionine	3.2	2.5	1.3	2.2	2.2	2.3	2.5	1.5	2.4	2.3	2.9	2.5	1.4	0.7
Phenyl-alanine	5.8	3.2	5.0	5.5	5.0	5.5	6.0	4.8	5.5	5.8	4.8	5.3	4.9	2.5
Threonine	5.0	3.7	4.0	4.7	4.8	4.8	5.0	5.1	4.9	5.4	5.1	6.2	4.6	3.3
Tryptophan	1.7	-	1.4	-	2.1	-	-	0.3	-	0.7	-	0.3	1.4	0.7
Valine	7.2	3.46	5.3	6.1	5.5	6.0	6.0	6.0	6.0	5.8	6.4	7.1	6.5	3.2
NON-ESSENTIAL AMINO ACIDS														
Tyrosine	4.2	3.65	3.7	4.2	3.4	3.9	4.0	3.2	4.0	3.7	4.8	5.3	3.9	-
Alanine	-	4.7	5.0	8.3	7.9	6.8	7.8	9.0	6.8	7.3	7.4	9.5	6.8	4.7
Arginine	6.2	5.8	7.4	7.1	6.4	6.0	6.6	7.1	6.0	7.3	7.4	9.5	6.5	3.8
Asparagine	11.0	7.8	1.3	9.4	9.0	9.1	10.5	8.4	9.2	10.4	7.6	7.3	8.6	4.7
Glutamic	12.6	11.2	19.0	12.9	11.6	13.8	13.6	10.7	13.8	12.7	16.1	10.3	12.6	7.8
Glycine	4.2	3.4	4.5	5.4	5.8	5.2	5.7	7.1	5.2	5.5	4.6	5.7	4.8	2.9
Proline	4.2	3.2	5.3	4.8	4.8	8.3	4.9	3.9	8.3	3.3	3.3	4.2	3.9	2.9
Serine	6.9	3.4	5.8	4.0	4.1	4.2	4.4	3.8	4.2	4.6	4.8	5.1	4.2	2.9
Cystine	2.3	1.1	1.9	0.4	1.4	0.1	4.0	0.6	0.1	1.2	0.3	0.9	0.4	0.2

2.3. Vitamins

Apart from macronutrients such as proteins, carbohydrates and fats, the human body requires several micro-nutrients for survival. These micronutrients act as either co-enzymes or as an active electron/proton carriers in breakdown process of the macro-nutrients. One such group of important micro-nutrients are vitamins. Deficiency of vitamins in humans is responsible for various diseases such as beriberi, scurvy, rickets, methyl-malonic academia, etc. Vitamins play a major part in energy metabolism of humans. Depeint et al. reported that vitamin B_6, B_9 and B_{12} essentially regulate the mitochondrial enzymes in order to maintain the mitochondrial one-carbon transfer cycle of amino acid metabolism [70].

Algal food products are rich in vitamins. In 1990, Fabregas and Herrero conducted a study to determine the vitamin content of various microalgal species. They noted that microalgae contained high concentration of four vitamins; provitamin A, vitamin E, vitamin B1 and folic acid, compared to conventional food sources. They reported that *Dunaliella tertiolecta* was able to synthesize vitamin B_{12} (cobalamin), vitamin B_2 (riboflavin), vitamin E (tocopherol) and provitamin a (β- carotene). Moreover, *Tetraselmis suecica* was an excellent source of vitamin B_1 (thiamin), vitamin B_3 (nicotinic acid), vitamin B_5 (thenic acid), vitamin B_6 (pyridoxine) and vitamin C (ascorbic acid) [71]. *Chlorella* spp. are reported to contain Vitamin B_7 (biotin) in high concentration. A study by Shim et al. concluded that around 9–18% of Chlorella strains are rich source of vitamin B_{12} [72]. Watanabe et al. reported that although Spirulina species are capable of synthesizing Vitamin B12, Chlorella species have better bioavailability [73].

