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Review

A review on bioenergy and bioactive compounds from microalgae and macroalgae-sustainable energy perspective

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ABSTRACT

Though microalgae and macroalgae are considered as a potential feedstock for biofuel and industrially important co-products extraction, still there are several research barriers on the commercialization of algae-based fuels and products. Based on these bottlenecks, this review underpins the biochemical composition of micro- and macroalgae regarding biofuel production and bioactive compounds extraction. Further, the second chapter summarizes the various cultivation systems for rapid generation of macroalgal biomass. Micro- and macroalgae are untapped for bioenergy production to assess the feasibility of future green fuel sustainability. In general, algae were considered as a potential source for various applications worldwide owing to their rich and enormous bioactive potential. Therefore, a separate section devoted to recognize the crucial role and biological activities of primary and secondary metabolites in micro- and macroalgal species, their significant contribution as functional foods or therapeutic agents in nutraceutical and pharmaceutical industries. The extensive discussion on the phenolics, flavonoids and pharmacological properties of other bioactive compounds extracted from microalgae has been provided. Further, carbohydrates, proteins (phycobiliproteins and phycoerythrin) and their organic extraction from macroalgal strains (seaweeds) were well described. This review paper describes the importance of bioactive compounds and their value in the various other markets besides biofuel production.

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1. Introduction

Altogether, the mainstream of energy comes through fossil fuel, and fossil fuels satisfy about 80% of the world's energy requirement as per qualified estimations (Mathimani et al., 2018; Mathimani et al., 2019), and human population perhaps require ~70%, 50%, and 50–80% of higher food, fuel, and low emission respectively by 2050 (Mathimani et al., 2017a). In the perspective of economic and environmental benefit, a quest for sustainable fuel has become an emergency to ensure the access of the biofuel from affordable, and sustainable bio-resource (https://www.un.org/sustainabledevelopment/wp-content/uploads/2018/09/Goal-7.pdf). Under sustainable development goals, goal 7 promotes affordable and clean energy to circumvent huge imbalance in the current energy system and to invest in inexhaustible energy sources, and further, renewable energy progress are measured in terms of total final energy consumption (http://in.one.un.org/page/sustainable-development-goals/sdg-7/). Tracking the energy progress report of 2018, 85% of Indian population accounts for accessing electricity, 41% for accessing clean cooking, and only 36% are confined to energy consumption from renewable sources (http://trackingsdg7.esmap.org/country/india).

Being a non-renewable feature of fossil fuels the usage of energy is likely to escalate from 550 EJ (Exajoule) to 865 EJ by 2040 (Creasey et al., 2014). In energy production and consumption among the countries, India is in the 7th and the 5th place respectively (Mathimani et al., 2018; Mathimani and Mallick, 2018). Further, fossil-based fuel contributes to a high segment of greenhouse gases emission (Hemaiswarya et al., 2012). Eventually, uncertainties in fossil fuel availability and its augmented greenhouse gas emission exemplify two major disputes such as a steady escalation in fuel demand and climatic hitches like global warming (Martín and Grossmann, 2017; Kaenchan and Gheewala, 2017; Raheem et al., 2018). These issues compel us to find technically viable, ecologically suitable, and an alternative fuel (Mathimani et al., 2016) to fossil fuels, which are the primary source of CO_2, CO and other pollutant emissions (Mathimani et al., 2017b). In this juncture, not exaggerated, the most often-touted substitute is biofuel, even though several substitutes are being explored to supplant the current high-pollutant - diesel (Koller et al., 2012; Loong and Idris, 2017; Medeiros et al., 2015). Among feedstocks used for biofuel, algae have emerged as a plausible feedstock for the biofuel sector (Saravanan et al., 2018). Exploring pertinent microalgae for biofuel will open the wide space as there are approx 3,00,000 microalgal species available (Sharma et al., 2011). Besides microalgae, worldwide 221 species of macroalgae are being exploited by humankind, out of which 66% of algal strains used for food production (Pereira, 2011; Milledge et al., 2014). Besides microalgae, macroalgae based biofuel is also regarded as an alternative in terms of fuel requirements for a fastest growing economy like India. In such economies, though the government is promoting small-scale industries for economic development and employment generation, it is growing with many environmental and social problems (Jiang et al., 2016).

In addition to biodiesel, the world bioethanol production reached 4.5 billion gallons in the year 2000, then increased to 22.7 billion gallons in the year 2012 (Brown, 2012). The production of synthetic ethanol is growing in Middle East countries, especially Iran (Yusoff et al., 2015). The largest synthetic ethanol plant in Germany and Scotland can produce 4.4 million gallons per year. There are several multinational companies which produce synthetic ethanol, such as Sasol (Europe and South Africa), SADAF (Saudi Arabia), Shell (UK and Netherlands), BP (UK) and Equistar (US) (Roozbehani et al., 2013). Even though the renewable energy sector is growing steeply in the present scenario using several renewable sources, the cost of the biofuel production from algae is still high, and also production is in its primitive stage. Further, the algal biodiesel production could be economical because of their functional advantages, but it still requires research efforts to get substantial productivity and the biofuel industry faces downfall since the cost of the algal biofuel production is higher than crude oil price. Further, to evade these shortcomings (production economics), biofuel production coupled with a biorefinery approach need to be practiced. Biorefinery refers to the extraction or production of all bioproducts from biomass by the sequential suitable processing methods of low environmental impact. Biorefinery approach or bioenergy produced should be coupled with high-value products extraction through an integrated and sequential extraction strategy to achieve commercial possibility. However, types of co-products extracted from microalgae and macroalgae should be known prior to use in an optimal process. In the biorefinery method, proteins obtained as a byproduct can be utilized as an animal feed. Both macroalgae and microalgae hold the potential to yield numerous ranges of bioactive compounds; can benefit several industries (Suganya et al., 2016). Producing fuels and products from algae avoids the competition with food production and further, food production might be diminished by cultivating microalgae on sites where no agriculture is practiced and also use sea or brackish water to mass cultivate algae (Kröger and Müller-Langer, 2012). Regarding the macroalgae, macroalgal cultivation in the open seawater creates a lot of diversity changes and it affects the aquatic life cycle. They can bypass energy expensive drying, lipid extraction, and transesterification to meet the positive economy of the biofuel. Therefore, it is an absolute need to understand the bioenergy potential of micro- and macroalgae and also the classes of the industrially important high-value products extracted from those strains. Further, there is an unconditional necessity to analyze and interpret more on renewable energy from algae for a long-term vision for bioenergy production.

Considering the bottlenecks in the biofuel and bio-products extraction from algae, the present article is written to review and summarize the various cultivation pattern, biofuel, and bioproduct of micro- and macro algae. This review initially discusses the biochemical composition and elemental composition (C:N:P) of microalgae and macroalgae. Then, the utilization of microalgae and macroalgae as renewable energy sources and merits and demerits thereof would be comprehensively discussed. The second part of this review evaluates the uses of algal components for industrially important co-products or high-value products extraction for the sustainability of the scientific research (Fig. 1). Further, biosensor application, pigment production of seaweeds would be discussed extensively.

