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This book is dedicated to my beloved parents, M.A. Sobhan and Rofia Sobhan*.*
Actually, my parents live in a village in Bangladesh, so science books may not change their lives or be within their reach. But, my love towards them will remain noted for as long as this book lasts.

— Md. Asraful Alam

Preface

Microalgae are predominantly fascinating sources of products ranging from human nutrition, food/feed additives, cosmetics, medicines, and health supplements to emerging sources including bioplastics, bio-based polymers, and vaccination agents for aquaculture organisms. The global market for microalgae products was valued at US$ 32.60 Bn in 2017 and estimated to reach US$ 53.43 Bn by 2026 (https://www.credenceresearch.com/report/algae-products-market). The major products currently being commercialized or under consideration for commercial extraction include human nutrition, animal and aquatic feed, phycobilins, β-carotene, polysaccharides, polyunsaturated fatty acids, vitamins, sterols, stable isotope biochemicals, biologically active molecules of antimicrobial, antiviral, antibacterial, and anticancer drugs for use in human and animal health; however, more new items are likely to be produced in the following decade. Moreover, commercial algae production is being lauded recently as a new agricultural phenomenon that can provide sustainable feedstocks of proteins and oils for hundreds of new products, absorb millions of tons of carbon dioxide, treat wastewater, and become a driver of economic growth around the world. Our previous book *Microalgae Biotechnology for Development of Biofuel and Wastewater Treatment* addressed microalgae, which represent a very promising biomass resource for wastewater treatment and producing biofuels; in that edition, we have vastly presented the culture and harvesting technology of microalgae in fresh or in wastewater either in open or close system. This book, *Microalgae Biotechnology for Food, Health, and High Value Products* has focused only on the various applications of microalgae ranging from human nutrition, food/feed additives, cosmetics, medicine and health, soil improvement, etc. It provides coverage of relevant, up-to-date research assembled by a group of contributors who are dedicated to the advancement of microalgae applications for human kind. We believe that this book will be greatly helpful for commercial algae producers, algae product developers, scientific researchers, students, or community people who are dedicated to the advancement of microalgae biotechnology for health, diet, nutrition, cosmetics, biomaterials, etc.

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Part I
Microalgae in Food Product Development

Chapter 1
Food and High Value Products from Microalgae: Market Opportunities and Challenges

Khondokar M. Rahman

Abstract Microalgae are a potential source of molecules for a wide range of food and novel high-value products and have good market opportunities. They can be used in biofuels, health complements, feed, medicine and cosmetics. The development of innovative and sustainable technologies with minimum energy inputs is required for large-scale cultivation and downstream processing of lipids and hydrocarbons in order for the production to be economically viable. In addition, the viability of bioenergy production from microalgae biomass is contingent on the net energy gain of the overall process, with exhaustive utilization of algal biomass for biofuel and other co-products for feed, food, and chemicals. The energy output from the biomass as fuel has to be greater than the energy required to produce and process the algae. Microalgae produce a comprehensive variety of bioproducts such as enzymes, pigments, lipids, sugars, vitamins and sterols. Moreover, its capability to alter atmospheric CO_2 into beneficial products such as lipids, carbohydrates, metabolites and proteins cannot be overstated. The key challenges appear to be high cost of operation, infrastructure and maintenance, selection of algal strains with high protein contents, dewatering and commercial scale harvesting. Optimizing the manufacture and commercialization of microalgae value products depend also on numerous factors (such as market and financial affairs). There is limitation of authentic and reliable data and statistics of microalgae market opportunities which make it difficult to assess their actual potential. Long-term research is needed to develop systems for the production of sustainable algal-based products, as sustainability is a key concern especially for food, feed and fuel.

Keywords Microalgae · High value product · Market challenges · Opportunities

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1 Introduction

Algae which grow through photosynthesis are a diverse group of simple plants that can range from microscopic (microalgae) to large seaweed (macroalgae). They play a vital role in many ecosystems. Algae are disseminated globally specially in the sea, in both fresh and wastewater.

Microalgae are unicellular, but some are larger, multicellular organisms (Ozkurt 2009), for example macroalgae (or seaweed) (Fig. 1.1). It is almost recognized in the academic community that microalgae are not viable for fuels commercially or sustainably due to the cost and nutrient inputs.

A number of microalgae have been examined for their prospect of value-added products with extraordinary pharmacological and biological potentials, animal and fish feed, cosmetics, chemicals and polymer, pollution control, etc. (Khan et al. 2018). Biotechnology for the cultivation of microalgae has developed since the middle of the last century for the production of biofuel when oil price increased dramatically but now numerous commercial applications have been recorded. The most widespread application of microalgal culture has been through aquaculture for farming of marine animals, including finfish, crustaceans and molluscs. There is potential to develop multi-trophic systems and utilize microalgae for the purpose of bioremediation of, for example wastewater or aquaculture wastes, which reuses the wastewaters for the growth of micro- and macroalgae. Wastewater provides nutrients, for example ammonia, nitrite, nitrate, dissolved organic nitrogen and phosphate (Abe et al. 2002), which can be used for the production of microalgae. Microalgae are photosynthetic with the potential to produce hydrocarbons and lipids whilst harnessing the energy of the sun and sequestering carbon dioxide. This chapter presents the outcomes of a review of current scientific, economic and market expansions in the various field of products derived from microalgae for food, feed and high-value products (HVPs). It delivers the existing and future projections on topics related to the field of microalgae. The areas covered in this study are as follows:

1. Microalgae Background and a Brief History of Algal Research.
2. Algae to Algae Product: A Value Chain.
3. High-Value Product from Microalgae.
4. Microalgae Product and Market.
5. Future Prospects of Microalgae Industry.

