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A state of the art review on the cultivation of algae for energy and other valuable products: Application, challenges, and opportunities

B. Ramesh Kumar [a], Thangavel Mathimani [b], M.P. Sudhakar [c], Karthik Rajendran [d], Abdul-Sattar Nizami [e], Kathirvel Brindhadevi [f,*], Arivalagan Pugazhendhi [g]

[a] Plant Metabolic Pathway Laboratory, Rajiv Gandhi School of Intellectual Property Law, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, 721302, India
[b] Department of Energy and Environment, National Institute of Technology, Tiruchirappalli, Tamil Nadu, 620015, India
[c] Marine Biotechnology, National Institute of Ocean Technology, Ministry of Earth Sciences, Chennai, 600100, India
[d] Department of Environmental Science, SRM University-AP, Andhra Pradesh, India
[e] Sustainable Development Study Centre, Government College University, Lahore 54000, Pakistan
[f] Institute of Research and Development, Duy Tan University, Da Nang 550000, Viet Nam
[g] Innovative Green Product Synthesis and Renewable Environment Development Research Group, Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Viet Nam

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ABSTRACT

Algae have long been investigated as a plausible reserve of several biofuel and bioactive compounds attributed to their fast-growing characteristics, shorter doubling time, and capability of accumulating lipids. Compounds extracted from algae are being studied in various sectors namely, pharmaceutical, cosmetics, cancer biology, nanoscience, food industry, etc. In view of the rich potentials of algae, this present review is aimed to highlight the significance of different cultivation aspects of microalgae like open pond and photobioreactor and advantages and disadvantages thereof. This state-of-the-art review provides the limitations of energy (biodiesel, bioethanol, biohydrogen, biomethane) products obtained from the algae in a perspective of shifting lab-scale into a field scale. In addition to the cultivation systems and biofuels, several non-energy products or value-added products obtained from algae were critically compared and presented. Data from plethora literatures discussing the advanced methods for the extraction of omega-3, omega-6 fatty acids, vitamins and nanoparticles from algae have been discussed extensively. Further, bioactive compounds extracted from several algal strains were listed. Considering the health benefits, anti-angiogenic, and anti–cancer properties of algal bioactive compounds were described along with other industrial applications. Overall, this comprehensive review will help in understanding status of algal biofuel, cultivation systems, metabolites and their application for the betterment of the human society.

1. Introduction

Petroleum or fossil fuels are considered as a depleting energy reserve against growing demand due to their non-renewable status, and unarguably poses a potential threat to the transportation sector [1]. Across all major sectors, expanding the population, increasing infrastructural and socioeconomic development would trigger fossil fuel consumption. Increasing depletion of fossil fuel reserves, uncertainty in their supply and rapid rise in petroleum prices have kindled search for alternatives to fossil fuels [2]. In addition, climate catastrophe accentuated by the potentially unfriendly gases from the fossil fuel combustion is an indisputable hazard to human society [3,4]. Owing to high fuel usage, petroleum prices were escalated up to a point where alternative fuel is competitive and needed to moderate an inevitable upward march of oil prices as well as to meet the socio-economic demand. Thus, the modern world has been urged to shift from petroleum fuel to carbon neutral, renewable, alternative fuel through multidimensional global strategies. Given this, there are vigorous research initiatives sought whilst aiming for new alternatives, which are likely to alleviate dependence on fossil fuel imports as well as to circumvent global warming calamity [5,6]. In this scenario, biofuel came to limelight specifically, microalgal based biofuel have gained increased attention as a sustainable fuel [7]. In

* Corresponding author.
E-mail addresses: kathirvelbrindhadevi@duytan.edu.vn (K. Brindhadevi), arivalagan.pugazhendhi@tdtu.edu.vn (A. Pugazhendhi).

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addition to biofuel production, microalgae can be used for the extraction of various non-energy products or high-value products or industrially important co-products either direct extraction method or integrated sequential bio-refinery technique. Algae contain proteins, carbohydrates, lipids, and nucleic acids as their biochemical components and notably, free fatty acids, triglycerides, phospholipids, and glycolipids from the lipid biomolecule serve as a source for substitute energy [8]. Further, culturing and maintaining indoor (laboratory grown) microalgal strain in outdoor ponds beyond one month is difficult since the strain is failed to acclimatize an unconducive outdoor environment, and often encounter cross-contamination as well [9]. Hence, maintenance, operation, and performance features of cultivation bio-system has to be improved through in-depth research efforts [9].

The algae of the marine environment have diverse species and thus, provides wide opportunities to produce functional foods from them for sustainable development [10]. In concern with the application of algal bioactive compounds in pharmaceutical industry, marine microalgal anti-cancer compounds were least studied and many investigations were carried out with extracts or fractions of microalgae acquired through liquid-liquid partitioning or solid phase low-resolution extractions [11]. Though various fuel and non-fuel products (valued added products) are produced from algae (Fig. 1), still it faces major challenges as several algal-based technologies are in a laboratory level and thus pilot-scale study needs to be undertaken. In concern with biofuel production from algae, the technical feasibility of the process to compensate the fossil fuel is comparatively high and not energy intensive. With reference to cultivation, various obstacles need to be addressed and untangled to develop effective mass cultivation technology for microalgae and it relies on meticulous understanding on photosynthetic, structural attributes of microalgae and dominance of target strain over alien strain/bacteria contamination and unavoidably biomass productivity per unit area. In concern with macroalgae for fuel production, macroalgal biomass generation is relatively simple due to its cultivation near seashore with ample sunlight availability, seawater availability, CO_2 mitigation. But, there are significant technical and economic challenges for third-generation bioethanol/biogas from macroalgae. Usage of chemicals, thermal energy and process time are the crucial part of the fermentation production of biofuel from macroalgae. Macroalgae cultivation depends on seasonal changes in the sea environment and also differs with country wise. Only few species of the macroalgae are cultivable throughout the world based on their country's native species. Still tissue culture development for the macroalgae species under infant stage and basically used to preserve the native genome for future use. Further for biofuel production macroalgae are viable only proper fermentation technology integration with seaweed industries along with other by products separation is must to reduce the cost of production. Potential bacterial/yeast strains are essential to produce higher yield of ethanol or biogas from seaweeds. These technical challenges have to overcome in future in order to achieve biofuel production economically. To achieve commercial viability of the micro/macroalgal products, cost-effective methods should be developed and a basic understanding of the process is essential. To achieve commercial viability of the microalgal/macroalgal products, cost-effective methods should be developed.

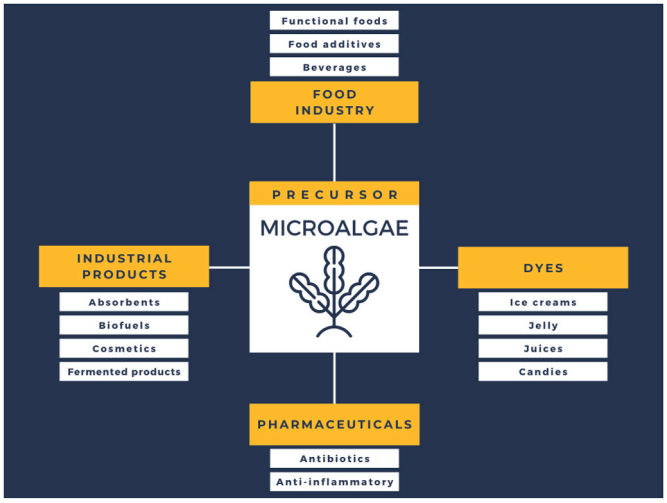

Fig. 1. Different applications of algal biomass.

Therefore, this review aims to provide a comprehensive view on the different cultivation systems of micro and macroalgae for energy and non-energy products. Then, different cultivation system being used for algae would be discussed in detail and merits and demerits of the cultivation types would be given to choose an optimal design. Eventually, this review analyses the reports dealing with the extraction of other products such as fatty acids, vitamins, nanoparticles and valued products from algae and their application in human health like anti-angiogenic, anticancer, and anti-inflammatory properties.

2. Methodology

Microalgal biofuel production is widely spoken topic in the avenues of alternative energy production. However, the issues that block the entry of microalgal biofuel in to commercially possible fuel status were also addressed before, yet it needs to be elaborated to comprehend the whole process from selection till production. The below methodology was followed in writing this review article.

1) To review the identified literature by searching in databases including Science Direct, NCBI, Springer, Scopus, PubMed and Google Scholar websites using various keywords such as microalgae, macroalgae, algal cultivation, cyanobacteria, lipids, biodiesel, biofuel bio-refinery, pigments, bioactive compounds from algae, vitamins from algae, omega-3 fatty acids from algae.
2) Planning the content of the reviewed literature by extracting information and framing certain set of questions which identifies the knowledge gaps in cultivation systems of microalgae and macroalgae and explores the opportunities of energy and non-energy products in various discipline.

The most recent and relevant articles were screened out which laid emphasis on the above contents mentioned after which the observations were discussed and analyzed for future directions. The contents of this review article have been categorized into three major components:

a) Various cultivation methods employed for both microalgae and macroalgae with advantages and pitfalls.
b) The obtained source of energy products from both of these algal species and their vital applications and limitations
c) The critical valuable products and their pivotal role in human health benefits.

The following questions have been framed and drove the literature review process to identify the extracted information:

✓ How to develop a cost-effective and efficient cultivation method for microalgae and macroalgae?
✓ How the selected cultivation methods address the present challenges involved in the production of biomass and the economical ways to produce biofuels from both of these algal types?
✓ How the different microalgae and macroalgae species have been exploited for the production of energy products in a most cost-effective manner?
✓ What are the limitations with these energy products and how it can be overcome with the present study?

- ✓ What are the other high values –low volume products that can be extracted from microalgae and macroalgae for frame an integrated bio-refinery?
- ✓ How do valuable products offer benefits on human health?
- ✓ What are the conclusions drawn from the present study and suggestions for future improvements?

Therefore, the key knowledge gap or challenges of microalgal biodiesel has been kept as a core content of this review topic. Keeping this as subject matter of this review article, a search was done in various scientific databases Science Direct, NCBI, Springer, and Google Scholar websites using the various keywords. The keywords include microalgae, cyanobacteria, lipids, biodiesel, biofuel bio-refinery, pigments, cultivation of algae, bioactive compounds from algae, vitamins from algae, omega-3 fatty acids from algae etc. Literature was sorted based on the anticipated content and critically analyzed for discussing the results. At first, numerous suitable research, review articles and short communication were downloaded and sorted into three major parts namely, cultivation of microalgae and macroalgae, biofuel from micro and macroalgae and their limitations, non-energy products or value added products from algae and their application. In concern with the section pertaining to cultivation of algae, about 90% of the research and review articles cited in this article cover the period from 2010 to the present. Further, biorefinery approach can be practiced to couple fuel production with the extraction of other value-added products for cost-effective fuel production from algae. Hence, a secondary scrutinize was carried out to bring together the relatable articles on nanoparticles from algae and cyanobacteria and high-value products and their application in anticancer and anti-angiogenic properties. Based on the assessment, the topic of this article is decided as the cultivation of algae for energy and non-energy products. In Apart from bio-actives from macroalgae, seaweeds are also rich in polysaccharides (phycocolloides) and its extraction was briefly explained with simple cost-effective methods. Valorization aspect of macroalgae with the current scenario of an integrated process to get maximum yield of all compounds from seaweeds are explained with current literature updates with challenges. Around the last 5–10 years of references analyzed for biofuel limitations of using seaweeds (macroalgae) and challenges were proposed towards future directions. A sufficient land and water resource for sustainable production of the long-term viability of algal biofuel was critically discussed in the later part of this review. Eventually, research and review articles pertaining to economic and environmental assessments of algal biofuel were collected and evaluated for facts and figures to provide an extensive discussion on the life cycle assessment and techno-economic assessment of algal biofuel.

3. Cultivation of algae

3.1. Cultivation of microalgae

Two types of cultivation systems are widely practiced for the cultivation of microalgae namely raceway pond and photobioreactor. In order to generate maximal biomass, outdoor cultivation system entailing open or closed raceway pond, laboratory scale cultivation using photobioreactor should be developed. On an economical annotation, most of the cultivation systems being practiced till date are carried at elevated cost, which is unfair for inexpensive biodiesel production and further expansion towards marketing. Hence, it is important to select an apt cultivation system for microalgae. For the cultivation of algae, there is different organic and inorganic carbon sources used. Organic carbon sources like glucose, glycerol, sodium acetate, and sucrose (under mixotrophic condition or single carbon supplement) and inorganic carbon source like CO_2, bicarbonates etc. were used for high productivity of energy materials such as lipids, omega-3 and other oils from microalgae [12–14]. Cultivation of microalgae requires various supplementary nutrients and conditions such as light intensity, temperature and pH. Green algae and cyanobacteria require more bicarbonate; nitrogen (KNO_3, $NaNO_3$ and urea) and light source (red, blue, green, white fluorescent lamps) for its growth and also require CO_2 and dark condition for biochemical production. The biomass can be increased with increase or decrease in nutrients or light or temperature. Only optimization of particular environment for particular algae fetches good amount of biomass yield and biochemical productivity [15]. Microalgae genetics, their culture conditions and the efficiency of cells recovery and products development are the bottlenecks for industrial bioprocesses from microalgae [16,17].