2. Methodology

Research articles were searched and collected using suitable keywords in various scientific databases such as Science Direct, NCBI, Springer, and Google Scholar websites to ascertain the knowledge gaps in the selected topic. The keywords used include microalgae, macroalgae, lipids, biodiesel, biorefinery, pigments, cultivation of algae, microalgae for biofuel production, etc. Further, bioactive compounds from algae and their application in human health were also included in the second part of this review based on the available literature collected using pharmacological properties of algae, value-added products, high-value products, industrially important co-products phenolics and flavonoids from algae, co-products from algae as a keywords search. Journal articles in relevance to the central part of the review deal were given importance. The selected core objectives of this article are bioenergy from micro- and macroalgae production and value-added products and cultivation from macro and microalgae. Concerning the section dealing with the biochemical composition and potentials of microalgae and macroalgae, about 90% of the scientific reports enunciated in this review covers the period from 2010 to the present, and very old literature reports like 1968, 1986 for analysis and comparison. Notably, feedstocks such as microalgae and macroalgae utilized for biofuel potential have been detailed from the most recent plethora of literature (2007–2018). On the basis of the filtered searches together with a thorough analysis of their subjective abstracts, the published articles for this present review were selected. Subsequently, a secondary search was also carried out with importance to more recent scientific advances in the context of bioethanol economic scenario using algae and fossil fuels.

3. Biochemical components and potentials of algae

3.1. Biochemical composition of microalgae

Algae are either prokaryotic or eukaryotic photoautotrophic organisms, which are capable of assimilating nitrogen and phosphorus from the medium into biomass during the course of their growth, and the generated biomass can subsequently be transformed to various bioproducts following apposite process (Ometto et al., 2014). The biochemical composition specifically protein and carbohydrate of microalgae make them attractive in producing several value-added compounds (Table 1). The ratio of biochemical components or the ratio of proteins/carbohydrates/lipid of algae is species specific. For example, *Spirulina maxima* is an excellent source for protein (60–71%w/w), *Porphyridium cruentum* is a rich source of carbohydrates (40–60%) and *Scenedesmus dimorphus* possess 40% lipids (Nigam and Singh, 2011), whereas *Botryococcus braunii* and *Chlorella protothecoides* are the predominant sources of terpenoids and glyceryl lipids, which are eventually processed to the shorter hydrocarbon of crude oil (Voloshin et al., 2016). In addition, elemental concentration in terms of C, H, O, and N of microalgae is higher than wood. The elemental composition of microalgae is strain specific (Ho et al., 2003). Further, the nitrogen content of microalgae serves as a preferable organic fertilizer to

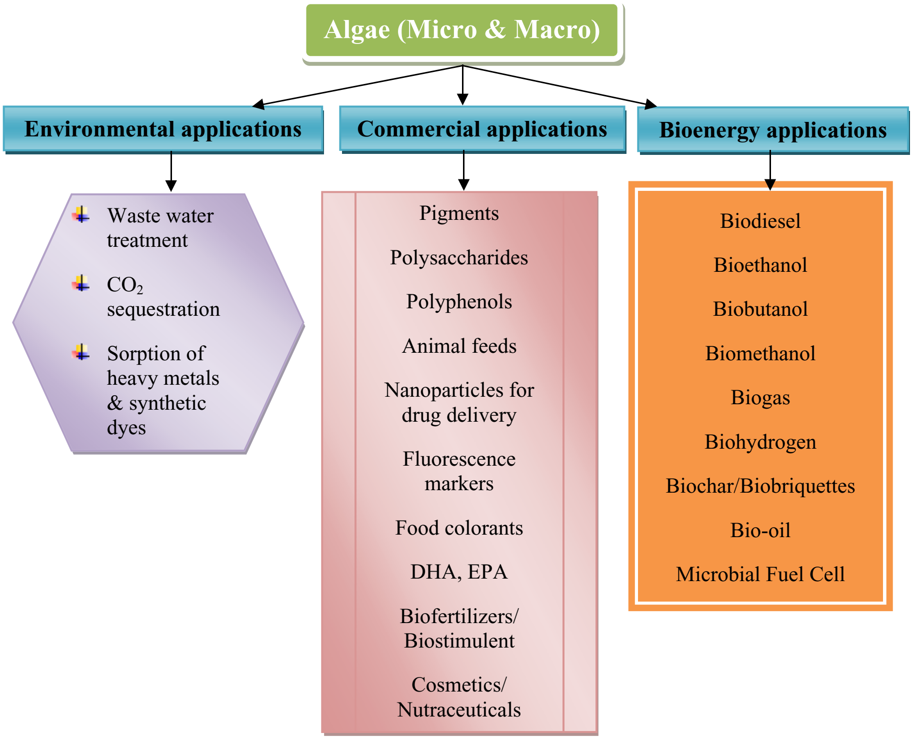

Fig. 1. Possible routes of algal biomass utilization for various applications.

Table 1
Biochemical composition of microalgae (Suganya et al., 2016; Trivedi et al., 2015).

Algae	Protein (%)	Carbohydrates (%)
Anabaena cylindrica	43–56	25–30
Aphanizomenonflos-aquae	62	23
Chlamydomonas reinhardii	48	17
C. pyrenoidosa	57	26
C. vulgaris	51–58	12–17
Dunaliella salina	57	32
Dunaliella bioculata	49	4
Euglena gracilis	39–61	14–18
Porphyridium cruentum	28–39	40–57
Scenedesmus obliquus	50–56	10–17
Scenedesmus quadricauda	47	–
Scenedesmus dimorphus	8–18	21–52
Arthrospira maxima	60–71	13–16
Spirulina platensis	46–63	8–14
Spirulina maxima	60–71	13–16
Synechococcus sp.	63	15
Prymnesium parvum	28–45	25–33
Tetraselmis maculate	52	15

ultimately reduce the reliance on chemical fertilizer, which poses environmental hazard particularly, to soil and water. Despite the several controversies on the factual C:N:P molar ratio in the microalgal cell, the Redfield ratio of marine strains was accounted to be 106:16:1 (Whitton et al., 2016). Further, the elemental composition of 15 microalgal biomass has been measured and the average quota of C:N:P:S in marine phytoplankton was determined to be 124:16:1:1.3, which is similar to the Redfield ratio (Ho et al., 2003). Nonetheless, the Redfield ratio might not be apt for freshwater algal strains since N:P molar ratios can be between 8:1 and 45:1 based on the structural composition of species (Droop, 1968). The C:N:P ratio of microalgae was making them a potential feedstock for the various sectors such as bioenergy, bioremediation, biofertilizer, pharmaceutical and immunology.

3.2. *Biochemical composition of macroalgae*

Macroalgae (seaweeds) are macroscopic in structure, naturally available or can be cultivated in the vast area of low tide seashore. Seaweeds utilize natural nutrients available in the sea for their growth. Seaweeds are well known since World War II for their potential bioactive compounds for the benefit of humanity. Seaweeds of various forms are available in large quantities throughout the coastal areas, especially in countries with more coastlines such as Japan, Philippines, Malaysia, Singapore, Thailand, the United States, Australia, India and most of the European countries. Nearly 8 million tons of fresh seaweeds are being harvested worldwide every year. The global production of macroalgae in the year 2008 was 15.5 million tons fresh weight, and 93% of it had good commercial value. The total annual production value is estimated to be US$ 6 billion, of which food products for human consumption contributes US$ 5 billion (Kılınç et al., 2013; FAO, 2014). Seaweeds are found abundantly in the southeast and west coastal areas of India with a coastline of about 7500 km, comprising about 271 genera and 1153 species. Nearly, 7 lakh tons of standing stock (wet weight) of seaweeds are found along different coastal states of India, of which Tamil Nadu alone contributes around 2 lakh tons (wet weight) (Subba Rao and Mantri, 2006). The littoral and sublittoral rocky areas along the Indian coast support good growth of different seaweeds. The luxuriant growth of several seaweed species occurs along the Tamil Nadu (Gulf of Mannar and Palk Bay) and Gujarat coasts, and around Lakshadweep, Andaman and Nicobar Islands. Fairly rich seaweed beds are present in the vicinity of Bombay, Karwar, Ratnagiri, Goa, Varkala, Kovalam, Vizhinjam, and Visakhapatnam, and in the coastal lakes like Chilka and Pulicat (Silas et al., 1986). Around 30–40% of the coastline in Tamil Nadu is covered with drift seaweeds (Subba Rao and Mantri, 2006). These drifted seaweeds remain unexplored and are rich in pigments such as phycobiliproteins, chlorophylls, and carotenoids. Seaweeds have simple parts than plants (hold fast, stipe and blade).