Fruits and vegetables are poor sources of vitamin B12 (cobalamin) as it is neither synthesized nor required by plants [74]. This justifies the vitamin B_{12} deficiency among people following vegan and vegetarian diet [75]. Therefore, micro-algal derived foods provide an essential source of vitamin B_{12} for the individuals that follow these diets. Studies conducted have reported that several sea vegetables such as *Gracilaria changii, Himanthalia elongate* and *Porphyra umbilicalis* have similar levels of Vitamin C compared to common vegetables like lettuce and tomatoes [76,77]. One species of brown microalgae, *Eisenia arborea*, reported to contain 34.4 mg of Vitamin C per 100 g of dry matter. This value is closer to that of mandarin oranges [78]. *Macrocystis pyrifera,* more commonly known as Kelp, is reported to contain α-tocopherol at higher concentration that plant oils that are rich in this vitamin, like soybean, sunflower and palm oil [76,79]. Additionally, the levels of β-carotene in *Codium fragile* and *Gracilaria chilensis* was reported to outnumber that of carrots [76]. Although microalgae vitamin secretion is comparable to certain fruits and vegetables, implementation of biorefinery approach on microalgal bio-active component extraction deems it a superior source compared to conventional sources [80].

The fat-soluble vitamins extracted from micro-algae need to be consumed with food items rich in lipids for effective absorption in the body. This co-relation is well understood, however, there is lack of literature data regarding edible microalgal biomass [79]. There are numerous studies that quantify the vitamin profile of microalgal species or study the potential of microalgal biomass as a functional food, although, there are no studies that incorporate both the aspects in one assessment [76,77]. Therefore, a comprehensive study which combines both these approaches need to be adopted for obtaining better insights on true potential of microalgae as a vitamin source [81].

2.4. Antioxidants

Human body continuously produces free radicals or reactive oxygen species (ROS) as a result of external stresses like smoking, chewing tobacco, excessive exposure to sunlight [82]. To counter

Table 4
Carotenoid and Phenolic activity of various microalgae strains. Adapted from [12,13]

Microalgae species	Carotenoid activity (mg/g DE)	Phenolic activity (mg GAE/g EW)
Botryococcus brraunii	2.10±0.07	1.99±0.17
Chaetoceros sp.	1.9±0.2	11.9±0.28
Chlorella sp.	0.3±0.04	8.1±0.16
Dunaliella sp.	10.8±2.02	14.0±0.43
Dunaliella salina	3.8±1.30	19.3±0.70
Haematococcus pluviallis	1.89±0.05	1.23±0.06
Isochrysis sp.	6.1±1.70	13.4±0.16
Nannochloropsis gaditana	3.0±0.24	32.0±0.57
Phaeodactylum tricornutum	6.3±0.10	16.8±0.33
Scenedesmus obliquus	0.44±0.06	1.94±0.16
Tetraselmis sp.	4.6 0.90	25.5±1.50

these free radicals, antioxidants are synthesized by the human cells. Additionally, human body has a balance between the oxidant to antioxidant ratio, any disturbance to this equilibrium will result in accumulation of free radicals. This phenomenon is known as oxidative stress. Oxidative stress is also related with numerous diseases such as diabetes, ageing, auto-immune disorder, cardiovascular disorder, atherosclerosis, rheumatoid arthritis, Alzheimer's disease, motor neuron disease and ocular disease [83]. Oxidative stress plays a pivotal role in cell and tissue damage which leads to chronic diseases such as cancer [84]. At the final stage of cancer, antioxidants are helpful in preventing further damage to human body due to carcinogenesis [85].

The production of the anti-oxidants in human body takes place in two pathways: in-situ and ex-situ. The anti-oxidants synthesized by human body in-situ or internally are known as endogenous anti-oxidants. Whereas, the anti-oxidants that are consumed externally or ex-situ through food supplements are known as exogenous anti-oxidants. The endogenous anti-oxidants are synthesized by enzymatic or non-enzymatic pathways. Although, this paper emphasises on the ability of microalgae to synthesize exogenous anti-oxidants. The anti-oxidants produced ex-situ are also known as nutrient oxidants due to their nature. They constitute of carotenoids, flavonoids, trace metals (zinc & selenium), vitamin C & E and fatty acids (ω-3 and ω-6 fatty acids) [83]. Table 5 illustrates PUFA composition of various freshwater and marine microalgae.