3.1.1. Open pond and its challenges

Shallow ponds, tanks, circular ponds and raceway ponds are the widely used open systems [18]. By and large, commercial-scale mass cultivation of microalgae is predominantly done with raceway ponds, and nonetheless, positive demonstration of raceway pond cultivation with respect to biomass yield was portrayed with very few microalgal strains e.g., *Spirulina* and *Dunaliella* [19]. Productivity of algal strains grown in different cultivation systems was shown in Table 1. The

Table 1
Productivity of algal strains grown in different cultivation systems [18,21].

Algal Strains	Cultivation style (value in parenthesis indicate volume in m^3)	Production
Spirulina sp.	OP, PBR	[a] 3000
Spirulina platensis	OP (135)	[b] 8.2
Chlorella sp.	OP, PBR	[a] 2000
Chlorella sorokiniana	IT	[d] 1.47
Dunaliella salina	OP, PBR	[a] 1200
Aphanizomenon flosaquae	OP, PBR	[a] 500
Haematococcus pluvialis	OP, PBR	[a] 300
Haematococcus pluvialis WZ	OP (20)	[c] 0.107
Haematococcus pluvialis 26	OP (100)	[c] 0.122
Haematococcus pluvialis	BC	[d] 0.06
Tetraselmis MUR 233	OP (25)	[b] 37.5
Tetraselmis suecica F&M-M33	OP (20)	[b] 8.37
Nannochloropsis sp. *F&M-M24*	OP (20)	[b] 14.1
Nannochloropsis sp.	FT	[d] 0.27
Botryococcus bruanii Kutz. AP103	OP (2)	[c] 0.114 g/L
Botryococcus braunii LB-572	OP (0.080)	[c] 0.1
Scenedesmus sp.	OP (20)	[b]17
Scenedesmus sp.	OP (0.023)	[c] 0.085
Scenedesmus sp.	OP (0.020)	[c] 0.16
Dictyosphaerium sp.	OP (8)	[b] 5.8
Pediastrun boryanum	OP (8)	[b] 9.2
Chlamydomonas reinhardtii (CC124)	Tubular	[e]0.6 mL/L/h
Chlamydomonas reinhardtii (CC124)	Stirred tank	[e] 1.53 mL/L/h
Chlorella pyrenoidosa C-101	BC	[e] 6.9×10^{-2} m^3/kgcell
Chlorella vulgaris MSU 01	Stirred tank	[e] 26 mL
Cryptheconidium cohnii	PBR	[a] 240
Schizochytrium sp.	PBR	[a] 10
Porphyridium cruentum	AT	[d]1.5
Phaeodactylum tricornutum	AT	[d] 1.2
Arthrospira platensis	URT	[d] 2.7

OP – open pond, PBR – photobioreactor, AT - Airlift tubular, IT - Inclined tubular.
URT -Undular row tubular, BC-Bubble-column, FP – Flat plate.
[a] Annual production in tones (in dry wt).
[b] Average areal biomass productivity (g/m^2/d).
[c] Average volumetric biomass productivity (g/L/d).
[d] Biomass productivity (g/L/d).
[e] Hydrogen production.

biomass productivity of microalgae grown under raceway pond was between 73 and 109,000 kg ha^{-1} yr^{-1} [20], and in high-rate raceway ponds, 127,000 kg ha-1 y^{-1} can be achieved due to the active photon flux with data for insolation and radiation [21]. Most routinely grown prokaryotic and eukaryotic algae in raceway pond are *Nannochloropsis* sp., *Chlorella* sp., *Tetraselmis* sp., *Arthrospira platensis, Dunaliella salina, Scenedesmus* sp., *Haematococcus pluvialis, Anabaena* sp., *Phaeodactylum tricornotum, Micractinium* sp., *Actinastrum* sp. etc [22–24].

In order to increase the biomass production rate through the open pond, several R & D initiatives are being undertaken across the world, particularly tie-up of government with companies. For example, it is noteworthy that a project featuring 92 million dollars between Aurantia Renewable Energy Company (Spain) and Green Fuel Tech of Massachusetts (USA) set a goal to generate 25,000-ton biomass per year from 100 ha greenhouses, which is further coupled with supplying CO_2 from a cement plant as a carbon source. Yet another effort made by Italian energy Company Eni, involves testing an open pond and photobioreactor at 1 ha pilot facility for microalgal oil production [25]. Further, as reported by Singh and Gu (2010), countries situated in the coastline of Mediterranean Sea bestowed with warmer climates, which are suitable, most efficient outdoor area to facilitate the algae growth in the open system. The green microalga *Scenedesmus* sp. was grown in a 23 L airlift-driven raceway reactor in both batch and continuous modes and biomass productivity of 0.085 L^{-1} day^{-1} were achieved in batch mode at 1% CO_2, and maximum CO_2 utilization efficiency of 33% whereas in continuous mode, it was 0.19 g L^{-1} day^{-1}. Based on high biomass production, CO_2 utilization and power efficiency, this proposed airlift-driven raceway design can be the cost-effective algal [26].

Life cycle analysis of biomass production and net energy ratio of oleaginous *Nannochloropsis* sp. grown under raceway ponds, tubular and flat-plate photobioreactors were compared and from the results it was drawn that horizontal tubular photobioreactors are not economically feasible (NER < 1) while flat-plate reactor and raceway ponds showed NER is > 1 and this figure can be increased significantly if lipid yield was improved to 60% [22]. The economic point of recycling electro flocculated culture supernatant on the growth of halotolerant green alga *Tetraselmis* sp. MUR 233 was examined in an open raceway pond over 130 days. Despite a salinity increase from 5.5% to 12% (w/v), NaCl, the strain produced 48–160% more ash-free dry weight per unit per day than when grown on non-recycled medium. Peak productivity of 37.5 $\pm$ 3.1g ash free dry cell weight (DCW) m^{-2} day^{-1} in open pond was reached in the recycled medium [27]. Self-designed system mimicking open pond has been established for the mass cultivation of *Haematococcus* species (*H. pluvialis* 26; *H. pluvialis* 30; *H. pluvialis* 34; *H. pluvialis* WZ) for astaxanthin extraction about 12 days. Among the strains, *H. pluvialis* WZ produced 1.61–2.48 g 100 g^{-1} dry wt astaxanthin in two 100 m^2 open raceway pond. This work portrays the possibility of cultivating microalgae in open pond for producing astaxanthin, and this culture system has already been effectively practiced for the mass cultivation of *Spirulina* and *Chlorella* strains [28]. Raceway pond facilitated algal cultivation has many advantages and disadvantages as given in Table 2.

Though raceway pond cultivation was being practiced widely to generate high voluminous biomass, it has certain challenges due to nutrients addition, CO_2 purging, process stability and separation of biomass from suspension [29]. Target or desirable algal cells are not able survive due to the presence of zooplankton, bacteria, and cross contamination with other undesirable strains. Therefore, it is imperative to choose indigenous strain and to monitor the growth of target strain regularly. In this case, maintaining the exponential growth of target culture and poly house based closed system may avert the cross-contamination [3]. In addition, the key challenge in open pond cultivation is the formulation of low cost medium as it occupies major fraction in the total cultivation cost. For the cultivation of microalgae in open system, a low-cost medium formulated using either sewage water or wastewater or seawater with fertilizer-grade nutrients (Phosphorous, Potassium, Nitrogen) is utmost important [7].

Table 2
Advantages and disadvantages of micro/macroalgae cultivation systems.

Algae	Advantages	Disadvantages
Microalgae	Cultivable throughout the year under controlled condition in all seasons	Outdoor cultivation possible only in seasonal
	Laboratory cultivation using photobioreactors	Limited scale up production only possible
	Automation process	Still requires manpower
	Raceway pond used for scale up	Seasonal and regular/frequent cleaning essential
	Flocculation, centrifugation, filter press used to harvest	Harvesting algae is complicated and economically high
	30–60 days for harvest biomass (depends on microalgae)	Short time biomass generation in tons not possible
	Fresh water algae easy to handle	Marine microalgae requires fresh water to clean
	Growth can be enhanced through nutrient modification and stress condition	Cost may increase while using synthetic medium
	Requires external light source for good growth	Increase cost of production by consuming energy
	Seed production for cultivation is easy and requires less biomass within a short time	Usually use 10–15% inoculum for scale up
	Land required	Maintenance is again increase cost
	Continues harvesting possible by adding additional nutrients and water	Waste water has to be treated properly before discharge into open land or river or sea
Macroalgae/ seaweeds	Cultivation possible in onshore or off shore	Rainy season may affect growth of seaweeds
	Photobioreactors used for particular species (*Ulva* sp.)	All seaweeds cannot grow in photobioreactors
	Man power required for all process	No automation
	Raft/rope cultivation required for scale up	May tear/break during cyclone season
	Manual/automated harvest	Cost/energy may increase while automation
	Biomass generation in tons possible in a short time (45 days)	60–90 days required to harvest depends on seaweeds
	Initial washing use seawater to remove debris	Fresh water required for cleaning salts/debris
	Requires natural sunlight for photosynthesis	Sunlight may even bleach seaweed during summer
	Small size (1–2 cm) thallus enough to generate huge quantity	Seed production requires sufficient seaweed quantity and time
	No land/external nutrients required	Possible only at particular seashore, rough sea affect the seaweed cultivation, damage raft
	No need of water treatment after harvest of seaweed	

3.1.2. Photobioreactor and its challenges

A major setback in the microalgal mass cultivation through photobioreactor is a dearth of in-depth understanding of hydrodynamic and mass transfer processes in photobioreactor [18]. Photobioreactor can be tubular or flat, serpentine or manifold, helical, made of acrylic glass. The flat-plate bioreactor is constructed with flat transparent materials for absorbing high light intensity. Advantages are high photosynthetic efficiency, suitable for immobilization of algae, high biomass production, effortless cleaning, readily tempered, low hydrodynamic stress on cells [18,21]. Tubular photobioreactors can be of horizontal, vertical, near horizontal, conical, inclined type made up of glass or plastic tube in which algal cultures were re-circulated either with pump or airlift system. Generally, it is suitable for an outdoor condition with substantial biomass productivities and cost-effective [18,21,30]. Vertical column photobioreactors are compact and easy to operate. High mass transfer of

nutrients to cells by adequate mixing, relatively high scalability, low shear stress, reduced energy consumption, sterilization feasibility of chamber to avert contamination, readily tempered, least photo-inhibition and oxidation [18]. Several researchers have used photo-bioreactors for biomass production from algae Table 2. Thermophilic green alga *Chlorella* sp. was grown in 40 L vertical bubble column photobioreactor at semi-continuous mode, and the CO_2 fixation rate was determined to be 25.65 mg/min [31]. Sato et al. [32] used a novel photobioreactor for culturing microalga *Chaetoceros calcitrans* which was found to yield maximum cell density of 37.3 g/m^2/day. To enhance the cyanobacterial biomass generation at outdoor, tubular undulating row photobioreactor was made by keeping 0.01 m (internal diameter) pipes to enable maximum absorption of solar radiation and biomass productivity and concentration of 2.7 g/L/d and 6.0 g/L were noted, respectively, with the cyanobacterium *Arthrospira* sp [33]. Outdoor helical reactor grew microalga *Phaeodactylum tricornutum* unveiled a 35% increase in biomass productivity (1.02–1.38 g L^{-1} d^{-1}) while increasing superficial gas velocity from 0.27 to 0.41 m s^{-1}. Further, the growth rate and photosynthetic efficiency of 0.068 h^{-1} and 15% were recorded, respectively, at 0.41 m s^{-1} gas velocity [34].