Seaweeds are appeared as red, green and brown based on the external color and classified as Rhodophyceae, Chlorophyceae, and Phaeophyceae respectively. The worldwide seaweed industry has increased exponentially over the last 50 years. The major biochemical compounds in seaweeds include carbohydrates, proteins, minerals (micro and macro elements), and plant growth promoters (Table 2). Carbohydrates present in seaweeds are polysaccharides such as agar, alginate, fucoidan, laminarin, ulvan, cellulose, carrageenan, etc. Phycobiliproteins are pigment proteins, can be used in various applications. Minerals such as micro and macro elements are present abundantly in seaweeds. The average annual growth was estimated as 8.13% in quantity and 6.84% in monetary value between 2003 and 2012. Over 23 million tons of macroalgae were produced in 2012 from the aquaculture industry, which worth about US$ 6 billion (FAO, 2014; Loureiro et al., 2015). Nearly 83% of seaweeds produced are used for human consumption while the leftover biomass is used as fertilizers, animal feed additives (Smith and Ross, 2016), medical and biotechnological applications (McHugh, 2003; Smit, 2004).

4. Bioenergy from microalgae

Bioenergy can be of biodiesel, bioethanol, biomethane, and biohydrogen. In all the cases, the source from which fuel obtained changes, rather than fuel composition. The first-generation feedstocks entail edible oil sources such as vegetable oil (soybeans, sunflower, rapeseeds), and corn, sugarcane, sugar beet, wheat and however, these feedstocks compete with food supply, produce low biomass and have weather influence on crop cultivation around the year (Doshi et al., 2016; Voloshin et al., 2016; Trivedi et al., 2015). To circumvent these problems, the second-generation biofuel feedstocks were used, which entails non-edible sources such as

Table 2
Biochemical composition of macroalgae (% dry weight) (Kaliaperumal et al., 2002; Suganya et al., 2016).

Algae	Protein	Carbohydrates	Lipids
Hypnea valentiae	11.8–12.6	11.8–13.0	9.6–11.6
Acanthophora spicifera	12.0–13.2	11.6–13.2	10.0–12.0
Laurencia papillosa	11.8–12.9	12.0–13.3	8.9–10.8
Ulva lactuca	11.4–12.6	11.6–13.2	9.6–11.4
Caulerpa racemose	11.8–12.5	16.0	9.0–10.5
Ulva reticulata	12.83	16.88	8.50
Enteromorpha compressa	7.26	24.75	11.45
Chaetomorpha aerea	10.13	31.50	8.50
Chaetomorpha antennina	10.13	27.00	11.45
Chaetomorpha linoides	9.45	27.00	12.00
Cladophora fascicularis	15.53	49.50	15.70
Microdictyon agardhianum	20.93	27.00	9.40
Boergesenia forbesii	7.43	21.38	11.42
Valoniopsis pachynema	8.78	31.50	9.09
Dictyosphaeria cavernosa	6.00	42.75	10.51
Caulerpa cupressoides	7.43	51.75	10.97
Caulerpa peltata	6.41	45.00	11.42
Caulerpa laetevirens	8.78	56.25	8.80
Caulerpa racemose	8.78	33.75	10.63
Caulerpa fergusonii	7.76	23.63	7.15
Caulerpa sertularioides	9.11	49.50	6.99
Halimeda macroloba	5.40	32.63	9.89
Codium adhaerens	7.26	40.50	7.40
Codium decorticatum	6.08	50.63	9.00
Codium tomentosum	5.06	29.25	7.15

oleaginous crops and agricultural wastes (bagasse, lumber, straw and leaves, lignocellulose); firewood, perennial grass, Jatropha, Cassava or lignocellulosic materials (Doshi et al., 2016; Voloshin et al., 2016; Trivedi et al., 2015). However, second-generation feedstocks require surplus arable land and high capital investment in high-end equipment and often affected by seasonal settings, and further, they are available in limited quantity (Nigam and Singh, 2011; Trivedi et al., 2015; Maity et al., 2014). In a line of demerits, terrestrial crop-based biofuel generation (first- and second-generation feedstocks) presents skepticism to biofuel researchers due to technicity issues, noticeably production and processing cost, emission of pollutants and carbon debt due to land clearance, food price rise and thus, they are ultimately unsustainable for techno-economical expansion (Suganya et al., 2016; Trivedi et al., 2015).

At this juncture, algae (microalgae and macroalgae) came to limelight as an alluring third-generation biofuel feedstock due to various environmental and economic benefits including higher lipid content than first and second-generation terrestrial crops (Table 3).

Microalgae are being considered as a plausible candidate for biofuel industry owing to their favorable attributes as mentioned below;

- High growth rate compared to terrestrial or oleaginous crop counterparts (Chen et al., 2015; Suganya et al., 2016).
- High biomass and lipid productivity over other oleaginous crops (Mathimani et al., 2015, 2017c).
- Doubling time or generation time of microalgae is < 24 h, which is quite preferable to achieve high cell density with a short cultivation period (Suganya et al., 2016).
- Bio-mitigation of CO_2 by microalgae shows duel benefit of environmental greenhouse gases reduction (Mata et al., 2010) and subsequent food, fuel, and feed production.
- CO_2 sequestration capability of microalgae exhibits carbon capture and storage process (Chen et al., 2015).
- The lipid yield of microalgae is higher about 40–80% dry cell weight (DCW) than other feedstocks, i.e., 15–300 fold higher than agricultural crops, and thus, lipid productivity per area is unquestionably maximal than oleaginous edible or non-edible crops (Suganya et al., 2016).
- Flexible cultivation (Chen et al., 2015), and the growth rate cannot be hindered by different weather conditions (Mata et al., 2010).
- They do not compete for fertile land or arable land for cultivation (Suganya et al., 2016), and can grow under adverse conditions, which are unsuitable for agricultural crops (Mata et al., 2010).

Table 3
Lipid content of various biofuel feedstocks (Trivedi et al., 2015; Ziolkowska and Simon, 2014).

Crop	Oil content (L/ha)
Corn	172
Soybean	446
Sunflower	952
Peanut	1059
Canola	1190
Rapeseed	1190
Castor	1413
Jatropha	1892
Karanja	2590
Coconut	2689
Oil palm	5950
Microalgae	58,700

- Do not affect food versus fuel debate (Suganya et al., 2016) and as a consequence, do not harm the food market.
- Photosynthetic efficiency of microalgae is 10–50 times maximum than land crops (Chen et al., 2015).
- Virtually sulfur-free, non-toxic and eco-friendly biofuel production to clinch fossil fuel utilization (Suganya et al., 2016; Tsolcha et al., 2017).
- Versatile to grow in seawater, or wastewater (Suganya et al., 2016) or fresh or brackish water and using non-portable water exhibits to lower water footprint (Chen et al., 2015).
- Ability to synthesize other high-value products for cosmetics, pharmaceuticals, aquaculture and food additives (Tsolcha et al., 2017; Mata et al., 2010) improves the economics of microalgal biofuel production.