1.1 Microalgae Characteristics and Composition: Background

Microalgae is a rich carbon source, and this can be utilized in biofuels, health supplements, pharmaceuticals and cosmetics (Das et al. 2011). They also have potential to bioremediate wastewater and CO_2 sequestration (Alam and Wang 2019). A wide range of bioproducts, as well as different materials such as polysaccharides, lipids,

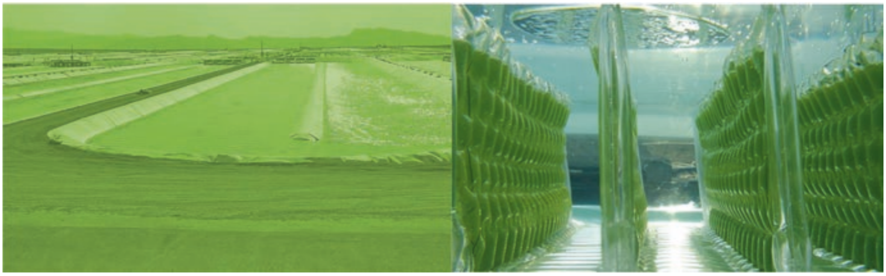

Fig. 1.1 Microalgae (DOE: U.S. Department of Energy and Wageningen University 2016)

pigments, proteins, vitamins, and antioxidants, are produced from microalgae (Brenna and Owende 2010). Advances in cultivation technologies and techniques and genetic engineering offer potential to expand their application and processing for high-value products.

Industrial-scale cultivation of microalgae to produce bioproducts and bioenergy has received increased attention in recent decades and its applications have been widespread. (Plaza et al. 2009). Algae is produced and sold directly as food and nutrient supplement, while it's treated goods are used in both the biopharmaceuticals and cosmetics industries (Luiten et al. 2003; Borowitzka 2013; Pulz and Gross 2004).

Microalgae and cyanobacteria are recognized as marketable sources of HVPs, for example β-carotene, astaxanthin, pigments and extracts from algae, which are used in cosmetics. Algal products are categorized into three types based on their market values, and they are: high-value, medium-value and low-value products (Fig. 1.2).

1.2 A Brief History of Algal Research

Algae have been used as a food source and for treatment of various illnesses for over two thousand years in China, Japan, Tawian and Australia (Gao 1998). Regarding microalgae use as an energy fuel, Meier (1955) and Oswald and Golueke (1960) recommended the use of microalgal cell from biological compound fraction for the production of methane via anaerobic digestion (AD). The detection of a number of microalgae species that can produce relatively high concentrations of lipids similar to the cellular oil under certain evolution circumstances times back to the 1940s (USDOE 2010).

Microalgae contain higher concentrations of lipids compared to any terrestrial plant. An average lipid content differs from 1% to 70% while under specific functioning circumstances few of them can reach up to 90% of oil weight by dry biomass weight (Mata et al. 2010; Georgianna and Mayfield 2012). There have been a number of serious global crises in oil production. For example, the two worst crises in the oil and energy sector were in 1973 and 1979 during the Yom Kippur War and

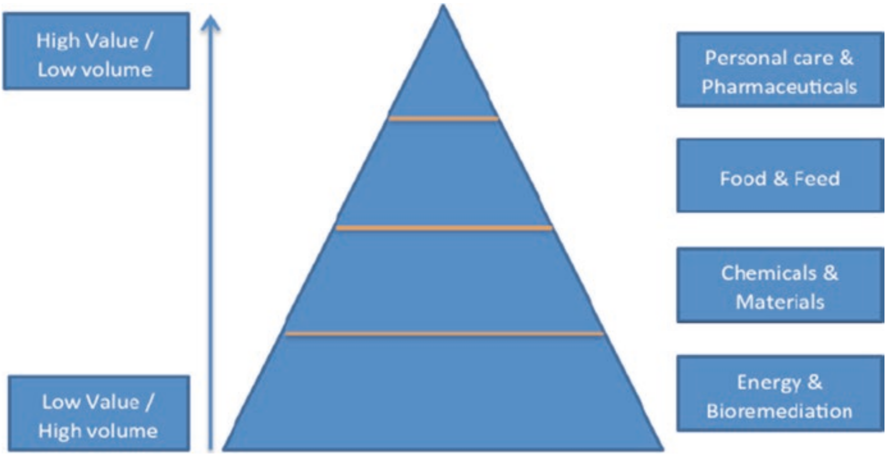

Fig. 1.2 Value pyramid: market value of microalage products (Voort et al. 2015)

the Iranian Revolution. This initiated disruptions in Middle Eastern oil dissemination (Oil Squeeze 2008; Duncan 2001). Research into microalgae as an alternative biofuel emerged in 1978 after an oil crisis struck. The use of microalgae for biofuel production has gained enormous research interests in recent years, mainly due to the ability to photosynthetically convert CO_2 into potential biofuel biomass, and food, feedstocks, and high value biochemical (Zeng et al. 2012).

By evaluating the physiology and biochemistry of microalgae, researchers (Hounslow 2016) narrowed their focus to potential lipid activates. For an example, under nutrient stress, lipid accumulation is favoured, and triacylglycerol (TAG) is formed as the main element. A number of studies have stated that most microalgal species can improve lipid accumulation and undergo transformation under nutrient stress.

There is a wide diversity of microalgae species with respect to the size and shape of the organisms that perform photosynthesis in eukaryotic cells. These eukaryotic microorganisms are crucial for life on earth. Planktonic algae, living in the oceans, perform nearly half of global photosynthesis (Behrenfeld and Falkowski 1997). Algal protein is a prospective source of fish and animal feed and this types of protein has been projected to get a related profile of amino acid (Gross 2013). For example, cyanobacterium *Arthrospira platensis* and many other marketable species of the single-celled green alga have 42–70% of dry weight protein (Milovanovic et al. 2012; Plaza et al. 2009) and these microalgae also have an amino acid that relates well with egg, albumin and soya (Williams and Laurens 2010) particularly comprising all of the vital amino acids which humans are unable create in their body but need to obtain from food (Gantar and Svircev 2008). Chlorophyll is a useful bioactive compound, and the process of its extraction from marine microalgae begins with dewatering and desalting the highly diluted microalgal culture (Hosikian et al. 2010).