Owing to the enormous changes in morphology and biochemical constituents of *H. pluvialis* cell during outdoor cultivation, comparative analysis of tubular and bubble column bioreactor for effective biomass and astaxanthin accumulation of *H. pluvialis* growth was performed. Among, the tubular reactor is pertinent for the production of biomass and astaxanthin from *H. pluvialis* due to high light penetration and it exhibited biomass concentrations of 7.0 g/L after 16 days and 0.41 g/L day (end of cultivation period) under the average photon density of 130 μE/m^2/s. Whereas, bubble column photobioreactor showed 1.4 g/L and 0.06 g/L day, respectively. Further, tubular and bubble column photo-bioreactors showed astaxanthin productivities of 4.4 and 0.12 mg/L day, respectively [35]. A new 0.2 m^3 outdoor photobioreactor was built and tested with *Phaeodactylum tricornutum* at different liquid velocities through a tubular solar receiver. At 0.050 h^{-1} dilution rate, 1.20 g/L/d (20 g m^{-2} d^{-1}) biomass productivity was obtained and tubular solar receiver liquid velocities of 0.50 and 0.35 m s^{-1} were also found to produce same biomass concentration and an adverse effect of high dissolved oxygen concentration on productivity was also observed. Further, the solar receiver helps to reduce oxygen accumulation for high biomass accumulation by increasing the liquid velocity [36]. Taking in account the different bioreactors used for algae cultivation, photobioreactor offers both merits and demerits. The primary gain of using photo-bioreactor is that volumetric biomass productivity and biomass concentration are determined to be 8 times and 16 times, respectively, higher and sustainable than open pond production [21]. Biomass productivities of photobioreactor were between 0.2 and 3.8 g L^{-1} d^{-1} compared to raceway ponds (0.12–0.48 g/L/d) [37]. In addition to ample productivity, less cross contamination, low oxygen buildup, efficient mass transfer of nutrients, is the added merits. Complex and expensive construction is the disadvantages of photobioreactors. The major challenge in PBR based algal cultivation is the total cost. The light provided by means of artificial light sources, like fluorescence lamps or LED [38] and air/CO_2 provided by the commercial cylinders from bottom of the reactors to ensure uniform contact between gas and micro-algae contribute major cost in photobioreactor. In some cases, automated sensors have also been used to measure the intensity of light [39]. Due to above said reasons; the cost of photobioreactor based cultivation still remains a challenge [40]. Further, the growth of algae on the wall, difficulty in scale-up, requirement of cooling system, is added bottlenecks [41,42].

3.2. Cultivation of macroalgae/seaweeds

Macroalgae well known as seaweeds are broadly divided into three types such as red, brown and green based on external colour difference. Seaweeds have parts just like plants such as hold fast, stipe and blade, but not cultivable on land instead use of seawater for their growth and reproduction. Seaweeds also reproduce through both asexual and sexual reproduction through spores formation then fertilization and gametes fusion respectively. Seaweed cultivation has become billion dollar industry due to potential use of seaweeds in various industrial sectors, depletion in natural resource and also seasonality. Seaweed cultivation emerged as a profitable business in many countries and started producing throughout the year both in onshore and offshore region of the sea through different methods [43]. Seaweed cultivation in many countries developed as profitable business due to water scarcity for agriculture and less fertile land, less profit and so on. Seaweed requires no external nutrients and fresh water for its growth. Only limited manpower required but daily maintenance is essential. There are different methods of cultivation used based on the place and seaweed type. They are raft, rope, tube-net, even photobioreactor method was developed for some *Ulva* sp. Harvesting seaweed need some advancement such as hydraulically-controlled suction cutters and processing of seaweeds requires fresh water to remove excess salt and other debris on it [44–46]. For seaweed cultivation environmental factors such as light, temperature, salinity, nutrients, cultivation depth, water movement, herbivorous fish and epiphytes has to be monitored/controlled in the natural sea environment [43]. Seaweeds are grown naturally at different depths in the sea. At present few species are suitable for tank, offshore and onshore cultivation [47]. At present, *Kappaphycus* sp., *Eucheuma* sp., *Gelidium* sp., *Gracilaria* sp., *Saccharina* sp., *Pyropia* sp., *Laminaria* sp., *Sargassum* sp., *Undaria* sp., *Ulva* sp. etc. were successfully cultivated globally. Each country differs in its natural seaweed population. At present natural harvest of red (agarophytes and carrageenophytes) and brown seaweeds (alginophytes) are highly explored for the production of agar, carrageenan and alginates. But seaweed production through mariculture supplies higher yield and meet the demand than natural harvest according to the FAO statistics [48]. Natural harvest would create ecological imbalance and socio-economic consequences [49]. Recently, the production of high quality seaweed biomass through minimal nutrient requirement for the sustainable land-based cultivation is highly encouraged for industrial needs [50]. The continuous supply of seedlings throughout the year for seaweed cultivation has become a big challenge for large-scale production. So maintaining macroalgal nursery to meet the demand and supply of seedlings for cultivation would create positive approach towards seaweed industry product development [51]. Different methods of seaweed cultivation followed according to the nature and environmental condition of the sea. Methods such as raft, net bag, longline, tube net, monocline, pouch, tank cultivation are followed in many countries. At present, many countries started Integrated Multi-Tropic Aquaculture (IMTA) and polyculture system to cultivate seaweeds along with cage culture of fish and other aquatic animals of commercial value [49].

4. Energy products and their challenges

Algal biomass is considered as a renewable resource to produce different types of biofuels, like biodiesel, bioethanol, biogas, bio-hydrogen and so on [52]. Both micro and macroalgae contributing for energy products but only certain limitations has to be overcome in the biomass productivity aspects [53]. Microalgae recently used for bioelectricity production (Microbial Fuel Cells) along with environmental remediation aspects. Still this research is in infant stage [54]. Another way is seaweed cultivation requires only proper and ideal sea shore for continuous maintenance and overcome natural calamities [55]. Huge quantity of seaweed biomass cultivated and extracted from the sea leads to a potential loss in terms of fish catches were recorded [56]. Biomass Assessment Tool (BAT) will fetch some basic details to meet land, biomass productivity, and CO_2 co-locating criteria [57]. The advantages of algae is many such as minimal area requirements, adaptation of unconducive environment and capability to sequester CO_2 [58,59]. They grow in fresh water, seawater, and brackish water, industrial

and domestic waste waters. The most important feature that makes algae a promising candidate for biofuel is the oil content is around 30 times higher than first and second generation sources [60]. The left over algal biomass after lipid extraction can also be supplemented as fertilizers or as feed.

4.1. Bioethanol

Bioethanol is a fuel produced from renewable substrates such as sugarcane juice, molasses, corn, rice, algae etc. Bioethanol is a clean and eco-friendly fuel with less carbon emission [61]. The need to control pollution from fossil fuel consumption and demand is an emerging issue day by day. There is an urgent need to develop an effective alternate fuel from renewable source and much needed at present situation throughout the world. Increase in fossil fuel price and depletion of natural source by human due to over usage of vehicles and industrial need for production, it is mandatory to develop an alternate fuel for daily usage [62]. Over a decade, bioethanol was produced majorly from sugarcane, molasses and corn [63]. There is a shortage in food crops for human consumption due to over exploitation of food crops for bioethanol production. An alternate source such as algae (rich in polysaccharides-sugar) was introduced a decade before for bioethanol production and many research has been done on this field [64]. There are different techniques used for bioethanol production using yeast and bacteria. Conversions of non-fermentable polysaccharides to fermentable simple sugars play a major role in ethanol production using algae [65]. Among the feedstocks, algae are being used for bioethanol production. Bioethanol to algae involves three steps: 1. Pretreatment, 2. Enzymatic hydrolysis, and 3. Fermentation. Macroalgae contains high concentration of carbohydrates and lower lignin contents which affords a milder pretreatment condition. Different treatment techniques were employed to convert complex sugars to simple sugars, which need more energy and time [66]. Techniques such as acid, alkali, enzymes, ionic liquids, heat treatment etc. are most widely used methods for pretreatment of biomass. Some processes are not economically viable for biofuel production and some treatments are not suitable for complete extraction of monosugars and typically forming furfurals and HMF [67,68]. Acidic extraction process conditions (acid, temperature and time) have a profound impact on the total yield, respective product yield and the molecular weight distribution [69]. The need for a pretreatment step is to make the celluloses available for the fermenting them to ethanol. Dilute acids are most preferred pretreatment method, which solubilizes hemicellulose and release the celluloses for enzymatic hydrolysis. Pretreatment is followed by an enzymatic hydrolysis for the conversion of celluloses to sugars. Cellulolytic enzymes including exo-, endo-glucanase, and cellobiose are the key enzymes involved in enzymatic hydrolysis [70]. Yeast is commonly used in fermentation process to produce ethanol.

Trivedi et al. [71] reported an ethanol yield of 0.21 g/g using *U. fasicata* as a feedstock and 0.1% Sulfuric acid as a pretreatment method. The overall conversion with respect to theoretical yield was 88%. Similarly, other studies have reported a theoretical yield varied between 73 and 93%, which varies depending on algae type, pretreatment method, and fermentation conditions [72,73]. Harun et al. [74] reported an ethanol concentration of 3.83 g/L using *Chlorocoum* sp. with a productivity of 38% (w/w). Some of the limitations of algae to ethanol include the bacterial contamination in fermentation and algae cultivation. Biomass cultivation costs, followed by pretreatment and enzymatic hydrolysis increases the production costs, which in turn affects the profitability. Other limitations of algae to ethanol include the limitation of floating algae [75].

4.1.1. Limitations in bioethanol production

There are certain limitations in producing bioethanol using microalgae and macroalgae. In case of microalgae, the biomass generation in the raceway pond and photobioreactor was a major challenge due to other microalgae contamination, poor growth rate during the rainy season, insect menace, low lipid and carbohydrate content, less biomass yield, harvesting cost, frequent maintenance and inorganic nutrient chemicals used. It also requires freshwater/seawater for cultivation and processing. Conversion of microalgae biomass to fermentable sugars requires pretreatment and effective yeast fermentation process for bioethanol production. Whereas in the conventional process use only yeast to ferment molasses. Periodic cleaning of pond and reactor is mandatory otherwise bacterial bio-film formation would affect the algae growth. Need fast-growing strains for mass production of bioethanol. But still microalgae yield and biofuel production continues in certain countries successfully with advancement in automation technology. This may reduce the cost of microalgae production. In case of macroalgae, bioethanol production needs seaweed biomass (natural harvest from the sea) which are rich in polysaccharides (agar-agar, alginate, carrageenan, mannitol etc.). On-shore and off-shore macroalgae cultivation need manpower to maintain daily monitoring of rafts. Seaweed takes 45–60 days to mature (ready to harvest) and this biomass should be processed to remove seawater salts for polysaccharide extraction. Some seaweed requires 90 days to harvest. Seaweed requires more pretreatment process for sugar extraction. Seaweeds are seasonal and need more attention on cultivation, natural calamities may affect the growth of seaweeds. Seaweeds contain different kinds of polysaccharides and it may not work for yeast fermentation. Each type of seaweed requires specific treatment process to yield more sugars. This may increase the cost of production and requires facilities separately [76]. Requires specific enzymatic pretreatment for red, brown and green seaweeds to extract sugars and it costs more. Reducing furfural and 5-hydroxymethylfurfural (HMF) during pretreatment is a major problem and cumbersome task. Specific adsorbents needed to remove these toxic chemicals [77]. Large scale plant facility yet to be established for algal biofuel production. No continuous process of biofuel production from algae available. Transport of seaweeds from seashore to production area will cost more. Storage of seasonal seaweeds increases the cost of production of biofuel.

4.2. Biodiesel

Biodiesel is a fuel produced from oil-rich plant seeds or from oil-rich microalgae. Biodiesel produced via conversion of triglycerides through transesterification process [78,79]. From decades ago biodiesel was produced from Jatropha seeds, waste cooking oil and some oil-rich plant seeds. Now, microalgae which are rich in triglycerides are used to produce biodiesel [80,81]. Microalgal based fuel production does not affect the food production because it cannot compete with food crops [82]. Microalgae consumers are very less whereas other food crops such as Jatropha, moringa, sunflower, safflower; soybean, cottonseed, rapeseed, and palm are cash crops and also used for oil extraction for various end products applications used by consumers in a day to day life. Food crops used for biodiesel production long ago but this will create food crisis in future whereas microalgae cultivation and conversion to biodiesel favors society to use as biofuel. Biodiesel production from algae is based on their rich lipid content (Table 3). Algal biodiesel involves a transesterification process where triglycerides are converted to methyl esters and glycerol in the presence of alcohol and a catalyst. Microalgae has a oil yield ranges between 58,700 and 136,900 L/ha. On a dry basis, microalgae contain 15–77% of oil, which makes it attractive for biodiesel production. The oil content depends on the type of species that is used for the oil production. The algal biodiesel is priced between 0.48 and 2.8 $/L, while another conventional biodiesel from palm or vegetable oil is produced at 0.52 $/L. The high cost is associated with microalgae cultivation and harvesting. In a situation where crude oil prices exceed 80–100 $/barrel, microalgae biodiesel is economically attractive. Some of the strategies in improving the economics of algal biodiesel include biorefinery option where electricity, methane, diesel, animal feed etc. are produced as a product. Such a multi-product

Table 3
Microalgae and macroalgae species with their lipid content.