Irrespective of the strain or species or biomass trait (dried or wet), three groups of methods were widely practiced based on product purity, expensiveness and eco-compatibility to produce bioproducts (Nigam and Singh, 2011; Chisti, 2007).

a) Biochemical entails hydrolysis, fermentation – natural process
b) Chemical entails hydrolysis, transesterification – catalyst facilitated
c) Thermochemical entails pyrolysis, gasification, liquefaction – high pressure and temperature
d) Direct combustion –heat to electron energy

Biodiesel production from microalgae has been carried out several researchers around the world, and various works were undertaken to convert microalgal biomass to biodiesel through transesterification process. In an attempt to enhance the microalgae for biodiesel production, *Tetraselmis subcordiformis* SHOU–S05, *Nannochloropsis oculata* SHOU–S14, and *Pavlova viridis* SHOU–S16) were cultured under nitrogen-limiting conditions, and results showed that low nitrogen increases both lipid content and prerequisite fatty acid for biodiesel production (Huang et al., 2013).

In a recent study, to produce maximal biomass and lipid from *Chlorella vulgaris* BDUG 91771, seawater amended with different consortia of $NaNO_3$ and K_2HPO_4 or urea and superphosphate) were optimized by central composite design. Among the permutations, low urea (2.20 mM) and low superphosphate (0.021 mM) augmented the lipid to 27.5% which is equivalent to analog nutrients. Further, seawater medium supplemented with low-cost urea and superphosphate showed a relative increase of C16:0, C16:1, C18:1 over control and exhibited preferable long chain saturation factor, the degree of unsaturation, cold filter plugging point (Mathimani et al., 2018). *In situ* transesterification process was carried out by Im et al. (2014) using *Nannochloropsis oceanic* yielded 90% biodiesel. Marine microalgae *C. vulgaris* BDUG 91771 accumulated 22% DCW at ambient condition, which was converted to biodiesel at 61% lipid conversion efficiency, and further, produced biodiesel that meets European and ASTM standards (Mathimani et al., 2015).

4.1. Jetfuel

Aircraft run by jet fuel emits greenhouse gases, particularly CO_2, CO, NO_x, SO_x. Worldwide, aviation industry uses 5 million barrels of oil per day. It is speculated that airline fuel consumption will be increased from 95 billion gallons to 221 billion gallons per year by 2026 (Hendricks et al., 2011). The aviation industry is determined to combat energy security task, cope up with climatic hazards and ozone layer depletion (Lee et al., 2010). Jet fuels are of Civil Jet fuel or Military Jet Fuel. Certain civil jet fuels contain kerosene or gasoline and kerosene blended whereas military jet fuel is a chemical fuel improved with antioxidants, dispersants, corrosion inhibitors (Trivedi et al., 2015). In this scenario, renewable or bio-jet fuel seems to bring down the gaseous emissions by 60–80%. While the technology is in its infancy, as an alternative fuel such as microalgal fuel or green fuel can also be used in the aviation industry by blending with petroleum fuel (Marian and Ihab, 2012). Microalgal lipids are hydrotreated (hydrotreated fatty acids and esters, HEFA) as per ASTM standard D7566 and blended with 50% fossil-based jet fuel. It is referred to as hydrotreated vegetable oil or bio-derived synthetic paraffinic kerosene (Trivedi et al., 2015). As a lead to use algal fuel in aviation, two flights namely Continental 737–800 and JAL 747-300 have been successfully tested using algal biofuel-jet fuel blend on January 2009 (Hendricks et al., 2011). Recently, India also tested its indigenous first algal biofuel for aviation blended with petroleum fuel.

4.2. *Bioenergy from macroalgae*

Macroalgae (seaweeds) are rich in phycocolloids such as agar-agar, alginate, carrageenan, laminarin, ulvan, etc. These phycocolloids are edible and used commercially for various industrial applications. Since phycocolloids are complex to break, it requires specific pretreatment process for biofuel production. Seaweeds can be used as an alternate source for bioethanol, biogas, biobutanol, biomethanol and biohydrogen production. Sugars such as glucose, cellulose, galactose, etc. in seaweeds can be effectively utilized for biofuel generation through aerobic and anaerobic fermentation process (Sudhakar et al., 2017). Bioethanol is a colorless liquid, transparent, neutral, volatile and flammable, miscible in water and oxygenated liquid hydrocarbons, which is having a pungent odor and sharp burning taste (Yusoff et al., 2015). Currently, large-scale galactose conversion to ethanol is still a challenging task, and proper data are not available in detail. Research on galactose fermentation is still not efficient. Similar to glucose, galactoses have hexose sugar. Galactose has an identical structure as glucose with just one difference in the C_4 carbon atom stereochemistry. However, most of the bacteria and yeast found to be effective in the fermentation of glucose substrate and also useful for the fermentative oxidation of galactose substrate (GB-Analysts Reports, 2009). *Saccharomyces cerevisiae* (yeast), well known for the fermentation process, was found to be capable of galactose fermentation. From the literature study, *S. cerevisiae* was showing evidence of exceptional fermentative performance on galactose (Goh and Lee, 2010).

Since the red seaweed *Gracilaria* sp. contains D-galactose in the form of agarose polymer, conversion of this polymer to ethanol by yeast is difficult. However, pretreatment and hydrolysis process make the substrate suitable for the fermentation by yeast to give high yields of ethanol. The difference in pH, temperature and dissolved oxygen content plays a major role in fermentation. Yeast converts simple sugars such as D-galactose into ethanol at the stationary phase of the fermentation process (Sudhakar et al., 2017). Continuous reduction of simple sugars happens due to ethanol conversion. The theoretical yield of ethanol depends on the amount of sugar present in the fermentation medium. One gram of sugar yields 0.5 g of ethanol through the fermentation process according to the theoretical calculation (GB-Analysts Reports, 2009).

5. Bioethanol economic scenario

The global productions of ethanol using seaweeds are increasing tremendously. The analytical studies towards the global ethanol production show that most of the ethanol is produced by a fermentation process which contributes 97%, while only 3% of ethanol is produced via catalytic hydration of ethylene, a petroleum by-product (Yusoff et al., 2015). The techno-economic analysis of macroalgae for the biorefinery approach was analyzed in detail by Murthy Konda et al. (2015) in which feedstock price, yield, moisture content of seaweeds, solids loading and enzymes loading were considered. Consider, feedstock price is US$ 100/MT, then the minimum ethanol selling price was observed to be in the range of US$ 3.6–8.5/gal and this will again reduce if the feedstock price reduced US$ 50/MT (Murthy Konda et al., 2015). The production of synthetic ethanol is economically less attractive as compared to fermentation in the United States due to the high cost of ethylene and abundance of agricultural feedstocks for ethanol production. The utilization of a low-value by-product from waste seaweeds for bioethanol production will pave the way towards the development of an economical biorefinery with zero-waste technology (Tan and Lee, 2014).

6. Cultivation of macroalgae

Cultivating seaweeds in off/onshore has become an important small-scale business, and it provides sustainable living in the coastal environments. It not only supports human consumption but also provides lives to other marine living and non-living organisms (Hafting et al., 2015). Cultivation includes many stages and methods (Subba Rao and Mantri, 2006). Various methods have been developed until now for sustainable cultivation of seaweeds for the benefit of fisherman livelihood (Figs. 2 and 3).

6.1. *Seaweed tissue culture*

The protoplast technique is an age-old technique in tissue culture of economically important plants. Recently, isolating protoplast, spores from healthy seaweeds (Reddy et al., 2008) and culturing economically important seaweeds at lab scale is gaining much importance to develop axenic seaweed cultivation for good quality products extraction and utilization from green (Gupta et al.,

Fig. 2. *Gracilaria salicornia* seaweed cultivation using raft method. a. Preparation of wood raft model (2.5 m length, 1.5 m feet breath), b. *G. salicornia* seedlings collected from sea for germination, c. Self help group people tying seedlings in the nylon rope (approx. 5–10 g),
d. Photo showing tied *G. salicornia* for germination, e. Tying of seedlings rope on the raft,
f. Raft moved into the sea for seaweed germination and growth.