2 Algae to Algae Product: A Value Chain

A 'value chain' has been defined by Bush (2019) as 'an interrelated functioning action businesses perform throughout the process of transforming raw materials into finished products'. The value chain and the development of high-value products from microalgae depends on composition, applications, formulation, production scale and comparative reference. An impression of the whole value chain required to derive energy from both macroalgae and microalgae. The stages of the value chain include cultivation, harvesting and biomass pre-treatment, and this includes washing, purification, dewatering and drying.

2.1 Nature and Characterization of Algae and Algae Products

Microalgae are versatile and can produce various composites like proteins, carbohydrates, lipids, carotenoids and different vitamins and minerals. The relative composition of these are dependent upon species and growth conditions (Koller et al. 2014; Hamed 2016). Various studies have been conducted on the characteristics of microalgae and to elucidate the key compounds of commercial interest. These include, for example, *Chlorella vulgaris*, *Arthrospira platensis*, *Nannochloropsis* sp. and *Phaeodactylum tricornutum* (Tibbetts et al. 2015; Matos et al. 2016); other species are *Dunaliella salina* (Muhaemin and Kaswadji 2009), *Haematococcus pluvialis* red stages (Shah et al. 2016) and green stages (Kim et al. 2015) and *Scenedesmus almeriensis* (Sánchez et al. 2008).

At present *Chlorella vulgaris*, *Arthrospira platensis*, *Haematococcus pluvialis* and *Dunaliella salina* are supported for the food, feed and nutraceutical sectors. Similarly, carotenoids and lipids, especially omega-6 and omega-3, find superior uses than existing in many markets, for example in fish and animal food, aquaculture, in protein and in cosmetics industry (Molino et al. 2018).

2.2 Principles of Value Chains: A Bio-Based Economies

The microalgae value will mostly depend on the following variables: (1) composition, (2) purity level, (3) applications and (4) formulation (Vieira 2016). The value of a product increases with its level of refinement or processing.

2.2.1 Value Depends on Composition

The chemical composition of microalgae includes: lipid at 20–30%, protein is around 50%, carbohydrate 20–30% and other compounds account for approximately 5%. The market value depends on the concentration and amount of the essential amino acids, polysaccharides, polyunsaturated fatty acid (PUFAs) and amount of essential vitamins (Vieira 2016).

2.2.2 Value Depends on Applications

Likewise, the value depends upon the application, for example what is the purpose of the use of algae and compared to similar alternative sources of this product. This includes the current application as food, feed, medicine and cosmetics and the additional application as fuels, fertilizers, wastewater treatment and chemicals (Vieira 2016).

2.2.3 Value Depends on Formulation

The value of the microalgae-based product depends upon its formulation, for example is it granular, small or bigger particle size, a paste, dry or wet. A number of dry algal products are used for food and feed, aquaculture and pharmaceuticals (Vieira 2016). This product value chain also depends on comparative reference—for example, microalgae high-value product in comparison source of algae link with others: soy and fish (oil and meal).

3 High-Value Products from Microalgae

Microalgae are progressively playing an important role in the development of cosmeceuticals, alternative of pharmaceuticals and high-value foods. High-value extracts from microalgae include: proteins, lipids, carbohydrates, different pigments, vitamins and anti-oxidants used in different sectors, such as cosmetics, nutrition and pharmaceuticals.

3.1 Algae: Human Food

Japan has a well-established market for edible products (algae soup) (Fig. 1.3a) from algae (Holdt and Kraan 2011) and according to Wellinger (2009) China and Japan have the highest production and consumption of dry algae globally. There is utilization as whole cell (e.g. nori or others) and extracts, which can be used as an ingredient.

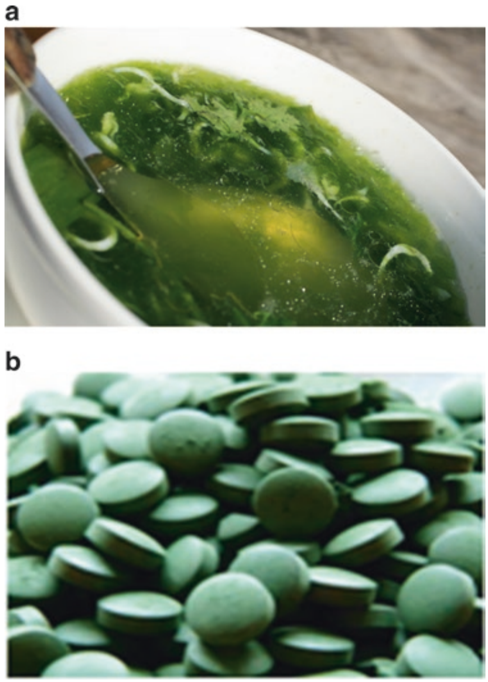

Fig. 1.3 (a) Cooking healthy soup from algae (Fresh Designpedia 2019). (b) Algae as medicine in a tablet format

3.1.1 Agar from Algae

Agar is a polysaccharide derived from seaweeds (macroalgae) of the rhodophyceae class, and the most commonly used solidifying agent (Mesbah and Wiegel 2006). Agar formulates double helices that combined to form a gel or balm, holding water within the opening (Tiwari and Troy 2015). This water-holding capacity makes this gelatinous substance a good thickener. Throughout Japan, Korea and China it was used as a desert and in other food ingredients, however, presently it is also important as a gelatine for growing organisms in medical and scientific studies.

3.1.2 Alginates from Algae

Alginates are a polysaccharide derived from Phaeophyceae, which are brown algae containing alginic acid salts and are the raw ingredients in alginates manufacture. It is a polymer made up of arrangements of α- β-D-mannuronic acid and L-guluronic acid. They are widely used in various food, beverage, printing, textile and pharmaceutical industries as a thickening agent, stabilizer, emulsifier and chelating agent (Hay et al. 2013).