Species	Lipid Extraction solvents	Lipid content (%)	References
Auxenochlorella protothecoides **(Chlorophyceae)** *Chlorella vulgaris* **(Trebouxiophyceae)**	ethanol (0–30% v/v) hexanes	39.3 26.0	[195]
Gymnodinium sp. **(Dinophyceae)**	hexane-chloroform (4:1 v/v)	29.6	[196]
Chalmydomonas reinhardtii **(Chlorophyceae)**	hexanes	21.0	[197]
Botryococcus braunii **(Trebouxiophyceae)**	chloroform-methanol (2:1 v/v)	28.6	[198]
Jania rubens **(Florideophyceae)** *Ulva linza* **(Ulvophyceae)** *Padina pavonica* **(Phaeophyceae)**	chloroform-methanol (1:2), hexanes	1.56–6.2	[199]
Spirogyra sp. **(Zygnematophyceae)** *Prymnesium parvum* **(Prymnesiophyceae)** *Euglena gracilis* **(Euglenoidea)** *Ulva lactuca* **(Ulvophyceae)** *Laminaria hyperborea* **(Phaeophyceae)** *Chondrus crispus* **(Florideophyceae)** *Fucus serratus* **(Phaeophyceae)** *Palmaria palmata* **(Florideophyceae)** *Undaria pinnatifida* **(Phaeophyceae)** *Ascophyllum nodosum* **(Phaeophyceae)** *Sargassum natans* **(Phaeophyceae)** *Caulerpa taxifolia* **(Ulvophyceae)**	Hexanes, dichloromethane Chloroform-methanol (4:5 v/v), hexanes	11–21 22–38 14–20 1–5	[200] [128]
Ulva armoricana **(Ulvophyceae)** *Solieria chordalis* **(Florideophyceae)**	Chloroform-methanol (1:1 v/v)	2.6 3.0	[201]
Ulva sp. **(Ulvophyceae)**	Petroleum ether, Chloroform-methanol (2:1 v/v)	9.4–12.2	[202]

refinery improves the energy recovery and economics of a process [83].

Fig. 2 shows a typical energy balance of microalgae based biofuel production. The total energy consumed to produce 1-kg of biodiesel was 107.3 MJ. The most energy intensive process in biodiesel production is consumed in the drying process, which consumes about 84% of the total energy needed. Heat consumes 74% and electricity needed was 8% in the drying process. However, the net energy yielded from biodiesel was 103.8 MJ. This means that there is a 3.3% energy loss in total. Nonetheless, for a useful production conversion many renewable energy systems faces such a negative energy yield [84]. Limitations of algal biodiesel production include the large footprint requirement for a raceway pond [83], production cost and economic feasibility of biodiesel for commercial viability, meeting the need for the engine standard in terms of octane number, calorific value, etc. Commercialization of algae to biodiesel depends on price of crude oil, how government subsidizes the biodiesel or taxing the gasoline products.

4.2.1. Limitations of biodiesel production

Certain limitations for biodiesel includes, microalgae cultivation needs huge size raceway pond, which produces a large quantity of algal

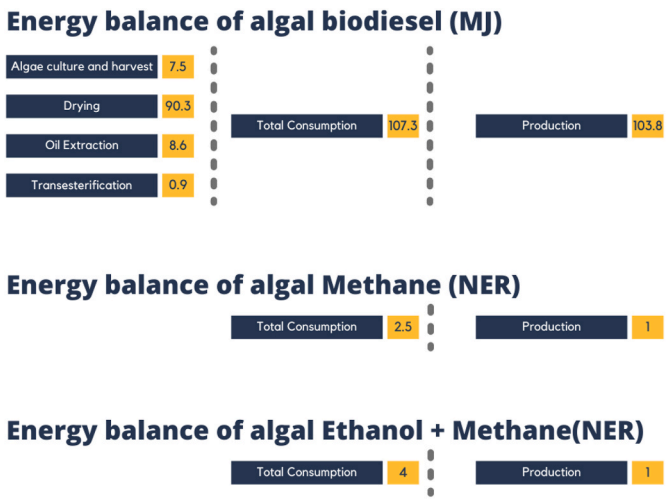

Fig. 2. Energy balance of algae biofuel process in MJ. Data from Ref. [84,194]. NER is Net Energy.

biomass for biodiesel production [83]. Only limited microalgae are rich in fatty acids or lipids and this will affect the production quantity thereby increase the cost of biodiesel production [85]. Conversion of lipids into biodiesel requires many steps and chemicals. Purification of biodiesel also very important in terms of purity to use in vehicles [86]. Energy value of biodiesel such as octane, cetane, calorific value, boiling point, freezing point, carbon emission value is also necessary to check and to produce good quality biodiesel. This needs a certain time and cost analysis [87]. Lipid quantity and quality may vary for every batch of microalgae cultivation due to climatic factors and different generation of algae used after repeated subculture. Vehicles engines at present have to be replaced with biodiesel compatible engines. It is a long term process for changing the engines in vehicles. Processing algae for biodiesel itself a long process and avoiding microbial contamination [88]. Production costs may increase due to rising in manpower and materials for pond and photobioreactor construction. This will increase the cost of production depends on environmental conditions every year. Genetically modified microalgae research in some countries are banned in order to retain the native wild species which yield less lipid production [89].

4.3. Biohydrogen

Hydrogen is a cleanest renewable fuel available today as water vapor is the only emitted particle upon combustion. Moreover, hydrogen has a high-energy density (142 kJ/kg) which reduces the volume needed to store it. There are four-ways in which algae to hydrogen conversion takes places including photo-fermentation, dark-fermentation, direct, and indirect photolysis. Dark fermentation involves *Clostiridum* sp., or *Thermotoga* sp., in the absence of sunlight converts the organic matter to hydrogen. This process is like anaerobic digestion of organics [52]. Photo-fermentation involves the conversion of organics in the presence of sunlight, via TCA cycle. The efficiency of dark fermentation is higher when compared with photo-fermentation due to the growth rate of anoxygenic photosynthetic bacteria [90] (Eqn (1)). Direct photolysis is the breakdown of water to hydrogen via photosystem I and II by green microalgae. This process is sensitive to oxygen availability and hydrogenase activity (Eqn (2)) [91]. Indirect photolysis involves two steps: 1. Splitting of water in the presence of light and storing the energy as sugars (Eqn (3)) and 2. Conversion of sugars to hydrogen (Eqn (4)). Cyanobacteria are helpful in indirect photolysis to produce hydrogen [92].

$$CH_3COOH + 2H_2O + \text{light} \rightarrow 4H_2 + 2CO_2 \quad (1)$$

$$H_2O \rightarrow H_2 + \tfrac{1}{2}O_2 \quad (2)$$

$$12H_2O + 6CO_2 + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2 \quad (3)$$

$$C_6H_{12}O_6 + 12H_2O + \text{light energy} \rightarrow 12H_2 + 6CO_2 \quad (4)$$

The stoichiometric hydrogen yield of different micro- and macro-algae can vary between 92- and 485-mL hydrogen/gVS. The theoretical hydrogen content varies in the range of 34 and 66% depends on the choice of species and its organic composition [93]. Two key parameters that affect the hydrogen yield in a dark fermentation process include temperature and pH. Predominantly, mesophilic conditions are used as its energy-intensity is less. Optimal pH for hydrogen production varies between 5.5 and 6.5. Hydrogen production is linked with volatile fatty acids production (VFA) and it can bring down the pH of liquid phase affecting the yield. A decrease in pH decreases the hydrogenase activity and changes in metabolic pathway [94]. A major challenge in algae to hydrogen is its yield and productivity. Lower yields and productivity are affected by accumulation of proton gradient, competitive inhibition by carbon dioxide, need for bicarbonate binding at PS-II, economic feasibility where hydrogen should be competitive with other fuels available, and finally the storage of hydrogen. Algae to hydrogen are an ideal fuel for the world, provided the shortcomings are addressed.

4.3.1. Limitations of biohydrogen production

Emerging biohydrogen field have some limitations like biohydrogen production requires high intensity of light for direct photolysis by microalgae ($H_2O \rightarrow H_2 + \frac{1}{2}O_2$). Indirect photolysis requires two steps

$$12H_2O + 6CO_2 + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2 \ldots\ldots\ldots\ldots \quad \text{Step 1}$$

$$C_6H_{12}O_6 + 12H_2O + \text{light energy} \rightarrow 12H_2 + 6CO_2 \ldots\ldots\ldots\ldots \quad \text{Step 2}$$

It needs more energy for conversion and time. Blue-green algae (cyanobacteria) are promising microorganisms for this. Dark fermentation involves more process and less hydrogen yield and CO_2 has to be removed during the process. It needs extra cost for hydrogen production. Photo-fermentation is a fermentative conversion of organic substrates into hydrogen and carbon dioxide by use of sunlight as an energy source.

$$CH_3COOH + 2H_2O + \text{light} \rightarrow 4H_2 + 2CO_2$$

Disadvantages are the need to nitrogen limit condition and pre-treatment of industrial effluent as it may be toxic. Liberating H_2 gas at ambient pressure is only a small part of the process. To reach an energy density that is useful the gas must be dried and then compressed to a few thousand PSI. Compressing gas consumes a lot of energy; most of it is not recoverable. So just because the H_2 can be produced does not mean that the process is worth the effort. That needs to be considered here [95]. Other challenges of the bio-hydrogen production include unstable hydrogen production possibly attributed to the metabolic shift of hydrogen-producing organisms. The optimization of key experimental factors, genetic modification and metabolic engineering of microalgae are the ultimate approaches to make hydrogen production cost-effective and sustainable [96].

4.4. Biogas/Biomethane

Anaerobic Digestion (AD) of algae results in methane, via a four-step process. 1. Hydrolysis: breakdown of complex lipids, carbohydrates, and proteins to its monomers; 2. Acidogenesis: conversion of monomers to fatty acids; 3. Acetogenesis: Conversion of fatty acids to final intermediates such as acetic acid, hydrogen, and carbon dioxide; 4. Methanogenesis: Conversion of precursors to methane and carbon dioxide. Methane, the useful component in a biogas is an energy carrier with potential applications including heating, transportation, and electricity production [97]. Algae is a potential source of biomethane production where carbohydrates range up to 69%, proteins up to 84% and lipids up to 63% on a volatile solid's basis [92]. Typical biomethane yield from algae ranges between 0.09 and 0.44 LCH_4/gVS [98]. . In theory, high-protein and lipid yields higher methane, however a balance on C:N ratio needs to be met for smooth functioning of the microbes' present. Most methanogens are sensitive to a fluctuation in C: N ratio and a recommended ratio in most AD systems is 20–30:1 [98]. In such scenarios, co-digesting with high-carbon substrates such as straw, sludge or switch grass helps to reach an optimum point. Several studies had reported that co-digestion improves the methane yield when high C:N ratio substrates such as algae are used. Taihu blue algae has a C:N ratio of 6, which when anaerobically digested yielded 160 mL methane/gVS. However, upon co-digestion with corn straw improved the methane yield to 234 mL methane/gVS (46% increase). The co-digestion improved the C:N ratio to 20:1 [99]. Similarly, co-digestion of *Ulva sp.* with cattle slurry improved the methane yield by 17% [100]. Advantages of algae to methane include negative emissions, avoiding food to fuel conflict, and a better energy-recovery ratio. However, there are shortcomings associated with it. These include: 1. Enhancing methane yield needs an additional step pretreatment process to improve degradability and access the cell wall; 2. Dewatering steps from cultivation and subsequent processes is energy-intensive; 3. Higher salt concentration in wild macroalgae affects the microbial degradation; 4. Finally, the economic feasibility of algae to methane is critical for commercializing it. Because of hindrances the economic feasibility might affect the industrialization of algae to methane.

Table 4 shows the comparison of various biofuels produced from algae and their yields and physical properties. The higher hydrogen to carbon ratio refers to a better clean fuel. This ratio is highest for hydrogen as there are no carbon in it, followed by methane, ethanol, and biodiesel. Most biofuels require a cetane number greater than 50, while ethanol has a lower cetane number of <12, which makes it unattractive form in current trend. All other energy sources including hydrogen, methane and biodiesel have a cetane number >50.