Fig. 3. *Gracilaria salicornia* seaweed cultivation using net bag method. a. Preparing net bag for seaweed seedlings by self help group people and b. One feet gap between the net bag seedlings tied in the rope for the cultivation.

2011, 2018; Balina et al., 2017) and red seaweeds (Mollet et al., 1995; Jayasankar and Varghese, 2002). Production of genetically and developmentally modified seaweeds through somatic variants, artificial hybrids and mutant's development was carried out by Charrier et al. (2015). Seaweeds are now well thought-out as likely feedstock for production of different industrial applications including food, feed, chemicals and fuel. Seaweeds produced through tissue culture can be utilized for the production of industry grade biomass fantastic for extracting products of pharmaceutical and nutraceutical value (Gupta et al., 2018).

Over the past few decades, different seaweed cultivation systems were adopted by different countries based on their sea conditions (Table 4).

7. Bioproducts from algae – production of industrially important co-products

In general, typical algae consist of three key compounds such as proteins, carbohydrates, lipids, and in addition, starch, pigments, antioxidants, vitamins, pharmaceuticals, biofertilizer, natural colorants, and animal feed were extracted from algae through biorefinery processes (Trivedi et al., 2015; Mata et al., 2010). Biorefinery indicates the extraction of all constituents from the cell using integrated sequential processes. Therefore, extraction of the value-added products or industrially important high-value co-products from algae is essential to reduce the cost of biodiesel. Marine food products can be considered as important functional foods whose consumption helps in growth and development, thus maintaining the body's structural integrity (Zhang et al., 2012). Most of the marine food products and by-products are being converted and utilized as valuable functional foods through recent development in marine bioprocess industry. This is due to the presence of bioactive compounds which are a powerful antioxidant in nature and are used as functional foods and nutraceuticals (Ngo et al., 2011).

7.1. Phenolic acids and flavonoids

Biologically active compounds are commonly found in algal species (Ludmila et al., 2015), and specific secondary metabolites are often restricted to a narrow set of species within a phylogenetic group, which has various health benefits. Scientific evidence has reported the presence of phenolic compounds in algal species (Raposo et al., 2013b). Several recent research works (Rodríguez-Meizoso et al., 2010; Onofrejová et al., 2010; Quirós et al., 2010) have been carried out to utilize the important biological properties of macro- and microalgal species exhibited by their bioactive components present. Microalgae have gained considerable and increasing interest as a major source of high-value products as they contribute more bioactive metabolites than macroalgae. The bioactive compounds of algae are rich in antioxidants, which display significant pharmacological properties. Algae synthesizes these bioactive metabolites owing to their diverse morphological and physiological features which have great commercial significance ((Kumar et al., 2019) Phenylalanine ammonia-lyase synthesizing cinnamic acid from phenylalanine was first identified in cyanobacteria (*Anabaena variabilis* and *Nostoc punctiforme*) and was characterized using X-ray crystallography in the year 2007 (Onofrejová et al., 2010). These groups of compounds are important precursors for the biosynthesis of more complex phenolic compounds. Secondary metabolites play an important role in defense mechanisms (Kumar, 2016). Secondary metabolites are classified into various groups of bioactive compounds depending on their structural configurations. The main classes include alkaloids, flavonoids, phenolics, tannins, terpenoids which exhibit significant pharmacological properties (Kumar et al., 2019).

The list of phenolic compounds identified across the algal species using chromatography and spectroscopic technique is summarized in Table 5. It is a well-known fact that aromatic compounds are oxidized by many bacterial species found in the soil. Phenolic acids are being used as a source of carbon by few microorganisms and some diazotrophs in restricted environments, as these compounds can undergo a transformation in the soil. Decaying plant residues are known to accumulate cinnamic acids, hydroxy and methoxy benzoic acids. Phenolic acids act as an effective precursor to synthesize phenolic lipids (Santi et al., 2010). The synthesized phenolic compounds commonly described as stress-induced compounds does not have any direct role in principal processes such as algal reproduction, cell division, and photosynthesis. However, they play a crucial role as chemically protective agents in stress-induced biotic factors e.g.settlement of bacteria and grazing. They are found in most of the algal groups, bromophenols being common to all. Different classes of flavonoids such as flavones and anthocyanins

Table 4
Different methods of seaweed cultivation in different countries.

Seaweeds	Method	Country	Reference
Eucheuma/*Kappaphycus* and *Gracilaria* sp.	Fixed and floating bottom farms	Philippines, Vietnam and Thailand	Critchley et al. (2006)
Porphyra sp.	Floating net	China, Korea and Japan	Critchley et al. (2006)
Kelp	Long-line systems	China, Korea and Japan	Critchley et al. (2006)
	Open ocean and off-shore farming	U.S.	Roesijadi et al. (2008)
	Long-line systems (modified)	Europe	Kelly and Dworjanyn (2008)
	Novel ring system	Germany	Buck and Buchholz (2004)
Kappaphycus sp.	Raft, floating net bag, long-line rope	India	Subba Rao and Mantri (2006)
Gracilaria sp.	Polyethylene tube method	Chile	Pizarro and Barrales (1986)
Gracilaria sp.	Spore-setting method	Malaysia and Hawaii	Oza and Krishnamurthy (1967); Santelices and Doty (1989)
G. verrucosa	Raft method	China	Ren-Zhi et al. (1984)
Gracilaria sp., *Ulva* sp., *Porphyra* sp.	Protoplast-seeded nylon threads	India	Reddy et al. (2008)

Table 5
HPLC–MS identification of phenolic compounds from algal species.

A	B	C	D	E
Haematococcus pluvialis	HPLC-QqQ-MS analysis, C18 analytical column (150 mm × 4.6 mm i.d., 3 μm)	Sol A- 0.1% acetic acid in water Sol B– methanol Mode:ESI negative	p-OH benzoic acid (137.1); Gallic acid (169.1); Syringic acid (196.9); Vanillic acid (167.1); Protocatechuic acid (153.1); Sinapic acid (223.1); Ferulic acid (193.1); Caffeic acid (179.1); Chlorogenic acid (353.1)	[Rodríguez-Meizoso et al., 2010]
Spongiochloris spongiosa ***Anabaena doliolum*** ***Porphyra tenera*** ***Undaria pinnatifida***	HPLC-ESI-MS, C18 analytical column (150 mm × 4.6 mm i.d., 3.5 μm)	Sol A- 0.2% acetic acid in water Sol B– acetonitrile Mode: ESI negative	p-OH benzaldehyde (121.2); p-OH benzoic acid (137.1); 3, 4, dihydroxy benzaldehyde (137.2); 2,3, di-hydrxoy benzoic acid (153.2); Gallic acid (169.1); Syringic acid (196.9); Vanillic acid (167.1); Protocatechuic acid (153.1); Sinapic acid (223.1); Ferulic acid (193.1); Caffeic acid (179.1); Chlorogenic acid (353.1); Vanillin (151.2); p-coumaric acid (163.2); Salicylic acid (137.2); Cinnamic acid (147.2)	[Onofrejová et al., 2010]
Cystoseiraabies-marina ***Undaria pinnatifida*** ***Sargassum muticum*** ***Chondrus crispus***	RRLC-MS/MS, C18 analytical column (150 mm × 4.6 mm i.d., 3.5 μm)	Sol A- 0.2% acetic acid in water Sol B– acetonitrile Mode: ESI negative	p-OH benzaldehyde (121); p-OH benzoic acid (137); 3, 4, dihydroxy benzaldehyde (137); Gallic acid (169); Syringic acid (197); Vanillic acid (167); Protocatechuic acid (153); Ferulic acid (193); Caffeic acid (179); Chlorogenic acid (353); Vanillin (151); p-coumaric acid (163); Salicylic acid (137)	[Borivoj et al., 2017]
Fucus serratus ***Saccharina latissima*** ***Chondrus crispus*** ***Gracilaria vermiculophyllum*** ***Enteromorpha intestinalis*** ***Sargassum muticum*** ***Dictyota dichotoma*** ***Polysiphonia fucoides*** ***Laminaria digitata*** ***Palmaria palmata*** ***Fucus distichus*** ***Fucus spiralis*** ***Porphyra purpurea*** ***Mastocarpus stellatus*** ***Fucus vesiculosus*** ***Ulva lactuca***	HPLC-DAD, C18 analytical column (150 mm × 4.6 mm i.d., 5 μm)	Methanol and ammonium acetate buffer (12:88 v/v)	Gallic acid, Protocatechuic acid, Chlorogenic acid, Vanillic acid, Syringic acid, Caffeic acid, Salicylic acid, Coumaric acid, Ferulic acid	[Sabeena and Charlotte, 2013]
Palmaria* sp.** ***Porphyra* sp.** ***Himanthalia elongata ***Laminaria ochroleuca,*** ***Undaria pinnatifida***	HPLC-ESI-MS, C18 column (15 cm × 0.4 cm, 3 μm)	Sol A- water: acetic acid (99:1 v/v) Sol B– water: acetonitrile: acetic acid (67:32:1 v/v/v) Mode: ESI negative	Gallic acid (169); Epigalocatechin (305); Catechin (289); Epicatechin (289); Epigallocatechingallate (457); Epicatechingallate (441); Catechingallate (441)	[Quirós et al., 2010]
Porphyra dentata	HPLC-ESI-MS, RP-C18 column (150 mm × 2 mm, 3 μm)	Sol A- 0.05% TFA/Acetonitrile, Sol B– 0.05% TFA/water, Mode: ESI (-ve)	Catechol (156); Rutin (611); Hesperidin (611)	[Katarzyna et al., 2010]