Microalgal biomass is considered to be superior source of nutritional anti-oxidants due to its higher production capacity compared to conventional plant-derived sources. Microalgae are also capable of producing multiple components in single species. For example, composition analysis on Chlorella Sorokiniana revealed that the total carotenoid content was 0.69% of dry matter. The α-tocopherol, β-carotene and lutein content were 112, 600 and 4300 μg/g of dry matter, respectively. These compounds possess high radical scavenging properties [86]. The antioxidant capacity of phycobiliproteins in *Phordium autumnale* was measured as 274 μmol trolox g^{-1} of dry biomass weight [46]. It is also reported that antioxidant such as astaxanthin extracted from microalgae have greater antioxidant activity compared to α- carotene, β-carotene, lycopene, lutein and Vitamin E. Although, it is lower than that from synthetically produced antioxidants such as Butylated hydroxyanisole (BHA) and Butylated hydroxytoluene (BHT) [87]. However, due to better awareness in the consumers, there is a huge demand for naturally sourced antioxidants. Moreover, as these compounds are included in pharmaceuticals, functional foods and beverages for human consumption, extraction of natural antioxidants is gaining traction [4]. To conclude, the bioavailability of antioxidants extracted from microalgae is higher than synthetic sources and provide better protection [17,18].

3. Market trends

In recent years, health related issues have been rising and there is a rising interest in consumption of 'healthy foods' or 'superfoods'. Superfoods are nutritionally dense functional foods which have added health benefits and may prevent or cure some chronic diseases. This has driven new research opportunities for evaluation of different sources for production of healthy functional foods [62]. Among the algal-derived products, the production of dried Spirulina spp. is the highest with around 12,000 tons per year, followed by *Chlorella* spp., *Dunaliella salina, A. flosaquae, Haematococcus pluvalis, C. cohnii* and *Shizochytrium* with 5000, 3000, 1500, 700, 500 and 20 tons per year, respectively [16]. However, these values are very low compared to terrestrial crops such as palm oil whose production per year is 40 million tons [88]. The recently published Credence Research market report on algal products states that Compound Annual Growth Rate (CAGR) of algae-based products is expected to cross 5.2% and the market value will stand at US$ 44.6 billion by 2023 [89]. Due to the rising demand of microalgae, particularly Spirulina, for applications in cosmetics and natural colorants, the CAGR of the global Spirulina market was expected to be around 10% with an estimated value of US$ 2000 million by 2026. On the other hand, Chlorella ingredients market is anticipated to achieve a CAGR of 25.4%, reaching US$ 700 million by 2022. The global market for natural sources of astaxanthin in aqua feed, cosmetics, food and beverages, and nutraceuticals also shows the potential of utilizing microalgae to provide the needs of the respective market demand [16]. Table 6 illustrates some of the examples and their benefits for human health.

4. Conclusion

Microalgal derived food and nutraceutical products possess a huge potential to decelerate the rate of malnourishment in developing nations. The abundance of proteins and other essential nutrients in microalgae can develop a massive algae-based food industry, dedicated towards commercialization of healthy and functional foods. Apart from complete EAA profile, microalgae contain various bio-active components which act as anticarcenogenic, antioxidative, antihypertensive and hepatoprotective agents. Moreover, microalgal derived biomass is utilized for other purposes like production of biofuels and feeds for animals, poultry and fishes. The utilization of microalgae-derived products have been growing exponentially in recent decades. How-

Table 5
LC-PUFA composition of various microalgae species. Adapted from [14]

LC-PUFA	*Chlorella vulgaris* (green)	*Chlorella vulgaris* (orange)	*Diacronema vlkianum*	*Haematococcus pluvialis*	*Isochrysis galbana*	*Spirulina maxima*
ALA	661±12	3665±1	14±1	3981±2	421±5	40±0.1
DHA	16±1	80±1	836±41	-	1156±40	-
EPA	19±1	39±1	3212±57	579±6	4875±108	-
Total ω-3 PUFA	971±14	4781±2	5407±146	5770±14	6461±153	58±35