4.4.1. Limitations of biomethane production

The limitations of different bioenergies from algae were given in Table 5. Both microalgae and macroalgae are needed proper hydrolysis before biogas production. In the case of seaweeds (macroalgae) the salts which are present will hinder the growth of bacterial degradation of algae. It needs water to remove salts [101]. Dry algae need to be chopped into small sizes before degradation otherwise improper degradation will occur during the process and limit the Acetogenesis process [102]. Hydraulic retention time (HRT) to be maintained throughout the process of biogas production [103]. Dry biomass allowing higher digester OLR [103,104]. Continuous feed is required for higher yield of biogas [105]. Biogas plants are facing ecological problems in villages [106]. Dedicated land will be mandatory for biogas plant [107]. The currently available techniques are not efficient to recover algal energy and microalgal cultivation and harvesting are very expensive and therefore, microalgal biofuel is costlier than fossil fuels [108]. Pilot-scale research is still missing and would help to evaluate the feasibility of full-scale implementation [109]. Polyphenols present in the seaweeds act as an inhibitory to anaerobic digestion [110].

Table 4
Comparison of various biofuels from algae [203–206].

Parameter	Unit	Ethanol	Diesel	Hydrogen	Methane
Energy Content	MJ/kg	23.4–26.8	37.8	120–142	55–55.7
Energy density	MJ/L	18.4–21.2	33.3–35.7	8.5–10.1	23
H/C ratio		3	2.5	–	4
Flash point	°C	13	>130	N/A	−188
Cetane number		<12	46–52	50–53	75–80
Yield		0.2–0.47 g/g	58,700–136,900 L/ha	92–485 mL/gVS	0.09–0.44 L/gVS

Table 5
Comparison of limitations in different energy production using algae.

Limitations	Bioethanol	Biodiesel	Biohydrogen	Biomethane
Availability of source	Natural/cultivation	Cultivation	Natural/cultivation	Natural/cultivation
Algae suitable type	Macroalgae/microalgae	Microalgae	Micro/macroalgae	Micro/macroalgae
Raceway pond/Photobioreactor	No	Yes	No	No
Fermentation process	Yes	No	Yes	Yes
Microorganisms involvement	Yes	No	Yes	Yes
Carbon source	Yes	No	Yes	Yes
Lipid source	No	Yes	No	Yes
Light source	No	Yes	Yes	No
More man power	Yes	Yes	Yes	Less
Time period for harvesting algae	45 days–90 days	Minimum 30 days	Minimum 30 days	30–45 days
Photolysis	No	No	Yes	No
Hydrolysis/extraction process	Yes	Yes	Yes	May or may not require
Immobilization process	Yes	No	Yes	Yes
Bioreactors	Yes	No	Yes	Yes
Aeration	Yes	Yes	Yes	No/partial
Salt removal	Yes	Yes	No	Yes
Pilot scale	Yes	Yes	Still infant stage	Still under development
Continuous process	Yes	Yes	No	Yes

Acetogenesis and hydrolysis were inhibited by the presence of polyphenols.

4.5. Biochar

Recent advancement in technological innovation has broadened the application of biochar in diverse sectors especially in bioenergy production, wastewater treatment, agriculture, carbon sequestration, and biorefinery etc. Biochar is solid carbonaceous products obtained from the thermochemical processing of biomass carbonaceous organic biomass materials in an oxygen-limited environment [111]. Various terrestrial and aquatic biomasses were used for the production of biochar. In this regard, the biochemical composition of algae makes them ideal feedstock for biochar production through thermochemical techniques. Biochar yield and quality from micro- and macroalgae differs between the strains. Biochar is produced by pyrolysis, hydrothermal liquefaction, and hydrothermal carbonization. Of the slow, intermediate, fast and flash pyrolysis methods, slow pyrolysis operated at moderate temperature, lower heating rate and longer reaction time yields mainly biochar as product, whereas, fast pyrolysis operated at higher temperature, faster heating rate, shorter reaction time yields bio-oil as the key product [112]. Further, biochemical composition of microalgae, reaction temperature, pressure, catalyst type changes the biochar yield and quality. The produced biochar can be modified or functionalized using various activation strategies to make them an efficient catalyst for biofuel production such as biodiesel and biohydrogen. Identifying optimal reaction temperature is also imperative for enhancing quality and quantity of biochar. Therefore, effect of temperature on solid char yield from algal biomass through thermochemical processes needs intense research. The biochar is being used in combustion process for various energy applications. Co-combustion of biochar with coal-fired power plants or direct combustion of biochar generates heat, which replaces coal without any modification [113,114]. Further, in combined heat and power plants utilizes biochar for generation of clean heat and power [115].

5. Other valuable products from algae and their applications

The marine environment includes variety of organisms (algae, bacteria, fungi, etc) which possess significant biological properties. These organisms represent underutilized natural sources to isolate bioactive compounds which can be effectively used in food and pharmaceutical industries [116]. Algae have been recognized as the richest sources of bioactive compounds with significant industrial applications [117] Algae are diverse group of prokaryotic or eukaryotic photosynthetic organisms [118] found in fresh or marine water, which accounts for about 40% of global photosynthesis [119]. In particular, the microalgal biomass is processed via various conversion techniques to obtain different by-products [120]. Microalgae are capable of synthesizing a broad range of bioactive metabolites which have tremendous commercial value [118].

5.1. Fatty acids and their positive effects on human health

The selection of specific strains/species, appropriate cultivation method and suitable extraction solvents are crucial to determining the lipid content of algae species [16]. Micro and macroalgae are a rich source of fatty acids and especially microalgae have gained considerable attention due to their potential applications in biofuel and food industries [121]. Microalgae are capable of producing various classes of lipids such as glycerolipids, glycolipids, and free fatty acids [122]. The lipid content of microalgae differs according to the species, and it usually ranges between 1 and 70% of the total biomass in dry weight [121]. Nitrogen limitation is a vital factor which increases the lipids production of these species. Lipid production of microalgae is 20 times higher that of oilseed plants. The lipid content of microalgal species can be modified based on their physiology, growth conditions and under the influence of external environmental conditions (nutrients, salinity, and temperature) [16].

It is predicted that the consumption of different types of fatty acids impacts human health [123]. Moreover, fatty acids are being studied for chemotaxonomic perspectives in cyanobacteria, higher plants, and microalgae. They are being studied as stress-responsive biomarkers in microalgae [121]. Among the fatty acids, Omega-3 fatty acids such as Eicosapentaenoic acid (EPA), Docosahexaenoic acid (DHA) offer key health benefits (act as dietary supplements). Autotrophic and mixotrophic algae mitigate atmospheric CO_2 as carbon source during photosynthesis for the production of Omega-3. Among the algal strains, marine microalgal species are the primary producers of DHA and EPA. Heterotrophic microalgal strains were also used for omega-3 fatty acids extraction, in particular, DHA. But, autotrophic microalgal strains do not need an organic carbon source but heterotrophic algae require additional carbon source or exogenous carbon substrate for Omega-3 fatty acids. However, research interest mainly focused on autotrophic algae for large scale industrial production of PUFAs [124]. Macroalgae can also be a potential source of PUFAs, and are being used as a food or food products for human diet. However, the yield of PUFAs is less compared to microalgae species. Various studies have reported the contents of PUFAs from different macroalgal species. 17 macroalgal species from three different phyla (Chlorophyta, Phaeophyta, and Rhodophyta) were screened for their fatty acids contents. The findings revealed that linoleic, arachidonic and eicosapentaenoic acids were the

major PUFAs observed in all the tested species with Phaeophyta, and Rhodophyta being the dominant species. The total concentration of EPA was found to be in the range of 15–27% of the total fatty acids except in *Asparagopsis armata*. Grave et al. [125], have reported wide range of PUFA contents (18–63%) in the red algae from Arctic and Antarctic waters. Similarly, the concentration of PUFAs was found to be (8–55%) in rhodophytes from the Bohai Sea [126]. Accumulated evidence reveals that some red algae species are significant EPA producers, which can be a potential source of this important PUFA with high nutritional value [127]. The fatty acid composition of seven sea weed species from the North Sea (*Ascophyllum nodosum*, *Chondrus crispus*, *Fucus serratus*, *Laminaria hyperborean*, *Palmaria palmate*, *Ulva lactuca*, and *Undaria pinnatifida*,) and two from tropical seas (*Caulerpa taxifolia*, *Sargassum natans*) were determined. The findings revealed that EPA was the most predominant fatty acid in *Palmaria palmate* yielding 8.3 mg g^{-1} of dry matter, constituting approximately 59% of the total fatty acids determined [128].

Polyunsaturated fatty acids (PUFA) are the major value added products obtained from microalgae. These products have high nutritional value and exert health beneficial properties. Microalgae are the predominant source of PUFAs. DHA and EPA are the most abundant PUFAs isolated from microalgal species. These two PUFAs are synthesized under different culture conditions including autotrophic, heterotrophic and mixotrophic by microalgal species. High productivity of DHA and EPA can be obtained by growing the microalgal species under balanced carbon and nitrogen sources, optimal pH and controlled temperature conditions. Breeding of strains and genetic engineering approach can enhance the contents of DHA and EPA of certain microalgal species. They are also used as by-products in the food and beverage industries. DHA is a long chain PUFA which plays a crucial role in maintaining the human brain, eye, and heart. They are also used as by-products in the food and beverage industries. EPA acts as a precursor for the synthesis of prostaglandin-3, leukotriene-5, and thromboxane-3 group of compounds. Regular consumption of EPA has positive effects against cardiovascular diseases [118]. The roles of DHA and EPA in the development of CNS in infants, reducing blood cholesterol levels, and their prevention mechanism against coronary heart diseases have been observed. It has been recommended that intake of 0.2–0.3 g/day of DHA and EPA is useful for normal human being whereas 1.0–4.0 g/day is suggested for patients with coronary heart diseases [129]. *Bacillariophceae*, *Chlorophyceae*, *Chrysophyseae*, *Cryptophyceae*, *Eustigamatophyceae*, and *Prasinophyceae* accumulates EPA in higher concentrations whereas DHA is commonly found in dinoflagellate (*Crypthecodinium cohnii*), along with *Schizochytrium* and its related species. *Nannochloropsis* is a well-known species exploited for the commercial production of DHA and EPA [118].

Both DHA and EPA play a crucial role as anti-inflammatory agents [130]. The main function of DHA/EPA is to regulate the functioning of the thylakoid membrane and membrane fluidity [131]. DHA and EPA are significant dietary nutrients and have positive role to maintain normal metabolism in the body. They play a pivotal role in reducing the occurrence of cardiovascular diseases such as arrhythmia, high blood pressure, and stroke. Further they improve the conditions related to asthma, dementia, depression, rheumatoid arthritis, and renal disorders. They do involve in the development of the fetal brain and normal growth of infants/children [132]. These two compounds exhibit various pharmacological properties. The antibacterial activity of the diatom (*Phaeodactylum tricornutum*) was tested. EPA was isolated from this marine species which showed efficient growth inhibiting mechanism against human pathogenic microorganisms such as *Bacillus cereus, Staphylococcus aureus* and *Listonella anguillarum* [133]. Daily consumption of PUFAs has shown positive effects on human health and some of the PUFAs are a good source of a vegetarian diet [118]. Extensive research is required to isolate PUFAs from a variety of marine algal species along with their significant biological properties to establish a continuous supply of these compounds for the betterment of human health. Various industrial applications of PUFAs from algae are represented in Table 6.

ARA is an important precursor of prostaglandins and important part of the phospholipid membrane present in the brain. According to WHO, it is recommended that the intake of ARA in neonates is essential for their proper growth and development. They play a major role in inducing inflammatory responses, blood-clotting, cell signaling, and acts as an effective immune-suppressive agent. ARA and their metabolites are useful in proper functioning of skeletal muscle and nervous system. They also increase resistance against allergens by triggering the immune response. Some of the ARA derivatives which are oxygen independent are known to be involved in the mechanism of emotions, pain and stress responses. Further, the deficiency of ARA may cause anemia, hair loss, degeneration of the fatty liver and reduced fertility in adults [134]. *Spirulina* (blue-green algae) contains γ-linolenic acid which is used as a food supplement for human and animal consumption. γ-linolenic acid helps against heart diseases, depression and acts as an inflammatory agent in arthritis [135]. Among all the algae based valuable products, the fatty acids could be cost-effective product and also be energy efficient if thermal processes are bypassed. In 2015, the omega-3 fatty acid was having an estimated value of 9.94 billion USD. The market value of PUFA depends on the production of DHA, EPA and ALA. The production of PUFA from phototrophic algae is economically viable. The expected market value of microalgae derived DHA and EPA is expected to be approximately $300 million and $1.5 billion, respectively [136]. It has been clearly demonstrated that the development of eco-friendly and sustainable technologies will provide a more economical way to produce fatty acids.