Note: A-Algal species, B-Technique and stationary phase used in HPLC, C– Mobile phase used in HPLC and ionization mode used in MS, D-Identified phenolic compounds by HPLC and MS, E-Reference.

are not yet identified or reported in algal species (Dagmar et al., 2011). Sulfated phenolic metabolites are widely distributed in the marine organism, and they play a crucial role as a storage form for more active metabolites with numerous ecological functions (Caroline et al., 2015). A study has reported the presence of Rutin and Hesperidin in *Porphyra dentate,* which are flavonol and flavanone respectively (Katarzyna et al., 2010).

7.2. Pharmacological properties of other compounds in algae

Numerous bioactive compounds with potent antioxidant capacities have been isolated and identified from different types of algal species including phlorotannins, sulfated polysaccharides, carotenoid pigments such as fucoxanthin and astaxanthin, sterols, catechins and proteins (Sabeena Farvin and Charlotte, 2013). Phlorotannins are well-known antioxidants that are extracted from algae with significant pharmacological properties. Based on the number of hydroxyl groups and phloroglucinol units, these compounds are categorized into six different subclasses: fuhalols, eckols, carmalols, fucols, phlorethols and fucophlorethols. They are synthesized through the acetate–malonate pathway during cellular damage (Mariana et al., 2014). Phloroglucinol-based polyphenols (phlorotannins) present in brown algal species contain phenoxy and phenyl units characterized by their low, medium and high molecular weight compounds (Li et al., 2011). Phlorotannins have shown anti-microbial activity, anti-inflammatory property, anti-photocarcinogenic effect antioxidant, anti-cancer, and anti-hypertension properties. Phlorotannins are also used in therapeutic purposes such as protection against vascular diseases, protection against glucose-induced oxidative stress and treatment of arthritis.

Some of the potent inhibitors of an alpha-glucosidase enzyme found in brown algae-derived phlorotannins are dieckol, fucodiphloroethol G, phloroglucinol, diphlorethohydroxycarmalol (DPHC) (Lee and Jeon, 2013). Polysaccharides are important components of algal cell walls mainly used in hydrocolloid industry; in particular alginate carrageenans from brown and red algae respectively. Other minor polysaccharides are ulvans, xylans and fucoidans are present in the cell wall of green, red and brown algal species, respectively. Storage polysaccharides are also found in red and brown algae species such as amylopectin-like glucan and laminarin. Fucoidans (soluble fiber) are an important group of polysaccharides present in brown algae and exhibit various biological properties such as antioxidant, anti-viral, anti-inflammatory, anti-tumour, medicinal properties (anti-coagulant, as lipids reducing agent, anti-immunomodulatory), anti-complementary properties and protective activity against gastritis, uropathy, renalpathy and hepatopathy.

Sulfated galactans with fucoidans are homopolysaccharides mostly identified in *Lomentaria catenata, Martensia denticulata, Halymenia dilatata, Sinkoraena lancifolia, Grateloupia elliptica, Grateloupia lanceolata, Chondrus crispus and Schizymenia dubyi* species. Sulfated galactans are well known for their anti-viral, anti-tumoral, immunomodulation, anti-angiogenic, anti-inflammatory, anticoagulant, and anti-thrombotic properties. Ulvans are sulfated heteropolysaccharide containing the subunits of sugars such as glucose, xylose and rhamnose along with uronic acids, mainly iduronic acid, glucuronic acid and sulfates and their biological properties include anti-hyperlipidemic and anti-tumour (Herrero et al., 2013) and notably, recent research reported that sulfated polysaccharides showed anti-proliferative activity against cancer cell lines *in-vitro*, and also, inhibit tumour formation in mice. The sulfated heteropolysaccharide shows potential anti-proliferative effects on U-937 (human leukemic monocyte lymphoma), CT-26 (murine colon carcinoma), HL-60 (human promyelocytic leukaemia) and B-16 (mouse melanoma) cell lines (Ngo, and Kim, 2013). Carrageenans are sulfated galactans mainly isolated from *Chondrus crispus* and from other closely related species including *Hypnea*, *Eucheuma* and *Gigartina* (Agatonovic-Kustrin and Marton, 2013). κ-Carrageenan contains 3,6-anhydro-α-D-galactopyranose which is commercially important as a gelling agent. Further κ-carrageenan possesses numerous biological properties such as antioxidant, anti-inflammatory and anti-tumour (Mariana et al., 2014). Alkaloids are rarely found in marine algae when compared with terrestrial plant alkaloids. The most common groups of alkaloids found in macroalgae can be categorized into indole, halogenated indole, 2-phenylethylamine, and 2,7-naphthyridine derivatives. Green algae mostly accumulate bromine- and chloride-containing alkaloids, whereas alkaloids of indole group are predominant in red algal species. The key pharmacological properties of the alkaloids reported in marine sources are anti-oxidant, anti-bacterial, anti-fungal, anti-angiogenic, anti-proliferative, larvicidal and specifically acts as a growth regulator and neuromodulator (Mariana et al., 2014).

Terpenoids (isoprenoids) are the predominant class of secondary metabolites commonly found in marine algae, and higher plants (Agatonovic-Kustrin and Marton, 2013) and terpenoids (marine sources) are used mainly in cosmetic industries. The biosynthesis of terpenoids such as sterols occurs via acetate/mevalonate pathway, whereas terpenoids that include carotenoids and phytol proceed through the 1-deoxy-D-xylulose-5-phosphate pathway (Shanura Firnando et al., 2016). They are powerful antioxidants and are skin-friendly due to their excellent penetration-enhancing ability, less toxicity and reduced irritation (Agatonovic-Kustrin and Marton, 2013). Red algae mainly represent fucoxanthin and neoxanthin, which are allenic and acetylenic carotenoids, respectively. They act as a protective agent from UV-B rays, and several studies have reported their anti-angiogenic, anti-inflammatory, anti-obesity and anti-diabetic properties (Balboa et al., 2013). Sterols commonly occur in macroalgae in free form, esterified (fatty acids) or in the form of glycosylated conjugates. Fucosterol was found to be the predominant sterol in Chlorophyta and Phaeophyta (Mariana et al., 2014). Brassicasterol, stigmasterol isolated from *I. galbana, Chaetoceros* sp., *Skeletonema,* and *P. lutheri* exhibits hypercholesterolemic effect (Raposo et al., 2013a). Anti-cancer, anti-diabetic, anti-fungicidal, anti-ulcerative properties of fucosterols have been reported from a wide range of algal species (Shanura Firnando et al., 2016). Tables 6 and 7 summarize the diverse biological applications of bioactive metabolites from different species of algae.