3.2 Pharmaceuticals and Health-Related Products

The application of algae-based products (e.g. from cyanobacteria) in the different sectors (e.g. pharmaceuticals) has increased globally (Sathasivam et al. 2019). Interest in microalgae-based antibiotics and pharmacologically active compounds (Fig. 1.3b) is also growing. There are a variety of products in the pharmaceutical sector derived from algae and their application such as: antivirals, antimicrobials and antifungals, and drugs and therapeutic proteins. The pharmaceuticals products derived from microalgae include: omega-3 fatty acids, EPA, DHA, beta carotene and astaxanthin (Sathasivam et al. 2019).

3.2.1 Omega-3 Fatty Acids/PUFA

Acids, for example EPA and DHA, from algae have received considerable attention because of their involvement in the inhibition and action of numerous diseases, including, thrombosis, atherosclerosis and arthritis. Although marine fish oil remains the traditional source of both EPA and DHA, there are studies that seem to indicate that greater quantity of EPA and some DHA can be gained from algae. Omega-3 and omega-6 are the two most important fatty acids, PUFAs have two important groups with a long chain of carbon atoms: carboxyl and methyl groups (Harris 2010). Microalgae is capable of supplying omega-3 fatty acids at high concentrations. Different species, for example *Crypthecodinium*, *Thraustochytrium* and *Schizochytrium*, contain the omega-3 fatty acid DHA, and the species of *Phaeodactylum, Chlorella* and *Monodus* contain Eicosapentaenoic acid (EPA). The human body can only form carbon–carbon double bonds after the ninth carbon from the methyl end of a fatty acid (Jones and Rideout 2014). Alpha-linolenic acid (ALA) is an essential fatty acids, and they must be obtained from the diet and that cannot be synthesized in the body (Jones and Papamandjaris 2012).

3.2.2 Astaxanthin

Astaxanthin is a xanthophyll carotenoid present in a variety of microalgae and this is the most abundant natural pigment existing in nature (Ambati et al. 2014). The main source of astaxanthin for human consumption is obtained via digestion of seafood or extracted from the microalga *Haematococcus pluvialis*. It is estimated that the global astaxanthin market is approximately US$257 million (Khattar et al. 2009). The majority of astaxanthin produced from microalgae is utilized for aquaculture, most of them in fish coloration. The astaxanthin market size was assessed at US$555.4 million in 2016 (Market Research Report 2017). Astaxanthin is mainly utilized by the salmon feed industry due to their potent antioxidant activity; it would also be beneficial for patients with cardiovascular, immune, inflammatory and neuro-related diseases (Wu et al. 2015).

Astaxanthin is produced commercially, but naturally occurs from the microalgae species *Hematococcus pluvialis*. Astaxanthin, which produced commercially, is most commonly used is in fish farming and it conveys colouring to farmed salmonids and crustaceans (Koller et al. 2014) (Fig. 1.4). It has been used widely in the nutraceutical and pharmaceutical industry due to its antioxidant activity and fortification (Cardozo et al. 2007). The marketable astaxanthin is led by the synthetic one since the market value for the natural one is higher than the synthetic version (Pérez-López et al. 2014; Li et al. 2011). The demand for the production of astaxanthin from the natural sources has increased because the demand for health-related food to the consumer has increased.

3.2.3 Beta-Carotene

Beta-carotene is a member of a family of molecules found in microalgae and plays a vital role in health because of its antioxidant exchanges to vitamin A. Beta-carotene is a good source of vitamin A, and the provitamin A function of beta-carotene contributes to vitamin A intake (Grune et al. 2010). The concentration of carotenoids (Table 1.1) in most algae is 0.1–2%, but *Dunaliella*, if grown in the right circumstances of high salinity and light strength, could yield up to 14% of beta-carotene. Global market revenue of beta-carotene is a

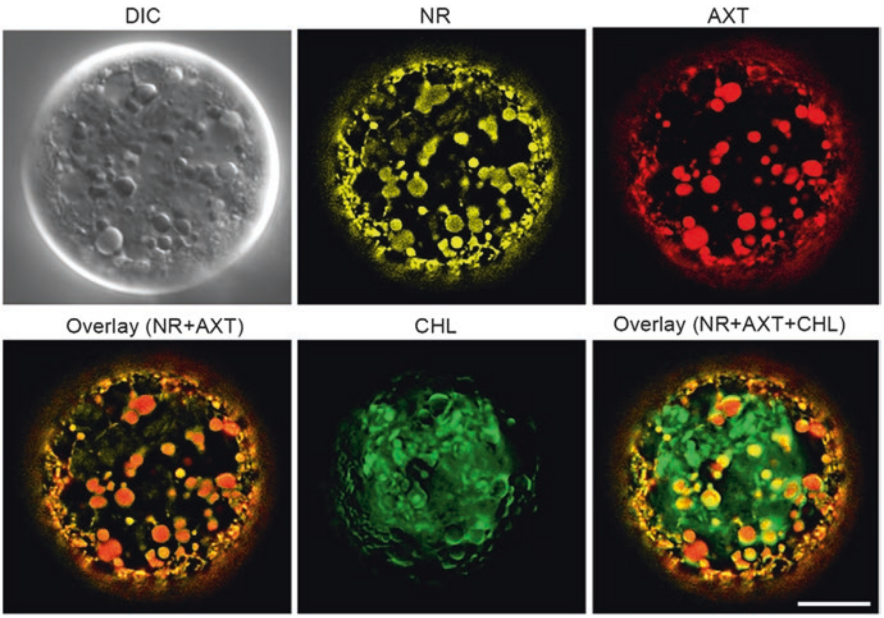

Fig. 1.4 Lipids, astaxanthin and chlorophyll in an astaxanthin-rich *H. pluvialis* cell. *NR* Nile Red, *AXT* astaxanthin, and *CHL* chlorophyll (Wayama et al. 2013)

Table 1.1 Ideal conditions of beta-carotene production by *D. salina* (Hermawan et al. 2018)

Processing condition	Reactor configuration	Productivity
Temperature: 25 °C; pH: 7.5 ± 0.5	Semi-continuous outdoor, closed tubular (55 L)	Biomass: 2 g m^{-2} d^{-1} Total carotenoids: 102.5 ± 33.1 mg m^{-2} d^{-1} (β-carotene: 10% of biomass)
Temperature: 29 °C pH: 7.5–8.6	Semi-continuous outdoor	The optimum Dissolved Oxygen (DO) 6.3–6.9 mg/L
Temperature: 30 °C; pH: 7.5	Continuous turbidostat, flat-panel (2.5 L)	β-Carotene: 13.5 mg L^{-1} d^{-1} (15.0 pg $cell^{-1}$)
Temperature 30 °C; pH: 7.5	Continuous turbidostat, flat-panel (1.9 L) with in situ extraction	β-Carotene: 0.7 mg L^{-1} d^{-1} β-Carotene: 8.3 mg L^{-1} d^{-1} (8.9 pg $cell^{-1}$)

CAGR (Compound Annual Growth Rate) of 3.5% and is US$224 million in 2018 (Transparency Market Research 2018).