5.2. Vitamins

Algae are a good source of vitamins. Microalgae and macroalgae synthesize vitamins and minerals due to their autotrophic nature. Microalgae contain large amounts of essential vitamins which play vital role as potential anti-oxidants [137]. The auxotrophy of vitamins is common in microalgae [138]. Vitamins such as ascorbic acid (Vit C), tocopherol (Vit E), Vit B1, B2, B3, B6, B9, B12 are found in microalgae

Table 6
Fatty acids from microalgae and macroalgae and their commercial applications.

Microorganism producer	Fatty acids	Potential applications	References
Chlorella minutissima *Schizochytrium* sp.	EPA DHA	Nutraceuticals and Food supplements.	[207]
Parietochlorsis incisa *Spirulina* sp.	Arachidonic acid Ɣ-linolenic acid	Food additives Nutraceuticals, and Baby foods.	[208]
Crypthecodinium sp. *Odontella* sp. *Ulkenia* sp.	DHA, EPA DHA	Anti-inflammatory Helps in brain development, treatment of heart and mental disorders.	[209]
Arthrospira sp. *Porphyridium* sp. *Nannochloropsis* sp. *Phaeodactylum* sp. *Schizochtrium* sp.	Ɣ-linolenic acid Arachidonic acid EPA EPA DHA	Aquaculture, Baby foods, and nutritional supplements.	[184]
Isochrysis galbana	Fatty acids	Animal Nutrition, Cosmetics	[130,185]
Phaeodactylum tricornutum	Fatty acids, EPA	Baby food, Nutritional supplements	[130]
Nitzschia sp.	Eicosapentaenoic acid	Aquaculture feed	[184]
Odontella aurita	EPA	Anti-inflammatory, Cosmetics	[185]
Ulva sp.	Linoleic	Animal nutrition	[202]

[10]. Vit B2 (Riboflavin) found in microalgae is an important source of mariculture animals. Vit E displays remarkable antioxidant properties and prevents the oxidation of fatty acids in algal species [137]. Accumulated evidence suggests that three vitamins are essential; Vit B1 (Thiamine), Vit B7 (Biotin), and Vit B12 (Cyanocobalamin) for maintaining the proper growth of the algal cells. Around 306 algal species have been screened for their vitamin contents which revealed that over 50% of the species require Vit B12, 22% of them need Vit B1 and 5% of them need Vit B7 for their growth and nutritional requirements [139]. It has been observed that algal biomass contain the highest amounts of vitamin B1, B2, B6, B12, and vitamin C than Baker's yeast. Most of the microalgal species are reported to accumulate high amounts of essential vitamins than cereals and soybeans [137]. *Spirulina* is an important class of blue-green algae commonly referred to Cyanobacteria. It is highly nutritious and has positive effects on human health. A study has revealed that *Spirulina* contains high amounts of β-carotene (about 10 folds) than any other food including carrots [140]. Further, their vitamin B12 contents are also reported to be higher than plant or animal food source. In comparison to green algae, spinach and liver, this genus accumulate considerable amounts of Vit E, Vit B1, Vit B7, Vit B12 and inositol [141]. Cyanocobalamin has been reported to accumulate in Vit B12 independent microalgae containing both B12 dependent and independent methionine synthases [142].

5.2.1. Extraction of vitamins from algae and their application

Micro- and macroalgae contain fat and water-soluble vitamins. *Hematococcus (*Chlorophyta), *Hymenomonas (*Haptophyta), *Nitzschia* (Heterokontophyta) and *Peridinium (*Dinophyta) showed the presence of cobalamine in significant amounts [139]. *Euglena gracilis* produce antioxidant vitamins such as β-carotene, vitamin C and E whereas *Isochrysis galbana* is the richest source of vitamin A & E, along with thiamine, riboflavin, pyridoxine, nicotinic acid, biotin, pantothenic acid, folic acid and cobalamine [122]. Vitamin levels in these organisms are affected by growth conditions to a great extent [138]. *Chlorella stigmatophora*, *Dunaliella tertiolecta,* and *Tetraselmis suecica* were also reported to contain to have substantial amounts of fat-soluble vitamins (A and E) and B-group vitamins including B1, B2, B6 and B12 [143]. Accumulated evidence has revealed the presence of vitamins among algal species. Four marine photosynthetic microalgae species namely *Tetraselmis succica*, *Isochrysis galbana*, *Dunaliella tertiolecta*, and *Chlorella stigmatophora* were assessed for their vitamin contents [144]. The results revealed variation in vitamin contents among these species. The highest concentration of ascorbic acid, nicotinic acid, pantothenic acid, pyridoxine, and nicotinic acid was found in *Tetraselmis succica*. *D. tertiolecta* showed highest concentrations of β-carotene, cobalamine, folic acid, riboflavin whereas biotin was found to be the major vitamin in *Chlorella stigmatophora.* The vitamin A contents were found to be higher among all the microalgal species ranging from (82300–493750 IU/kg dry weight) followed by tocopherol and ascorbic acid. Characterization and quantification of vitamin B12 from the dried powders of *Chlorella* were investigated to identify their role as health supplements [145]. Vitamin B12 contents were assessed in *Chlorella* sp. Vitamin B12 contents were found to be in the range of 0.1–415 μg/100 g per dry weight with *C. pyrenoidosa* reporting higher vitamin content than *C. vulgaris*. Vitamin E (tocopherol) contents of 17 microalgal species belonging to Chlorophyceae, Phaeophyceae, and Rhodophyceae were examined [145]. The tocopherol contents in mg/kg of dry weight were determined by dipyridil-$FeCl_3$ technique. The content of tocopherol was in the range of 0.35–24.50 mg/kg of dry weight. *Sargassum tenerrimum* (Phaeophyceae) yielded the lowest amount whereas *Dictyota sp.* was highest among all the species. Another study was carried out to assess the levels of tocopherol under certain conditions in *Euglena gracilis* [146]. The tocopherol was extracted using organic solvents including methanol, petroleum ether, and the obtained filtrate was analyzed using HPLC for qualitative and quantitative analysis. The results showed a time-dependent increase in the contents of α-tocopherol. At 72 h, the α-tocopherol contents were found to be 0.38 ± 0.09 mg (g DW)$^{-1}$, 0.65 ± 0.13 mg (g DW)$^{-1}$ and 1.8 ± 0.1 mg (g DW)$^{-1}$ in GM, Ethanol and GM + Ethanol media respectively. After 5 days, the concentrations were increased to 0.72 ± 0.11 mg (g DW)$^{-1}$, 1.3 ± 0.17 mg (g DW)$^{-1}$, 3.7 ± 0.2 mg (g DW)$^{-1}$ in GM, Ethanol and GM + Ethanol media respectively showing 2.8- and 4.7-folds increase in GM + EtOH than that obtained with the EtOH and GM media, respectively. Similarly, the contents of vitamin E were increased to 2.4 ± 0.1 mg (g DW)$^{-1}$ and 2.3 ± 0.1 mg (g DW)$^{-1}$ in G + Gluc and M + Gluc + NH_4 media respectively at 120 h.

Two marine microalgae species namely *Dunaliella tertiolecta* and *Tetraselmis suecica* were studied for their increase in α-tocopherol content under the influence of light conditions. The microalgal cultures were placed in incubators at a photon flux density (PFD) of 50–70 μmol m^{-2} s^{-1} under a 16-h light: 8-h dark cycle. Different mediums were used for cultivation of these microalgae species. *T. suecia* was cultivated only in batch-wise whereas *D. Tertiolecta* was cultivated in batch and repeated batch-wise. All the batch cultivation was done in a bubble column reactor, and the reactors were illuminated with two 500 W tungsten halogen lamps with an average PFD of 230 μmol m^{-2} s^{-1} on the surface of reactors. The cultures were maintained for 6 days under the above-mentioned conditions and the samples of the last 3 days were used for the analysis. α-tocopherol was extracted using petroleum ether and diisopropyl ether. Then the residues were dissolved in methanol and injected into HPLC for quantitative estimation. It was observed that the contents of α-tocopherol were increased per cell with an increase in cell density during batch growth. Light influenced the increase in contents of α-tocopherol in both the species. Further, it was seen that the addition of nutrients (nitrate and phosphate) significantly increased the α-tocopherol content in the linear phase (0.39 mg g DW^{-1}) than in the stationary phase (0.19 mg g DW^{-1}) [147].

A study was carried out to evaluate the Ascorbic acid (Vitamin C) contents in eleven microalgal species namely *Chaetoceros calcitrans, Chaetoceros gracilis, Skeletonema costatum, Thalassiosira pseudonana, Isochrysis* sp., *Pavlova lutheri, Tetraselmis suecica, Dunaliella tertiolecta, Nannochloris atomus, Nannochloropsis oculata, and Chroomonas salina*. These microalgal species were cultured in medium f_2, medium f_E containing EDTA or medium G_2. All the cultures were maintained at 20 °C within the pH range of 7.4–7.8. Duplicate samples were collected from each microalgae species and analyzed during the logarithm and stationary phases of growth. The extraction was carried out using metaphosphoric acid, acetic acid under dark conditions at 4 °C. It was observed that the levels of ascorbic acid were significantly increased during the stationary growth phase for *Skeletonema costatum* and *Dunaliella tertiolecta*. The quantitative analysis revealed the ascorbic acid values in the range of 9.3 fg cell^{-1} (*Nannochloropsis oculata) to* 770 fg cell^{-1} (*Skeletonema costatum*) in the stationary phase. The average percent values for vitamin C was calculated per dry weight. It was found to be 0.11% (*T. pseudonana,* stationary phase) to 1.62% *(C. gracilis,* logarithmic phase). These species were found to be a good source of vitamin C used in mariculture, though they have varied contents [148]. A similar study was done to evaluate the vitamin contents in four Australian microalgae species including *Nannochloropsis*-like sp., *Pavlova pinguis*, *Stichococcus* sp. and *Tetraselmis* sp. The microalgal cultures were grown in medium f_2. The cultures were illuminated with white fluorescence light (100 μmol photon $m^{-2}s^{-1}$) under light and dark conditions. All the cultures were collected from the logarithmic phase for *in-vitro* studies. The extraction was done using ammonium formate, and the obtained residues were freeze-dried and stored at −70 °C. The results displayed a three to four-fold increase in the contents of vitamins between the species. All the contents of vitamins were expressed per dry weight from 1.3 to 3.0 mg g^{-1} (ascorbic acid), 0.37–1.05 mg g^{-1} (β-carotene), 0.07–0.29 mg g^{-1} (tocopherol), 29–109 μg g^{-1} (Vit B1), 25–50 μg g^{-1} (Vit B2) 17–24 μg g^{-1} (total folates), 3.6–17 μg g^{-1} (Vit B6), 1.1–1.9 μg g^{-1} (Vit B7) and 1.70–1.95 μg g^{-1} of (Vit B12). It was observed that the vitamin contents in *Nannochloropsis* sp. showed significant variation among all the other species. Similarly, the individual

thiamine contents were assessed in six non-Australian microalgal species namely *Chaetoceros muelleri, Isochrysis* sp, *Nannochloris atomus, Nannochloropsis oculata, Pavlova lutheri,* and *Thalassiosira pseudonana.* The culture and extraction conditions were the same. The value of Vitamin B1 was almost similar in the range of (40–82 μg g^{-1}) in comparison to Australian strains of microalgae species, and the values were reported to increase during the stationary phase of growth. Thus, it was concluded that the contents of vitamins present in microalgae species are vital as a primary source in the aquatic food chain, and more focused studies are required to understand the bioavailability of vitamins in them [149]. To estimate the folic acid level in algae, six macroalgal species namely *Himanthalia elongata, Laminaria ochroleuca, Palmaria* spp., *Porphyra* spp., *Saccorhiza polychides,* and *Undaria pinnatifida* were assessed for their folic acid (Vit B9) contents [148]. HPLC analysis was done using fluorescence and UV detectors for the purified folates. The findings reveal that folic acid contents were in the range of 61.40 ± 9.28 to 161.59 ± 6.10 μg per 100 g dry weight.