7.3. *Bioactive compounds from macroalgae*

7.3.1. *Protein in seaweeds*

The protein content of seaweeds differs according to species and also varies according to a seasonal cycle. It is low for brown seaweeds (3 ± 15% of dry weight), moderate for green algae (9 ± 26% of dry weight) and high for red seaweeds (maximum 47% of dry weight) (Table 8).

However, high protein content was recorded in certain red seaweeds (Fleurence, 2004). *Porphyra yezoensis* contains up to 47% of proteins expressed according to dry mass (Fujiwara-Arasaki et al., 1984). *Palmaria palmata*, red seaweed, contains ~35% of protein (dry mass) (Morgan et al., 1980). Algal peptides could also be of nutritional interest and therefore promote the appearance of novel foods. Information is limited about the biochemical composition and biological activities of these peptides. Some peptides rich in glutamic acid derivates were, however, isolated from brown seaweeds. Proteins and peptides are currently the fastest growing class of prophylactic and therapeutic molecules. Red seaweed proteins seem to possess lower amounts of glutamic and aspartic acids than those recorded from other algal groups (Fleurence, 2004). The protein nutritional value is determined in terms of two factors, amino acid profiles and protein digestibility. A protein with an excellent amino acid composition will have a fair nutritional value if its digestibility remains low (Wong and Cheung, 2001a, 2001b). Numerous seaweeds (*Porphyra* sp., *Palmaria palmate*, *Ulva pertusa*, *Enteromorpha* sp. and *Monostroma* sp.) rich in proteins are used in processing and preparing seafood. Algal proteins or purified protein fractions are very little used at present as ingredients in the food industry. Only phycocyanin from a cyanobacterium *Spirulina* sp. was used in Japan for food applications as a blue colorant. Phycoerythrin from red algae is still under consideration for food applications because no toxicity evidence was recorded.

7.3.2. *Phycobiliproteins and phycoerythrin pigment*

The brilliant colors of the phycobiliproteins originate from covalently attached, linear tetrapyrrole prosthetic groups known as phycobilins (Scheer, 1981; Sudhakar et al., 2015). The red colored phycoerythrin (PE) exhibit great diversity in spectral properties as well as in their chromophore and subunit compositions. PEs carries only one or two chromophore types. The subunit chain length varies considerably for PEs. C-PE-I is the largest molecule among the APC, PC and PE phycobiliprotein families; its subunits being 4 to 17 residues larger than related subunits (Sidler, 1994). Phycobiliproteins are water-soluble pigments found in the cytoplasm or in the stroma of the chloroplast. Red seaweeds are the only source for reddish-pink pigment, phycoerythrin, which acts as the major light-harvesting pigment, and their main function is to trap light energy between 495 and 650 nm wavelengths and transfer it to chlorophyll *a* of the photosynthetic reaction center.

Phycobiliproteins include phycocyanin (blue color), allophycocyanin (blue color) and phycoerythrin (red or pinkish red color)

Table 6
Algal polysaccharides and their biomedical applications.

Polysaccharides	Source organism	Biomedical applications	References
Alginate	Brown algae	Drug delivery, anti-fungal, anti-tumour	[Manivasagan and Oh et al., 2016]
Carrageenan	Red algae	Anti-oxidant, drug delivery	[Manivasagan and Oh et al., 2016]
Porphyran	Red algae	Cytotoxic, drug delivery	[Manivasagan and Oh et al., 2016]
Ulvan	Green algae	Tissue engineering	[Manivasagan and Oh et al., 2016]
Exopolysaccharides	*Porphyridium cruentum*	Anti-bacterial	[Raposo et al., 2013b]
Spirulan	*Arthrospira platensis*	Anti-coagulant, anti-thrombic activity	[Raposo et al., 2013b]
Fucoidans	*Cladosiphon novae-caledoniae, Undaria pinnatifida, Turbinaria ornata, Fucus vesiculosis, Macrocystis pyrifera, Laminaria japonica, Hizika fusiformis*, Brown algae	Anti-tumour, anti-viral, anti-inflammatory, Osteo-arthirits, Gastric ulcers, Cytotoxicity	[Balboa et al., 2013], [Manivasagan and Oh et al., 2016]
Sulfated polysaccharides	*Adenocystis utricularis, Grateloupia longifolia, Laminaria guryanovae, Codium atlanticum, Monostroma nitidum*	Anti-HIV, Anti-tumour, Anticoagulant	[Balboa et al., 2013]

Table 7
Phenolic compounds from algae species and their biological applications.

Phenolic compounds	Source organism	Biomedical applications	References
Rutin, Catechol, Hesperidin	*Porphyra genus*	Anti-inflammatory	[Herrero et al., 2013]
Fucosterols	*Pelvetica siliquosa, Sargassum vulgare, Undaria pinnatifida, Himanthalia elongata, Chondrus crispus, Porphyra* sp. *Cystoseira* sp. *Ulva* sp.	Inhibition of cholesterol absorption, anti-cancer, anti-diabetic, anti-fungicidal, anti-ulcerative	[Ibanez et al., 2012]
Fucoxanthins	*Myagropsis myagroides* Brown algae	Anti-inflammatory Anti-angiogenic, anti-diabetic	[Balboa et al., 2013]
Terpenes	*Bifurcaria* sp., *Dictyota* sp., *Sargassum* sp.,	Antioxidant, anti-viral	[Balboa et al., 2013]
Chromenols	*Bifurcaria bifurcate, Cystoseira tamariscifolia, Desmarestia ligulata, Dictyota dichotoma, Halidrys siliquosa*	Cytotoxicity	[Ibanez et al., 2012]
Phlorotannins	*Ecklonia cava*, Brown algae, *Ecklonia stononifera, Ecklonia bicyclis, Ecklonia arborea, Ecklonia stolonifera, Ascophyllum nodosum, Ulva lactuca, Palmaria palmate, Alaria esculenta, Hizika fusiformis, Ishige foliacea, Cystoseiranodic tamariscifolia*	Anti-microbial, anti-inflammatory, anti-hypertension, anti-cancer, Radio-protective effect, anti-photo-carcinogenic, anti-HIV, anti-diabetic, anti-allergy, anti-proliferative, anti-allergic, anti-aging, Matrix metallo proteinase inhibition	[Li et al., 2011], [Balboa et al., 2013], [Lee and Jeon, 2013], [Ngo and Kim 2013], [Sanjeewa et al., 2016]
Phenolic compounds, Alkaloids, Terpenoids	*Anabaena flos-aquae, Anabaena oryzae, Nostoc humifusum, Nostoc muscorum, Oscillatoria* sp., *Spirulina platensis, Phloromedium fragile, Chlorella vulgaris*	Anti-oxidant, anti-cancer	[Sanna et al., 2012]
Hydroxy-cinnamic acids, Hydroxy-benzoic acids, Kaempferol, Euganol, Chrysin, Galangin, Pinostrobin	*Spirulina maxima*	Anti-oxidant, Hepatoprotective activity	[Abd El-Baky et al., 2009]
β-carotene	*Dunaliella salina, Haematococcus* sp.	Anti-oxidant, anti-inflammatory, anti-cancer	[Elena et al., 2015]
Sulfated polysaccharides	*Dinoflagellate, Gyrodinium impudicum*	Anti-inflammatory, anti-cancer, Immunomodulating	[Elena et al., 2015]
Brassicasterol, Stigmasterol	*I. galbana; Chaetoceros, Skeletonema; P. lutheri*	Hypocholesterolemic activity	[Raposo et al., 2013a]

Table 8
Available protein content in few important commercial types of seaweed.