Naturally, beta-carotene, which is a carotenoid compound, is derived from algae *Dunaliella salina*. The bioactivity of beta carotene is comparatively higher and this is why it is broadly used in medicine and used as provitamin A supply, precise growth and sight. Due to its antioxidants characteristics, beta-carotene is considered an inhibitor of some genes and it exhibits anticancer properties (Berman et al. 2014; Harasym and Oledzki 2014; Zhang et al. 2016).

3.3 Algae in Nutraceuticals

Algae and their extracts play an important role in the nutraceutical industry. The key species currently utilized include *Spirulina* and Chlorella, and products related to algae nutraceuticals include poly unsaturated fatty acids (PUFAs, such as DHA, ARA, GAL and EPA), beta-carotene and Astaxanthin. Dried *Spirulina* used in food supplements contains about 60% protein, with a composition which is rich in all vital amino acids (Nicoletti 2016).

Spirulina and *Chlorella* species are leading the worldwide microalgae market as they are getting acceptance in food- and health-related supermarkets and stores (Koyande et al. 2019). The two popular usable species of *spirulina* are *Arthrospira platensis* and *Arthrospira maxima* (Tomaselli 1997). Their cell wall is similar to the Gram-positive bacteria, subsequently they comprise of glucosamines and muramic acid linked to peptides (Falquet 1997). The wall of *Spirulina* is not digestible, is fragile and makes the cell content readily available to digestive enzymes.

3.4 Animal and Fish Feed

In aquaculture, microalgae are used as vital sources of live feeds and supplements for larval and juvenile animals, which include oyster spat, juvenile abalone and rotifer. The product related to food from algae is aquaculture feed, shrimp feed, shellfish diet and livestock feed. Microalgae are a significant direct and indirect feed source for the primary growing phases of many farmed finfish, shellfish and invertebrate species (Shields and Lupatsch 2012).

3.5 Algae in Cosmetics

Many algae species are used to produce high-value cosmetics. They are used as thickening agents, antioxidants and water-binding agents in cosmetics. Irish moss, AlgaVia proteins, different types of vitamins, sugar, starch, different micro-and macro-nutrients are other forms of algae. These are useful for skin, either as ointments or antioxidants and the associated invention are algae in cosmetics, carrageenan and alginates. The most common applications are in skin care, protection from sun and hair care, toothpaste, shaving cream, lotions and antibacterial creams (Pimentel et al. 2018).

3.6 Algae Chemicals

Next to the extraction of oil from algae—they commonly referred as algae cake and these cake can be used as organic manures instead of chemical or inorganic fertilizers. Microalgae as a chemical and the related products are chlorophyll, phycocyanin, fucoxanthin and the potential applications are: defoamers, inks, algae based resins, stable isotopically labelled compounds, dyes and colourants (Kruus 2017).

3.6.1 Phycocyanin

It is one of the major pigment molecules (chemical formula $C_{165}H_{185}N_{20}O_{30}$) found within *Spirulina*. The dietary and aesthetic values of phycocyanin have been well known (Romay et al. 2003). It is a dye of blue colour which fits to Phycobilli proteins found in blue green algae.

3.6.2 Phycoerythrin

This is a red protein pigment complex produced by blue-green microalgae *Arthrospira platensis*. This is generally used as natural colouring agent in the food industry (Taufiqurrahmi et al. 2017). The price of any chemicals (e.g. phycocyanin) is an important issue as it states its market capability. The cost of cultivation is one of the main factors that determine the price of phycocyanin. The carotenoids produce by certain forms of microalgae, particularly red ones, or rhodophyta, comprise phycocyanin and phycoerythrin (Becker 1994).

3.6.3 Fucoxanthin

Fucoxanthin (with formula $C_{42}H_{58}O_6$) is an explicit carotenoid found in brown seaweeds with extraordinary natural properties. Ishimozuku (*Sphaerotrichia divaricata*), an edible brown alga, has morphology that is almost indistinguishable to that of Okinawa-mozuku. Ishimozuku contains various anti-oxidant ingredients and is more likely to improve human health (Maeda et al. 2018).

4 Microalgae Product and Market

Economic feasibility depends upon the market value and production costs (e.g., biomass production costs and biorefinery costs). The algal product types are: hydrocolloids, carotenoids, and omega-3 PUFA, and their applications are in food and feed, nutraceutical, cosmetics and chemicals.

4.1 Market Opportunities: Algae-Derived Products

Commercial-scale cultivation of microalgae has already improved, even though the total production cost of some microalgae biomass is more than the industrial expectation. To develop the competitiveness of microalgae-based products, many aspects of their value chain need to be improved. The technical and the economic aspects, including maintenance, market awareness and following regulations, are important factors for wider algal market opportunities and scope. It is important to understand the regulatory framework, environmental and ecological law, and risk management for the development of microalgae based market product.

