Chapter 4
Energy and Carbon Balance of Microalgae Production: Environmental Impacts and Constraints

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Abstract The continuous development of human civilization needs continuous supply of energy, but resources for energy production are limited as it is non-renewable. So, to sustain the pace of development, there is time to opt a sustainable energy production system, i.e., the biofuel. Several options have been assessed for the production of biofuel, but most of them have many limitations. Among them, microalgae are most suitable ones due to their many advantages. Microalgae have already been cultivated for a long time to produce food, feed, and other substances and can also be used to produce biodiesel, bioethanol, biomethane, and biohydrogen as alternatives for fossil resources. Microalgae grow quickly with concentrated CO_2 or reuse CO_2 from other resources to produce bioenergy sources.

4.1 Introduction

Access to the energy is the key requirement for the well-being of the human civilization, and the sun is the ultimate source of energy for the living world, which has been captured in biomass by the photosynthesis by the green plant. Energy requirement initially and even today is mostly fulfilled by fossil fuels, but it produces large amount of carbon dioxide and other greenhouse gases, responsible for global environmental change, having adverse impact on environment. So, a balance needs to be established between development and its environmental impact. For sustainable development to attain high standard of living, access to sufficient energy is required. With increase in world population, there is increased demand of energy, which is responsible for energy crisis globally not only due to growing population but also due to heavy industrialization. The natural resources like coal, natural gas, diesel, and petrol like basic sources for energy are near to exhaustion. Such extensive use of natural resources also has vast impact on our environment due to libration of large

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amount of harmful gases. The level of greenhouse gas in the environment has reached an alarming point in the post-industrialization era.

Natural causes and intensive human activities are the major causes of raised temperature which is responsible for global warming (Rastegari et al. 2019a). To reduce the emission of greenhouse gas related with the energy production, we have to shift energy production from reduced carbon or carbon–neutral resources, like solar, wind, ocean, geothermal, hydroelectric, and biofuel as sustainable alternative resource, to fulfill the energy requirement (Schiermeier et al. 2008). The renewable energy sources need to be derived from microalgae biomass in option of nonrenewable energy systems for effective use of current infrastructure for petroleum-based energy sources, which is an energy dense liquid form as well as efficient in reducing the emission of greenhouse gases and may act as an environmentally sustainable energy source. So, the production and use of biofuels as an alternative source of energy is gaining importance in the world. The commercial production and use of biofuels are already initiated in many developed countries.

There are several resources like agro-wastes, cereal crops, fruits wastes, wastes of timber wood, household wastes, or macro/microalgae which are the best alternative sources for the production of biofuels like bioethanol and biodiesel. The sustainable energy solutions with reduced global carbon emission are the biofuels. Biomass produced by microalgae has been fermented to generate ethanol, but it has only half energy density compared to fossil fuel. The mass production of biomass for biofuel production requires energy input as various stages as soil tillage, irrigation, increased soil respiration, use of pesticides, fertilizers, herbicides, and transportation of the feedstock require additional input of energy, and two-thirds of the carbon in the biomass has been emitted as CO_2, when fermented for production of ethanol (Hill et al. 2006). Also, the production of biofuel has limitations of available crop land because land is limited for fulfillment of the demands for food, fiber, and other important things necessary for the humankind. So, the alarming concern is selection of alternative source of energy having high potential for enhanced energy as well as low CO_2 emission to reduce environmental pollution and such alternative is algae. Algae are wide groups of marine photosynthetic plant with high ability for oil production and in extenuating CO_2 emissions. It can efficiently grow in oceans, ponds, lakes, rivers as well as in wastewater and has high tolerance against salinities, high light intensities, extreme temperatures, and pH. Any reservoirs can be used for the growth of algae to be used for the production of biofuel, where it either grows independently or in association with other organisms.