Seaweed	Protein content (% DW)	References
Brown		
Undaria pinnatifida	11.0–24.0	Fujiwara-Arasaki et al. (1984)
Laminaria digitata	8.0–15.0	Augier and Santimone (1978)
Ascophyllum nodosum	3.0–15.0	Smith and Young (1954)
Green		
Ulva lactuca	8.7–32.7	Fleurence (1999a)
Ulva pertusa	17.5–26.0	Abdel-Fattah and Sary (1987)
Red		
Porphyra tenera	33.0–47.0	Morgan et al. (1980)
Palmaria palmata	8.0–35.0	Nisizawa et al. (1987)
Chondrus crispus	21.4	Young and Smith (1958)

forms a phycobilisome, and the name begins with the letter R- indicating the Rhodophyceae family as certain microalgae also produce phycobiliproteins, the names of which begins with C— (Cyanophyceae family) and B— (Bacillariophyceae family) (Apt et al., 1995). The molecular weight of phycocyanin, allophycocyanin and phycoerythrin was reported as 100, 100 and 240 kDa, respectively (Senthilkumar et al., 2013). Phycocyanin, allophycocyanin, and phycoerythrin emit red and yellow fluorescence, respectively (Glazer et al., 1982; MacColl and Guard-Friar, 1987). Based on absorption properties, phycobiliproteins are generally divided into three classes such as phycoerythrins (PEs), which absorb light at 495 and 540–570 nm; phycocyanins (PCs), which absorb light at 610–620 nm; and allophycocyanins (APCs) which absorb light at 650–655 nm (Kumar et al., 2010a; Boobathy et al., 2010; Baghel et al., 2014). There are several methods available for the extraction of phycobiliproteins such as physical, chemical and enzymatic methods (Guillard et al., 2015; Munier et al., 2015; Martins et al., 2016). Phycoerythrin purity is confirmed through spectral readings using A_{565}/A_{280} ratio. Various chromatographic methods such as ion exchange, size exclusion, gel filtration, hydroxyapatite, etc. as well as membrane filters are used for the separation of PE from crude phycobiliprotein pigments (Denis et al., 2009; Dumay et al., 2015).

Seaweeds are generally used for phycocolloid production and in food materials as a stabilizer. Colors from seaweeds are normally used in cosmetics and pharmaceuticals. The global natural food colorant market represented around 55% of the total food colorant market in 2015 and is expected to account for over 60% of the overall market by 2026. The market growth is estimated at a healthy CAGR of 5.4% in terms of value over the estimated period of 2016 through 2026 (http://www.futuremarketinsights.com/reports/globalnaturalfoodcoloursmarket).

7.3.3. *Organic solvent extract*

Seaweeds contain photosynthetic pigments such as chlorophylls, carotenoids, xanthophylls, fucoxanthin, lutein, etc., and these pigments play a major role in photosynthesis and defense mechanism against pathogens. These pigments are extracted using solvents such as acetone, ethanol, methanol, chloroform, ethyl acetate, diethyl ether, petroleum ether, etc. (Jensen and Jensen, 1959; Sudhakar et al., 2013a,b). Some of these pigments are widely used as an antioxidant in pharma products and as a natural colorant.

7.3.4. *Biosensor applications*

A biosensor is an analytical device that converts a biological response into an electrical signal (Velusamy et al., 2010). Biochemicals such as pigments, polyphenols, sugars, lipids, enzymes act as potential chemicals can be used in biosensor for various applications such as food, water quality analysis, medicinal (disease diagnosis) and other research applications (Nikoleli et al., 2018; Wong et al., 2018; Vaidya and Annapure, 2019). So algae as a whole or/and its compounds can be effectively used for biosensor applications in the future.

7.3.5. *Carbohydrates in seaweeds*

Seaweeds contain several polysaccharides called phycocolloids such as agar, alginate, carrageenan, fucoidan, ulvan, cellulose etc. Phycocolloids are made of several monomers such as glucose, galactose, mannuronic acid, guluronic acid, mannitol, laminarin, etc. Usually, seaweeds are composed of 30–60% of carbohydrates (Sudhakar et al., 2017; Ashokkumar et al., 2017). It was also reported that seaweed containing high carbohydrate and low ash make macroalgae most suitable for biofuels (Sudhakar et al., 2013b; Deniz et al., 2015). β-1,3-glucan is an important algal carbohydrate and is of higher significance than other carbohydrates due to their technical applications, such as the gelling or thickening compound agar (produced by macroalgae belonging to the Rhodophyta group), alginates, etc. β-1,3-glucan are also added to novel food products such as functional beverage, functional bread, ready-to-serve soups, functional snack foods and a variety of sauces, creamers, bakery products, and additional food products (Martin et al., 2014; Sudhakar et al., 2015).

8. Conclusion and way forward

Algae contain various components that are considered to be highly valuable with vast application potential. Carbohydrate used for the fermentation process, lipid used for biodiesel production, protein, fatty acids, pigments are used for nutraceutical and pharmaceutical application. Though concerted research works are being undertaken between public and private collaboration in utilizing algal strains economically, still this area demands further research. Therefore, this review article suggests that production of biofuel products and other bioactive compounds from various algal strains. Certain research gaps exist in the production of clean fuel from algae due to low yield and expensive conversion methods, and overall outlay of production and therefore, the scope discussed in this review would categorically pave the way for biofuel concept development with an integrated low-cost biorefinery industry. Various studies indicate that phenolic substances present in algal species are an important contributor as antioxidants, but further identification of these compounds in the purified state is needed for an improved understanding of their structural-functional relationship. The identified chemical components in algal species can exert synergistic effects when they are consumed entirely for greater health benefits. Various in-vivo clinical studies are still needed to explore the pharmacological and other biological properties of marine-derived algal products. As a positive note, utilization of microalgae provides the triple benefits, viz. biofuel production and value-added compounds extraction through biorefinery and also protects the environment from harmful effects through CO2 mitigation. In addition to microalgae, macroalgae (seaweed) cultivation is an opportunity for wealth and sustainable livelihood for coastal communities. Further, seaweeds can act as a potential source for clean fuel generation, such as bioethanol, biobutanol, biohydrogen and biogas. There are different field emerging based on seaweed utilization. Tissue culture and cell suspension culture aspects of growing seaweeds will fetch certain secondary metabolite production with high market value. Less research was recorded in this field especially the design of reactors and process optimization. Cultivation of economically viable genetically modified seaweeds through offshore cultivation will yield different types of compounds for medicinal and food applications. Like agriculture, seaweed training center has to be started for seaweed cultivation along with seed bank. In the future, due to climate change, we may loose precious high-value seaweeds through natural calamities and cyclone. To preserve our diversity seaweed data bank is essential for long term diversity preservation. With an aim to transform complete biomass into several bioactive products or co-products through a well-standardized approach, choosing an apposite algal candidate (microalgae) and its attributes in terms of elemental composition and compatibility and sustainability at outdoor condition are foremost criteria. The algal biomass cultivation (both microalgae and macroalgae) require much more advanced research to sustain itself for continuous production. Further, this comprehensive review would lay a roadmap for widespread applications of algal components in biofuel, medicinal, food, nutraceutical, and cosmetic industries.

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