4.2 Important Determining Market Opportunities and Challenges

Algae biomass contains not only proteins and lipids. In fact, even if these products currently represent most of the algae market, further high-value bioproducts can be obtained by processing algae in efficient ways, such as pigments for food coloration; pharmaceutics and phenolics as cosmetics, skin care emollients and sun protection products. The European Biomass Industry Association (EUBIA) is currently working on this front, preparing projects and strategies to make algae biorefinery a real competitive solution. At present the manufacture of food and feed from microalgae in European countries assures 5% of global market (Enzing et al. 2014). Currently the United States, Asia and Oceania dominate the market but Europe could also be another leading country in microalgae-based bioproducts in the next decade but needs to focus on specific policies to launch specific targets.

4.3 Microalgae-Based Products: Market Opportunities and Key Challenges

4.3.1 Market Scope of Spirulina

This is a microscopic and filamentous cyanobacterium whose name originates from the spiral or helical nature of its fibres and it has been stated that it was used during the Aztec civilization (Dillon et al. 1995). *Spirulina* or *Arthrospira* is a blue-green alga which achieved fame after it was successfully used by NASA as a dietary supplement for spacemen on planetary tasks. A number of studies exploring the efficacy and the potential clinical applications of *Spirulina* in treating several diseases have suggested anticancer, antiviral and anti-allergic effects (Karkos et al. 2011).

The market for food companies was not well organized and control in 1970–1980 when *Spirulina* was introduced on the market. The current main providers of *spirulina* are located in the USA (Earthrise), Hawaii and Thailand (Bosschaert 2002). Regarding the market scope of *Spirulina*, the logistics are simple, and Merredin's location is ideal for logistics purposes.

4.3.2 Market Scope of Omega-3 Fatty Acids/PUFA

Omega-3 PUFA market is predicted to grow at a CAGR of 13.5% (Market Watch 2018). Omega-3 poly unsaturated fatty acid (PUFA) is a type of necessary fatty acid which cannot be synthesized by the human body and which needs intake through omega-3-rich food. Omega 3 PUFA is used to enhance the cardiovascular and cognitive functioning of the human body. The ingredients of Omega-3 PUFA are sourced from various fish oil, krill oil, chia seed, flaxseed and other plant sources (Market Research Future 2019). The Global Omega-3 PUFA Market is segmented into Europe, North America and Asia Pacific along with rest of the world (RoW). Among these, North America holds the major market share in the global Omega-3 PUFA market both in terms of value and volume. This is attributed by the rising number of health conscious people in the USA and also presence of companies in the North American region such as Unilever, Abbott, and Nestle SA. Also, vital companies are introducing new products in the North American region in order to retain their existing customers and also to acquire new customers. The Asia Pacific region is expected to grow immensely during the forecast period (Market Research Future 2019). According to FAO statistics (2010) the market size of EPA and DHA are 300 million and 1.5 billion USD, respectively, and the price is 0.2–0.5 USD/gm and 18–22 USD/gm, respectively.

Over 75% of the manufacture volume of microalgae was used in the health food marketplace as nutritional enhancements (Chacon-Lee and Gonzalez-Marino 2010). The algae-based valued food additives and ingredients, e.g. DHA, represent a rising market. Martek's (now DSM) algae-derived DHA is found in 99% of all baby foods in the USA (Eckelberry 2011).

4.3.3 Market Scope of Astaxanthin

The demand for natural astaxanthin is now increasing and it has been increased into a billion dollar market potential of nutraceuticals (Martín et al. 2008). The Global Astaxanthin Market is segmented into five regions: (1) Asia Pacific, (2) North America, (3) Europe, (4) Latin America and (5) Middle East and Africa. North America holds a major share of the market due to the growing demand for carotenoid pigments in feed, supplements, food, health care products, and others. The feed segment is predicted to witness a rapid growth in the market due to growing consumption of *Haematococcus pluvialis* to produce high standard astaxanthin in countries such as the USA, Canada and Mexico. It is estimated the health care products section is set to witness a higher growth in market share during the forecast period 2017–2023 (Market Watch 2019). It is projected that the astaxanthin market is set to spectate a higher growth owing to growing use of carotenoid pigments during the forecast period (Market Watch 2018). According to Shah et al. (2016) the total value of astaxanthin synthesis is estimated at more than $200 million, which corresponds to 130 metric tons of product annually. The average market price is above USD 2000 per kilogram, and the cost is estimated at USD 1000 per kilogram (Shah et al. 2016; Milledge 2011). Recent investigations showed that microalgae-derived astaxanthin was only responsible for less than 1% of the total commercialized market, ascribed to its higher product prices than those of synthetic products and technological challenges of large-scale cultivation and harvesting of microalgae (Koller et al. 2014). The chemical components and structures of natural astaxanthin improve its bioavailability and biological activities (especially antioxidant activity), which highlight the commercial value of the carotenoid. Due to the growing market demand on natural astaxanthin, the market value is estimated at US$1.1 billion and projected to reach 670 metric tons by 2020 (Shah et al. 2016). In the case of *Haematococcus* astaxanthin, the market value is estimated in the range US$2500/kg to US$15,000/kg, depending on products' purity (Koller et al. 2014; Pérez-López et al. 2014). The market size and country wise market sector and future market potential of Astaxanthin are presented in Tables 1.2 and 1.3, respectively.

4.3.4 Market Scope of Beta-Carotene

Europe held the largest market share of beta-carotene in 2017 (Market Watch 2019). The growth in the food and beverages (Fig. 1.5), pharmaceutical and personal care industry has caused a rise in the beta-carotene market. Food and medicine industries in developing countries, for example China and India, is contributing to the increase in demand for beta carotene market in Asia Pacific (Table 1.4). The market share of

Table 1.2 Market size and potential market of microalgae products (Molino et al. 2018)

Market sectors/area	Market size (year 2009) (Million US dollar)	Potential market (year 2020) (Million US dollar)
Colouring agents	300	800
Antioxidant nutraceuticals	30	300
Pharmaceuticals/ chemicals	Developing	500
Cosmetics/makeups	Emerging/rising	30

Table 1.3 Prominent countries having market sectors and future market for Astaxanthin