5.3. Nanoparticles

The products or materials having dimensions of 1–100 nm are known as nanoparticles (NPs) or nanomaterials which possess high surface area to mass ratio [150]. The emerging trend of nanotechnology is widespread and gaining popularity among the scientific community owing to their applications across different fields [151]. Marine resources are found to be useful and provide a safer environment for the synthesis of NPs [152]. Algal species are widely cultured and recognized as important organisms in green nanotechnology. They are effectively utilized in the synthesis of metallic nanoparticles, which has been exploited for their role in agriculture, biotechnology clinical diagnostics and in the field of cosmetics, paints, electronics etc. These metallic NPs have economic and eco-friendly benefits [150]. Phyconanotechnology has emerged as an important research field in NP synthesis as algae are utilized as a "bio-factory" for the synthesis of the metallic nanoparticle. Ag-NPs were synthesized from *Microcoleus* sp. and evaluated for their antimicrobial activity [153]. The results showed a significant inhibitory activity of the Ag-NPs against *E. coli*, *P. vulgaris*, *S. typhi*, *V. cholera*, *B. subtilis*, *S. aureus*, *Streptococcus* sp. and *Corynebacterium* sp. Further (Ag-NPs) synthesized from *Turbinaria conoides, Colpomenia sinuosa, Sargassum illcifolium, Gelidiella acerosa* have shown anti-biofilm activity, anti-diabetic, *in-vitro* cytotoxic activity and anti-fungal activity [152]. A recent study has demonstrated the catalytic activity of the (Au-NPs) synthesized from *Turbinaria conoides* and *Sargassum tenerrimum.* The synthesized nanoparticle reduced the organic dye molecules (Rhodamine B and Sulforhodamine 101 hydrate) [154]. Similarly, the green synthesis of iron nanoparticles was done from the soil microalgae (*Chlorococcum* sp. MMII) [155]. The iron nanoparticle was tested for their reducing activity against chromium, a strong environmental pollutant. The iron nanoparticle was able to reduce Cr (VI) to Cr (III) by 92% which was found to be higher than obtained from bulk iron (25%). Various other metals have been used to synthesize nanoparticle from algal sources. Cadmium sulphide nanoparticles (CdSNPs) were prepared from the extracts of cyanobacteria (*P. tenue* NTDM05) [150,156]. The prepared nanoparticles were spherical in shape of size around 5 nm in size. These were used as a capping agent. Similarly, aqueous extracts obtained from *S. muticum* (brown algae) were utilized to prepare cubic-shaped magnetic iron oxide NPs (Fe_3O_4NPs). The synthesized nanoparticles showed reducing capability to convert Fe^{3+} ion in $FeCl_3$ [152].

5.4. Bioactive compounds from algae: anti-proliferative/anti-tumor activity

Algae are an interesting source for synthesizing bioactive compounds. Bioactive compounds or secondary metabolites play a vital role in defense mechanisms [157] and protect algal cells against stress conditions (UV and pathogen attack) [158]. Phytochemicals are such compounds that can be targeted as effective chemopreventive and therapeutic agents due to their easy bioavailability, non-toxicity and minimal side effects [159]. These phytochemicals include phenolics, flavonoids, tannins, alkaloids, terpenoids etc. They display significant pharmacological activities thus providing health benefits [160]. Many of these bioactive regulate the biological process such as apoptosis, cell proliferation and metastasis in cancer cells [158]. Cancer is the abnormal growth of cells and tissues, represented by unique properties of invasion and metastasis and is mostly caused due to environmental and genetic factors [161]. Recent studies on marine organisms especially microalgae and cyanobacteria have revealed their potential anti-tumor activity both *in-vitro* and *in-vivo*. Fourteen marine cyanobacteria strains belonging to the genera *Synechocystis* and *Synechococcus* (LEANCYA-5, 11, 13, 16, 17, 18, 19, 20 and 21) were used to determine their cytotoxic activity [162]. The extracts prepared from these species were tested against HL - 60 cells. The results revealed significant inhibition of apoptotic cells in the methanolic and DCM extracts of strains LEANCYA- 5, 11, 13, 19 and 20, whereas the aqueous extract of the strain LEANCYA-19 showed apoptotic effects. Eight cyanobacterial species (*Anabaena flous-aquae*, *Anabaena oryzae*, *Nostoc humifusum*, *Nostoc muscorum*, *Oscillatoria sp*., *Spirulina platensis*, *Phormedium fragile*, *Wollea saccata* and one green alga (*Chlorella vulgaris*) were tested for their anti-proliferative activity against human hepatocellular cancer cell line (HepG2) and Ehrlich Ascites carcinoma cell (EACC) [163]. The cell growth inhibition range was (15.68–87.25%) for EACC and (9.5–89.4%) for HepG2 cell lines. The anti-proliferative activity was found to be maximum for *Nostoc muscorum* extracts against both the cell lines (87.25% in EACC and 89.40% in HepG2) followed by *Oscillatoria sp.* (67.40% in EACC and 77.80% in HepG2).

Anticancer activities of the microalgae *Chlorella ovalis* and *Nannchloropsis oculata*, *Phaeoductylum tricornutum* and *Amphidinium carterae* were investigated [164]. Homogenized powder of algal samples was sonicated with 80% methanol for 90 min at 25 °C and the methanol was evaporated using a rotary evaporator, and the remaining residue was concentrated and finally subjected to solvent-solvent partition chromatography. Four different solvents were used including n-hexane, chloroform, ethyl acetate and water to obtain individual solvent fractions. The anti-proliferative activity was tested against human promyelocytic leukemia cell line (HL-60), human lung cancer cell line (A-549) and mouse melanoma cell line (B16F10). Ethyl acetate fraction of *C. ovalis* and chloroform fraction of *A. carterne* inhibited the growth of HL-60 cells significantly at dose levels of 25 μg/mL and 50 μg/mL. Polysaccharides are the main components in diatoms. Chrysolaminaran, a storage polysaccharide was isolated from *Synedra acus* and evaluated for its anti-tumor activity against human colon cancer cells (HCT-116 and DLD-1) at 25, 50 and 100 μg/mL dose for 72 h [165]. The results revealed significant inhibition of the cancer cell lines at IC_{50} values of 54.5 μg/mL for HCT-116 and 47.7 μg/mL for DLD-1. In a similar kind of study, the anti-proliferative activity of extracellular polysaccharides *isolated from Graesiela* species was tested against human hepatocellular carcinoma (HepG2) cells and human colon cancer (Caco-2) [166]. The aqueous extra polysaccharides (AEPS) within a concentration range of (0.01–2.5 mg/mL) inhibited the growth of these cancerous cells in a concentration-dependent manner. AEPS inhibited 91% of CaCo-2 cells growth inhibition at an IC_{50} value of 2.5 mg/mL whereas 70.4% inhibition was observed for Hep G2 cells.

Another study was undertaken to assess the anti-cancer activity of 21 diatoms, 4 flagellate and 7 dinoflagellates, against human melanoma cancer cell line (A2058), [167]. The antiproliferative assay revealed a significant inhibition of cell growth at low concentrations of 100 μg/mL for *S. marinoi*, *A. minutum*, *A. tamutum*, and *A. andersoni.* Ethanol and dichloromethane extracts of *Dunaliella tertiolecta* were tested against breast cancer cells (MCF-7, MDA-MB-231), lung adenocarcinoma cells (A549) and prostate cancer cells (LNCaP) [168]. The growth of breast cancer cells (MCF-7) was inhibited at 60 μg mL^{-1}. DCM extracts

inhibited the growth of LNCaP cells at a concentration of 60.9 μg mL^{-1}. However, both the extracts didn't reveal any inhibition against MDA-MB-231 cells. So, the DCM extracts showing inhibitory activity against both the cell lines were selected to purify anti-proliferative molecules by fractionation. The anti-cancer effect of *Chlorella sorokiniana* (CS) in two human non-small cell lung cancer (NSCLC) cell lines (A-549 and CL1-5 human lung adenocarcinoma cells) was evaluated. Further, the effect of CS on tumor growth in a subcutaneous xenograft tumor model was investigated. The powdered CS sample was extracted with distilled water, and the solution was filtered. The filtered solution was evaporated to dryness at 60 °C under a rotary evaporator, and the solid residue was obtained. The cells (A-549 and CL1-5) were treated with the CS extracts with various concentrations ranging from 15.625 to 1000 ng/mL, and the cell viability was determined. The results showed a reduction in cell viability in a concentration-dependent manner. Further, the CS extract induced apoptosis in human NSCLC. The exposure of A-549 and CL1-5 cells to CS for 24 h resulted in decreased levels of Bcl-2 protein and increased expression of Bax protein. The oral intake of CS extract was also found to inhibit the tumor growth of subcutaneous xenograft [169]. Anti-proliferative activity of brown seaweed (*Sargassum filipendula*) was evaluated against HeLa (human cervical cancer) cells. Fucans are sulfated polysaccharides mostly found in brown seaweeds. Fucans isolated from algal sources exhibit various biological properties including anti-coagulant, anti-inflammatory, anti-viral, anti-adhesive, etc. In the present study, hetrofucan was isolated from *Sargassum filipendula*, and the cells were treated with heterofucan at concentrations of 0.1, 0.5, 1.0, 1.5 and 2.0 mg/mL for 24 h, 48h and 72 h at room temperature. MTT assay was used, and the results revealed time and dose-dependent inhibition of cell growth. The anti-proliferative activity of heterofucan was found in the range of 32.7%–72.5% at concentrations (0.1–2.0 mg/mL). Further apoptosis-inducing mechanism of this compound was tested in HeLa cells. It was observed that heterofucan induced apoptosis by releasing the apoptosis inducing factor (AIF) from mitochondria to the cytosol. In addition, it increased the expression levels of Bcl-2 protein and increased the levels of Bax protein [170]. Similar anti-cancer effects of fucoidans were reported against breast cancer [171] and prostate cancer cell lines [172]. Another study reported the anti-cancer effects of water-soluble sulfated polysaccharides isolated from *Monostroma nitidum* against human gastric carcinoma cells (AGS) and human cervical cancer cells (HeLa) [173].

The high-value pigments like carotenoids, astaxanthin, carotene, lutein, and zeaxanthin are extracted from *Chlorella* species. Anti-proliferative activity of carotenoids isolated from two green algae species *C. ellipsoidea* and *C. vulgaris* were evaluated against human colon cancer (HCT116) cell line [174]. MTT assay was used to measure the cytotoxicity of microalgal extracts with 24 h of exposure. IC_{50} values for both the *C. ellipsoidea* and *C. vulgaris* were found to be 40.73 ± 3.71 g/mL and 40.31 ± 4.43 g/mL respectively, which was much higher than the value (21.02 ± 0.85 g/mL), obtained for pure lutein. In the recent past, pigments extracted from microalgae have shown prominent anti-proliferative activity. Lycopene, isolated from *Chlorella* sp. was evaluated for its anti-proliferative and anti-cancer activity against prostate cancer cells (PC-3 and DU-145) [175]. Lycopene inhibits the growth of prostate cancer cells (PC-3 and DU-145) at dose levels of (20 and 50 μM) respectively. Further, it induced apoptosis and reduced colony formation. The results showed the better activity of lycopene isolated from *Chlorella* than the lycopene isolated from tomatoes. The same *Chlorella* genus (*Chlorella sorokiniana)* were tested against hepatocellular carcinoma (Hep G2) cell lines which revealed the invasion inhibition effect, apoptosis-inducing mechanism and reduced cell viability of the tested sample [176]. Carotenoids isolated from other species such as *Odontella aurita* [177], *Haematococcus pluvialis* [178] were also reported to inhibit cancer cell growth.

Fucoidans are sulfated polysaccharides abundant in brown algae. A study was carried out to investigate the anti-tumor activity of fucoidan from *Fucuc vesiculosus* (brown algae) against human colon cancer cells (HCT-15) [179]. HCT-15 cells were treated with fucoidan at concentrations of 1, 10, 30, 50 and 100 μg/mL for 3 days. The results revealed anti-proliferative activity of fucoidans in a dose-dependent manner by 1.8%, 24.3%, 49.8%, 54.0%, and 62.0% respectively. Moreover, at the same concentrations, fucoidans were shown to induce apoptosis, decreased the levels of Bcl-2 protein and increased the levels of Bax along with increased expression levels of caspase-3 and caspase-9 in a time-dependent manner. In a similar kind of study, fucoidan from cultured brown seaweeds (*Undaria pinnatifida*) was isolated and tested for its anti-tumor activity against prostate cancer (PC-3), cervical cancer (HeLa), lung cancer (A549) and hepatocellular carcinoma (HepG2) [180]. The anti-tumor activity of isolated fucoidan was compared with that of commercial fucoidan. The isolated algal fucoidan showed slightly lesser activity than the commercial one against PC-3 and A-549 by about 20% and 10% respectively at a concentration of (0–0.8 mg/mL). The anti-tumor activity of fucoidan was found to be more significant against HeLa and A549 cells than PC-3 and HepG2 cells. The above studies reveal significant anti-proliferative activity against human pathogenic cell lines. Some of the examples of micro and macroalgal species exhibiting anti-tumor properties are represented in Table 7. In addition to the above, algae have enormous potential to be used as an effective cosmeceutical agent. The bioactive compounds from microalgae, when combined with other antioxidant compounds protects the skin against sun-damage [181]. Arthrospira extracts were tested for their skin-repairing mechanisms. The study showed that these extracts were capable to prevent early skin ageing and stria formation along with tightening effect. Another study has revealed the skin repairing mechanisms of *C. vulgaris* where the extracts were able to stimulate collagen synthesis in the skin, promoted tissue regeneration and reduced wrinkle formation [181]. Carotenoids and mycosporine like amino acids (MACs) isolated from microalgae species have been reported to exhibit cosmeceutical properties [182]. Astaxanthin, a by-product of β-carotene has been reported in *Haematococcus pluvialis*. It is highly antioxidant in nature and plays a crucial role against various skin conditions [183]. More recently, several plants producing *H. pluvialis* as a source of astaxanthin have been established in the USA and India [184]. *H. pluvialis* can accumulate up to 5% DW of astaxanthin and is considered as the best natural source of carotenoid [185].