Table 6
Microalgae incorporation in food products

Type of product	Microalgae species	Addition	Benefit	Ref
Biscuits	*A. platensis*	1.63,3,5,7,8.36% w/w	Nutritional and Techno-functional properties (protein, fiber and anti-oxidative content)	[15]
	A. platensis, Phycocyanin Extract	0.3,0.6 and 0.9% w/w to wheat flour	Nutritional properties	[16]
Bread	*A. platensis, C. vulgaris, P. tricomutum and T. suecica*	2 and 6% w/w	Nutritional and Techno-functional properties (anti-oxidative activity)	[17]
	I. galbana	1 and 3% w/w	Nutritional and Techno-functional properties (ω-3 PUFAs)	[18]
	A. fusiformis	1 and 3% w/w in the flour		[19]
	A. platensis	11% w/w in flour		[20]
	A. platensis (gluten free bread)	2-5% w/w in flour	Nutritional and Techno-functional properties (proteins and mineral content)	[21]
	A. platensis and O. amphibian	5% w/w algal protein in flour		[22]
	Arthrospira sp.	2,2.5 and 3% w/w in flour		[23]
	Dunaliella sp.	10% w/w with algal biomass, biomass without β-carotene and biomass without β-carotene and glycerol.		[22]
	I. galbana, N. gaditana, S. almeriensis, T. suecica	0.47% w/w in flour		[24]
Cookies	*C. vulgaris*	0.5, 1.0, 2.0 and 3.0 % w/w in flour	Colouring agent	[25]
	H. pluvialis	5, 10 and 15% astaxanthin in flour	Nutritional and Techno-functional properties (antioxidative activity)	[26]
Extruded snacks	*Arthrospira sp.*	0.4, 1.0, 1.8, 2.6 and 3.2% w/w	Nutritional and Techno-functional properties (proteins content)	[27]
Emulsions: Oil/water	Green and orange *C. vulgaris* (after carotenogenesis)	2% w/w	Techno-functional properties	[28]
	Green and orange *C. vulgaris* and red *H. pluvialis* (after carotenogenesis)	*C. Vulgaris*: 0.25-2.0% w/w *H. pluvialis*: 0.05-2.0% w/w	Colouring agent and nutritional properties (antioxidative activity)	[29]
Fermented milk	*A. platensis*	3 g/L	Nutritional properties	[30]
Frozen yogurt	*Arthrospira sp.*	2-8% w/w	Nutritional properties	[31]
Pasta	*A. maxima,* green and orange *C. vulgaris* after carotenogenesis	0.5, 1.0 and 2.0% w/w in flour	Nutritional and Techno-functional properties	[32]
	A. platensis	1-3% w/w in flour	Sensory quality and nutraceutical potential	[33]
		5, 10 and 20% w/w in flour	Nutritional and Techno-functional properties (antioxidative activity)	[34]
	D. salina	1-3% w/w in flour	Nutritional and Techno-functional properties	[35]
	D. vlkianum and *I. galbana*	0.5, 1.0 and 2% w/w in flour	Nutritional and Techno-functional properties (ω-3 PUFAs)	[36]
	S. platensis	5 and 10% w/w in flour	Nutritional and Techno-functional properties (protein enrichment)	[37]
Probiotic Yogurt	*A. platensis*	0.1-0.8% w/w	Nutritional and Techno-functional properties	[22]
Processed cheese	*Chlorella sp.*	0.5 and 1.0% w/w	Nutritional and Techno-functional properties	[38]
Vegetarian food gels	*A. maxima* and *D. vlkianum*	0.1- 1.0% w/w	Nutritional and Techno-functional properties (antioxidative activity, ω-3 PUFAs)	[39]
	A. maxima, C. vulgaris, D. vlkianum and H. pluvialis	0.75% w/w		[40]
	A. maxima and *H. pluvialis*	0.75% w/w		[41]
Yogurt	*Chlorella sp.*	Powder extract: 0.25% w/w Liquid extract: 2.5-10%	Nutritional and Techno-functional properties	[42]

ever, micro-algal based functional foods have not been utilized up to its potential capacity due to the high cost associated with microalgae harvesting step and component extraction. The major hurdle towards success of micro-algae derived foods is the lack of incentives for microalgal-based foods production coupled with low awareness about its health benefits. As these obstacles are settled, incorporation of food and nutraceutical industry with microalgae will benefit the health and well-being of humans. Additionally, it will also tackle issues related with climate change and potentially overcome the dietary requirement of expanding global population.

Conflict of interest

The authors declare no conflict of interests.

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