Company	Location	Production capacity of pure Astaxanthin
Alga Technologies	Israel	N/A
Cyanotech	Hawaii	N/A
Stone Forest Astaxanthin Biotech Co Ltd	China	1200 kg/year
Yunnan Baoshan Zeyuan Microalgae Health Technology Co., Ltd	China	500 kg/year
Jingzhou Natural Astaxanthin Inc	China	N/A
Beijing Gingko Group	China	900 kg/year
Yunnan Alphy Biotech Co Ltd	China	600 kg/year
Yunnan SGYJ Biotech Co Ltd	China	400 kg/year
Algaetech International	Malaysia, Indonesia	N/A
Parry Nutraceuticals	India	N/A
Mera Pharmaceuticals Inc.	Hawaii	N/A
Fuji Chemicals	Japan, Sweden	N/A
Valensa International	Florida	N/A

N/A: data not available

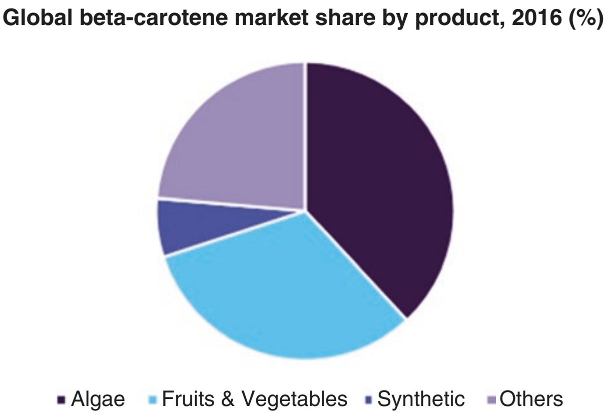

Fig. 1.5 Market share of beta-carotene from algae (Market Research Report 2016)

Table 1.4 Prominent companies in the beta-carotene market (Market Watch 2019)

Company	Location/area
Aqua Carotene	USA, New Zealand
Cognis Nutrition and Health	Australia
Fuqing King Dnarmsa Spirulina Co., Ltd.	China
Cyanotech	Hawaii, USA, UK
Nikken Sohonsha Corporation	Japan
Tianjin Lantai Biotechnology	China
Parry Nutraceuticals	Asia/India
Seambiotic	Israel
Muradel	Australia

beta-carotene in 2017 is estimated as US$247 million, but this amount was increased to US$285 million by 2015 which is a CAGR of 1.8% (Rastogi et al. 2017).

4.3.5 Market Scope of Phycoerythrin

Phycobiliproteins is a protein produced commercially from *Spirulina* and the red microalgae *Porphyridium* and *Rhodella* (Becker 1994; Singh et al. 2005; Borowitzka 2013; Spolaore et al. 2006). Ultrafiltration was used to isolate phycoerythrin protein from *Grateloupia turuturu* following cell homogenization, which was testified to retain 100% of the protein without denaturation (Denis et al. 2009). Phycoerythrin can establish a significant amount of the complete protein content in red algae, with levels of 1.2% reported for *P. palmata* (Wang et al. 2001).

The key companies in phycoerythrin market are: Europa Bioproducts, Sigma-Aldrich, Jackson Immuno Research, Thermo Fisher Scientific, SETA BioMedicals, Binmei Biotechnology, Algapharma Biotech, Phyco-Biotech, Norland Biotech, Columbia Bioscience and Dainippon Ink and Chemicals. The main regions which play a vital role in phycoerythrin market are: North America, Europe, China, Japan, Middle East and Africa, India and South America. The most important types of Phycoerythrin products: PE545, R-phycoerythrin and B-phycoerythrin (Market Watch 2019). The prominent commercial market sources of Phycoerythrin are: Europa-bioproducts, Cambridge, UK, and Invitrogen, NY, America.

4.4 European Guidelines on Marketing of Microalgae Products

The key challenges of marketing microalgae products in the European Union are: biomass production cost, technical breakthroughs, access to venture capital and regulatory, academic and industrial training (Fig. 1.6). It is very important to understand, monitor, observe and practice the regulation for food and feed prior to use and marketing.

The market size based on the amount of nutrient obtained from microalgae are still less compared to the ones derived from cereals and other crops. But still the sector has seen an impressive and exceptional growth. Even with the challenges due to the climatic situations together with the inadequate domestic demand and the difficulty of the EU Novel Food regulation, a survey discovered that the EU can improve its market position in the next decade (Vigani et al. 2015). The general

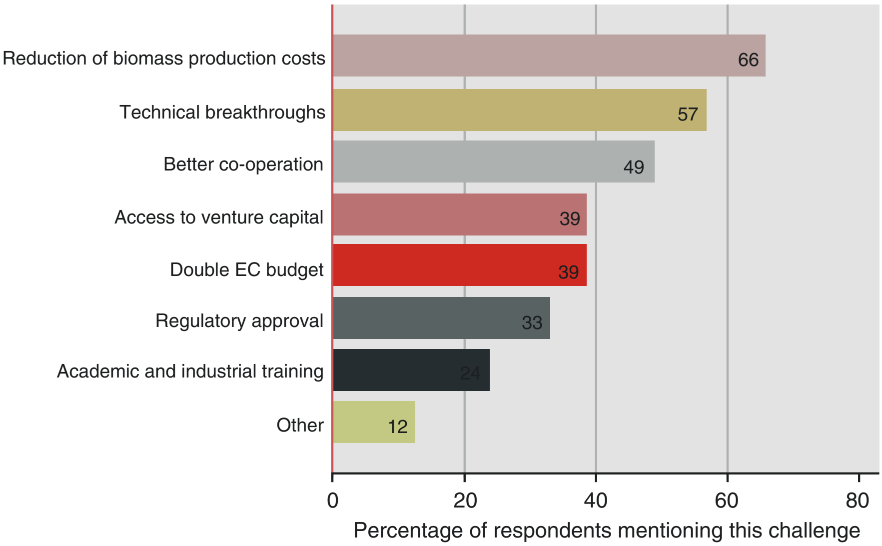

Fig. 1.6 Key challenges in the development of microalgae market in the EU (Salimbeni 2014)

principles and requirements of EU food law are controlled under Regulation (EC) 178/2002. Other relevant regulations include (Parker et al. 2014):

- Regulation (EC) 258/97 on novel foods and ingredients.
- Regulation (EC) 767/200 on the marketing of feed materials and compound feed.
- Regulation (EC) No 41/2009.
- Regulation (EU) No 1169/2011.
- Commission Implementing Regulation (EU) No 828/2014 (European Union 2014).
- Directive 89/107/EEC on food additives.
- Regulation (EC) 1831/2003 on the authorization, and labelling of feed additives.
- Regulation (EC) No 852/2004 on food hygiene.
- Regulation 183/2005 on feed hygiene.
- Regulation 1829/2003 on GMOs for food and feed.
- Regulation (EU) No 828/2014.