6. Economics and environmental impacts of algal biorefinery

6.1. Feasibility assessment

Economics and feasibility play a pivotal role in commercializing algal biorefineries. There are several routes and products that can be produced via such biorefineries, however not all products are feasible for large-scale productions. Understanding the economic feasibility helps in shortlisting the product pathways which might be economically feasible over the horizon. Some technologies need maturity in terms of market and other aspects, while some need a higher technology readiness level (TRL). The associated costs in an algal biorefinery include cultivation and harvesting of algae, processing and purification of algae, logistics and distribution of produced products. Flat panels are cost-effective method to produce algae where the production cost reaches 3.4 EUR/kg for a size of 100 ha [186]. The operational expenses for algae cultivation are three times higher than the up-front investment costs. Based on the investment cost, the reactors from most to least expensive are as follows: 1. Raceway pond, 2. Horizontal tubular reactor, 3. Vertical stacked reactors, and 4. Flat panel reactors. Biomass harvest and separation is a challenging process, which is a major bottleneck in algae cultivation and processing [187]. Cultivation of algae via raceway ponds are cheaper at 1.2 EUR/kg, of which harvesting costs corresponds to a quarter of it. However, in closed and higher biomass concentration, this cost could be reduced up to 17% [188]. When compared with lignocellulose based biorefineries, microalgae

Table 7
Bioactive compounds extracted from different algal species and their significance.

Name	Class	Family	Extraction solvent	Isolated Bioactive Compounds	Targeted Cancer Cell lines	Active conc.	Reference
Neochloris Oleoabundans	Chlorophyceae	Neochloridaceae	Ethanol	Monoesters & Diesters and Carotenoids (violaxanthin, lutein and zeaxanthin)	Colon cancer cells (HT-28 and SW-48)	250 μg/mL and 27 μg/mL	[116]
Odontella aurita	Coscinodiscophyceae	Eupodiscaceae	Ethanol, Dichlorom-ethane and Water	Carotenoid (fucoxanthin)	Bronchopulmonary carcinoma and lung cancer cells (NSCLC-N6 and A 549)	10–25 μg/mL	[177]
Phaeodactylum Tricornutum	Bacillariophyceae	Phaeodactylase	Methanol	Fatty alcohol ester (nonyl 8-acetoxy-6-methyloctanoate)	Human promyelocytic leukemia and lung cancer cells (HL-60 and A549)	50 μg/mL	[164]
Chlorella sp. *M.C.* sp. *Scenedesmus* sp.	Trebouxiophyceae Chlorophyceae	Chlorellaceae Scenedesmaceae	Water	Proteins and pigments	Human lung carcinoma, human breast adenocarcinoma, human melanoma, human prostate cancer cells (A549, MCF-7, MDA-MB-435 and LNCap)	5 mg/mL and 10 mg/mL	[117]
Dunaliella salina	Chlorophyceae	Dunaliellaceae	Water	Whole extract (Biomass)	Breast cancer cells (MCF-7)	25 μg/mL and 50 μg/mL	[210]
Haematoccus Pluvalis	Chlorophyceae	Haematococcaceae	–	Carotenoid (astaxanthin)	Colon cancer cells (HCT-116)	5–25 μg/mL	[178]
Thraustochytriidae sp.	–	–	Water and Ethanol	Exopolysacc-harides	Ovarian cancer cells (BG-1), Breast cancer cells (MCF-7), Colon cancer cells (SW-620)	10^{-11} dilution	[119]
Chlorella sorokiniana	Trebouxiophyceae	Chlorellaceae	80% ethanol	Carotenoids (β-carotene and lutein) and pigments (chlorophyll *a* and *b*)	Human hepatoma cells (HepG2)	500 μg/mL	[176]
Botryidiopsidaceae sp.	–	–	Ethanol	Whole extract	Cervical cancer cells, Colon cancer cells, Breast cancer cells (HeLa, HCT116, Hs678T and A537)	25 and 50 μg/mL	[158]
Chlorella marina	Trebouxiophyceae	Chlorellaceae	–	Carotenoid (Lycopene)	Prostate cancer cells (PC-3 and DU-145)	20 and 50 μM	[175]
Undaria pinnatifida	Phaeophyceae	Alariaceae	–	Polysaccharides (Fucoxanthin)	Prostate cancer (PC-3)	10–200 μg/mL	[172]
Monostroma nitidum	Ulvophyceae	Monostromataceae	85% ethanol and Water	Sulfated polysaccharides	Human gastric carcinoma cells and human cervical cancer cells (AGS and HeLa)	125 μg/mL, 250 μg/mL and 500 μg/mL	[173]
Cladosiphon navae-caledoniae Kylin	–	Chordariaceae	–	Sulfated Polysaccharides (Fucoidan)	Breast cancer cells (MDA-MB-231 and MCF-7)	400 μg/mL	[171]

based biorefineries face high economic hurdles due to cultivation and harvesting costs [189].

Pyramid of product value and cost shows that biofuels are lower priced vector while products such as pigments, cosmetics or food-feed have higher value (Fig. 3). However, higher value products need better purification and refining, which in turn increases the investment and operational expenses [190]. The levelized biorefinery cost to produce biofuel would be 1.8 EUR/kg, while that of feed, and cosmetics ranges about 4.1–4.3 EUR/kg. Around 80–85% of the cost are running expenses, which means energy and consumables directly affect the process [188]. Key parameters that are sensitive to cost include photosynthetic efficiency, air flow, cleaning, temperature, and workers [189].

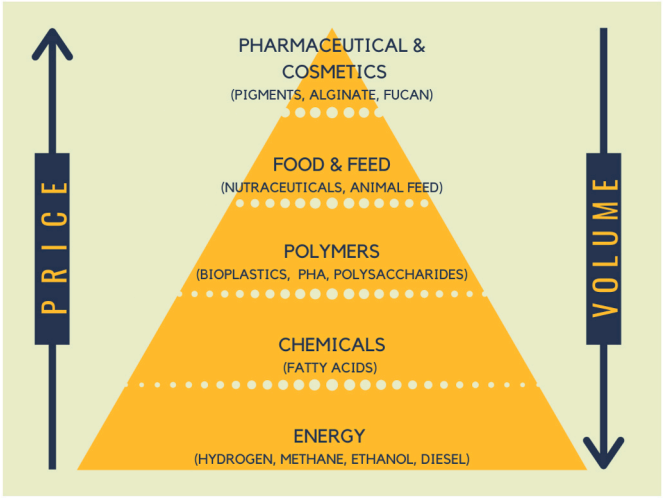

Fig. 3. Product hierarchy with their cost and volume. More volume products are lower priced, while higher value products are produced at lower volumes.

6.2. Environmental impacts

Environmental impacts assess how the various pathways react to stress indicators such as global warming, acidification, and resource depletion. These impact assessments indicate the higher stress contributing sector, which needs to go through an environmentally friendly alternative. Microalgae as a feedstock capture carbon from atmosphere and helps in carbon mitigation. However, the process in which conversion of microalgae to products is also critical as the saved emission needs to be transformed throughout the value chain. Barlow et al. [191] have studied lifecycle of a rotating algal biofilm reactor for biooil

production via hydrothermal liquefaction. The study suggests that bio-crude yield, productivity of biomass and the reactor cycle plays a vital role in determining the global warming potential. In a business as usual scenario 1-MJ of bio-oil emits 80 gCO_2, while an optimized scenario with better productivity and crude yield emits −44 gCO_2. The ratio between energy stored and energy required in a process is a critical parameter in a lifecycle assessment. This is called as Net Energy Ratio (NER). For algae cultivation, the choice of reactor increases or decreases the NER. For example, raceway pond has a NER of 8.3, while flat reactor has 4.5 and tubular reactors of 0.2, respectively [22,192]. This net energy ratio affects the overall energy balance which intern affects the other environmental impact parameters such as global warming, acidification potential and resource potential. Global warning potential is an important environmental parameter that indicates the emissions of a system. Usually, global warming potential is expressed in equivalence units of CO_2. The different greenhouses gases potential is converted to CO_2 equivalence to express in a common term. Algal biorefinery as such is a carbon sequestration process which reduces the emissions overall. However, biomass drying consumes a lot of energy which reduces its negative effect. For instance, algal diesel via pyrolysis has a detrimental effect of GWP of 210 gCO_2/MJ. While hydrothermal liquefaction has a net emission of −10 gCO_2/MJ. In comparison, conventional diesel has a net emission of 15 gCO_2/MJ [193].

7. Challenges and future perspectives

Though microalgae and macroalgae are potential organisms with biotechnological, industrial and environmental application, still the production cost of algal fuel remains higher than the fossil based fuels. In fact waste water and flue gases has been used to reduce the nutrient cost, but other mechanical equipment and technologies are high cost. In short, fundamental steps employed for algal biofuel production and commercialization still remains a major constraint. Likewise usage of chemicals, technology, electricity and manpower becomes a major hurdle in producing cost effective biofuel from microalgae. Microalgae cultivation performed under suitable model of closed and open reactors with optimized pH, temperature and light will help in promoting rapid doubling of microalgae producing high biomass. Alteration in the growth condition, nutrient stress, and physical modification will develop a better strategy to increase the compound of interest in the microalgae. Apart from this, producing value added products like pigments, enzymes, proteins and other polysaccharides is also limited due to the low productivity of these molecules and metabolites in microalgae. Therefore, routes to maximize the valued products from algae need to be ascertained. In recent trends, green synthesis of metallic and non-metallic nanoparticles has been performed using the extract or cells of algae. The yield of nanoparticles synthesized using algae is comparatively low to physical and chemical methods. Therefore, there is always a lack of knowledge in overcoming the problems with production yield, high expenses and commercialization of microalgae based products and resources. Development of new extraction methods, expanding microalgae and aquaculture and usage of microalgae whole cell can be done to reduce the cost of high value compounds. More detailing has to be done for the whole genome data of microalgae to make genetic engineering a success in microalgae growth and production. In concern to molecular approach, transformation and strain selection methods are the two major key for achieving the target product. Nonetheless, screening the concentration of antibiotics used for transformation is time consuming and strain specific. The modern gene editing tools CRISPR-Cas9, TALEN, and ZFN 17 are used to edit the genomes of nuclear, mitochondria, and chloroplast of microalgae. Therefore Omics approaches will be a revolution for developing high end techniques. But till now CRISPR technology holds the key for developing a potential solution to change the future of microalgae for biofuel and value added products in more efficient and commercial way.

8. Conclusion

The outlay of algal biodiesel remains higher than petroleum-based fuels due to numerous concerns like nutrient cost, cultivation system, cost of dewatering, lipid extraction chemicals, and production method. Further to biofuel production, value-added products like pigments, enzymes, proteins, and other polysaccharides from algal strains are also limited attributed to the low yield of the macromolecules and metabolites in microalgae. In recent trends, non-energy-based products from microalgae like omega-3, 6 fatty acids, vitamins and pigments have also been extracted. In this case, this present review has provided insights on the cultivation of microalgae and macroalgae for energy and other industrially important co-products. A holistic understanding of the selection of efficient microalgae strain will also help in discovering their biotechnological potentials. Microalgal cultivation in open pond and photobioreactor and macroalgal cultivation challenges were initially present in this review. Further, this state-of-the-art review provides the research status and bottlenecks in various biofuel such as biodiesel, bioethanol, biohydrogen, biomethane acquired from the algae. Eventually, various industrially important co-products like omega-3, omega-6 fatty acids, vitamins and nanoparticles and other bioactive compounds from algae and their application in various fields have been discussed in-detail.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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