A significant number of other European Union regulations and directives cover the production and distribution of animal feedstuffs, while Regulation 183/2005 is the key measure for algal production. Market introduction of food products using the whole microalgae (e.g. *Spirulina* or *Chlorella*) or microalgal ingredients which are incorporated into pasta with the green algae colour are subject to food safety regulations that apply to all food products. Production through engineering technology and marketing of food and feed from microalgae are mainly regulated into the European Community by the Food Safety Regulation (EC 178/2002) and the Novel Food Regulation (EC 258/97) (Enzing et al. 2014) (Table 1.5).

Table 1.5 EU and USA safety guidelines regarding investigation, manufacture and market of microalgal products for food and feed applications (Modified from Enzing et al. 2014)

	Europe	United States
Research	– Commission Implementing Regulation (EU) 2017/2470. – EC directives 2009/41/EC (GM algae). – EC directive 2001/18/EC (GM algae).	– NIH rDNA Guidelines. – EPA Standards, under the Toxic Substances Control Act (TSCA).
Production	– EC directives 2009/41/EC (contained use of GM algae). – EC directive 2001/18/EC (deliberate release of GM algae).	– TSCA Environmental Release Application (TERA). – Microbial Activity TSCA. – USDA Plant Protection Act.
Market introduction	– Regulation on Food Safety (EC 178/2002). – Regulation EC 2017/2470 Directive 2002/46/CE (Borowitzka 2013). – EC Regulation on Genetically Modified Food and Feed (EC 1829/2003). – Regulation EC2017/2470 and 2002/46/CE. – EC Regulation on Nutrition and Health claims made on foods (EC 1924/2006).	– Food, Drug and Cosmetic Act. – Dietary Supplement Health and Education Act.

5 Future Prospects of the Microalgae Industry

To ensure the sustainability of the microalgae biorefinery process, an advanced microalgae biorefinery needs to be applied through the production of manifold products in the form of HVPs and biofuel. Algae can play an important role in the biobased economy and they are efficiently cultivated in places that are unsuitable for agriculture and where nature is not harmed (Wolkers et al. 2011). Recently, microalgae cultivation has received increased attention because this could synthesize larger amounts of HVPs, such as pigments, vitamins, PUFAs, anti-oxidants and many more.

Algae are considered the most diverse group of organisms on earth and therefore have potential for advanced use in the future, however based on its demand and potential supply and technology. Algae and algae-derived products have future prospects in the industrial sector based on the demand in this sector and having the capability of algae for industrial use. The use of algae-based products in pharmaceuticals (bioactive and new drugs), nutraceuticals (probiotic, antioxidants) and also use in industry as biofuels, chemical/enzyme, new cosmetics/cosmeceuticals which is currently limited, has a wider scope to expand. Future prospects of product areas of algae are: nutrient-rich food, bioenergy, bioactive medicine, novel enzymes, specialist chemicals, biofertilizer, clean insecticides and bioremediation. Despite potential demand, supply and technical expertise, technological issues hinder the future prospects of algal applications. The major constrains include: engineering difficulty in production, formulation of invention, strain stability and productivity. Refining of algal fuel and bioproducts technology from an experimental scale to a profitable level is possible by overcoming the challenges and limitations associated with this technology.

6 Conclusion

The nature, characteristics and composition of algae are diverse and the reason product types and formulations are different. Based on an extensive overview on microalgal research, it was found that significant research on microalgae, microalgal product and their market potential have been conducted at the lab, pilot and in large scales. The value chain of microalgae and algal products is a biobased economy and the value depends on its composition, application and formulations. The potential high-value products (HVPs) from microalgae are: food, agar, alginates, astaxanthin, beta-carotene, omega-3 fatty acids, phycocyanin, phycoerythrin and fucoxanthin; these are used mainly in pharmaceuticals, nutraceuticals, cosmeceuticals and industrial sectors. High value product that extracted from microalgae improve the economics in a biorefinery approach and have its market scope and opportunities. However it need to understand whether it is market driven or technology driven. Production economics such as the cost effectiveness of the system is also important for further investments. The technology also needs to be robust and reliable for its market flow.

Microalgae is not currently considered economically viable for the production of fuel but has proven potential for the production of food and high-value products. This chapter provides insights on the broader algae-based value chain, high value products derived from microalgae, their market scope and opportunities and biorefinery of microalgae for the production of high-value products. The proper and modern use of technology and tools gives higher yield, comfort of operation and helps economic processing. The potential for production of multiple products from microalgae has led to more effective and efficient invention pathways in the use of materials and energy. An understanding of the environmental impacts and legislations is important in the evaluation of technology and economic performance of a biorefinery system and its marketing. From an algal value chain analysis, it was found that value depends on composition, application, formulation, production scale and comparative reference. To increase the market opportunities of algae-derived products, it is important to determine market opportunities and challenges and find a sustainable solution. It is very important to practice and understand the rules, regulations and legislation related to algae in high-value products and their supply chain stages. There is no formal regulation related to algae and algae high-value products in many developing countries, but there are a few regulations in the EU, USA and other parts of the developed world. These regulations are on novel food and ingredients, feed material and compound food, food additives, food hygiene, and GMOs for food and feed. It is important to emphasize on research, production and market introduction for better prospects in the microalgae industry.

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