Algae are classified on the basis of size into microalgae or macroalgae. As name indicates, microalgae are single cellular microscopic in size, while macroalgae are multicellular large in size and can be visualized by naked eyes. Photosynthetic microalgae having ability for carbon fixation are rich source of carbon and must be a suitable source for production of biofuels and mitigation of atmospheric CO_2. The potential of microalgae enhances interest as a sustainable and renewable feedstock for production of biofuel. Such microalgae at the same time having ability to grow efficiently in wastewater can be used for wastewater treatment. Microalgae are fast growing organisms found in marine or freshwater which have important positions in aquatic ecosystems and establishes the basis of aquatic food chains. The fast growing microalgae have source of large enough biomass for biofuel production and rapidly influence global climate. Microalgae are fast growing organism and highly adaptable to the surrounding environment, due to its unicellular it is useful to capture nutrients as well as concentrate useful chemicals in an economical way.

4.2 Carbon and Nitrogen Metabolism of Algae

Microalgae are microscopic plant having same metabolic activities as photosynthetic plant cell. The metabolic activity of microalgae depends on the surrounding it grows, as it decides the types of nutrient for its growth and development. Nitrogen and carbon are the two most important elements in metabolic pathway of photosynthetic organism, which directly influence the mass of cell, carbon assimilation in biomass, protein, chlorophyll, nucleotides, and other important biomolecules (Jha 2019a, b, c). Like photosynthetic plant, in algae also carbon gets incorporated in the glucose during photosynthesis and converted into glucose-6-phosphate for growth, respiration, and storage in sunlight. No carbon assimilation takes place in absence of light as well as no fermentation of stored glucose takes place in algae in absence of enzyme lactate dehydrogenase.

In algae, predominantly the only pathway that takes place for carbon assimilation is Embden–Meyerhof and Pentose phosphate pathway (PPP), and conversion of available glucose into oligosaccharides and polysaccharides takes place. At the same time, nitrogen is one of the most abundant nutrients in the environment and is important contributor to the dry weight of algae. There is interconnection between C and N metabolism in all photosynthetic organism including algae. Nitrogen in the form of ammonia is the contributor for amino acids required carbon skeleton (Jha, 2019a, b, c). So, incorporation of C and N requires coordination for the synthesis of important metabolites for the survival of the algae. Most important feature of microalgae is their ability to trap carbon in form of CO_2 from the atmosphere and surrounding water source in the form of bicarbonate. Photosynthetic algae have bicarbonate transporters on its plasma membrane and on chloroplast envelope for efficient use of bicarbonate from water, which has been converted into CO_2 inside chloroplast for photosynthetic dark reaction (Enamala et al. 2018).

4.3 Bioenergy and Microalgae

There is continuous increase in the demand of fuel energy with increase in population and rigorous use of fossil fuels. It will be at the merge of finish due to its non-renewable nature and non-sustainability. So, alternative renewable and sustainable option for fossil fuels, that is, biofuels are now drawing attention (Kour et al. 2019a;

Rastegari et al. 2020). Biofuels such as bioethanol and biodiesel are exceptional substitute of fossil fuels, which have been generated from variable resources of biomass, such as agriculture wastes, fruits, food, crops, woods, and algae (Rana et al. 2019). Burning of fossil fuels generate about 29 gigatons CO_2 per year and other greenhouse gases responsible for global warming. The biofuel has about 10–45% of oxygen and very less sulfur content in comparison to fossil fuel. So, advantage of biofuel is its sustainability, renewability, accessibility, non-polluting, and locally available. Microalgae can fix 1.83 kg of CO_2 per kg of biomass and are non-toxic and eco-friendly.

Microalgae species having potential for high lipid content (50–70%) accumulation in biomass can accumulate about 60,000 L oil per hectare biomass, and is capable of producing biofuel of about 121,104 L per hectare biodiesels (Gardner Dale et al. 2017).The bioethanol is an ecologically clean fuel which has several benefits over fossil fuels as (i) burning of bioethanol produces minimum amount of greenhouse gases due to the presence of high oxygen contents in it, (ii) bioethanol can be directly used without any further modification, in present energy infrastructure/automobile industry due to similar feature, (iii) bioethanol can be directly mixed with classical fuel due to similar nature, (iv) bioethanol can reduce the wear and tear of the engines due to having high octane content, which prevents knocking of oil cylinders. Production of bioethanol has been dynamically enhanced worldwide up to 100 billion soon from 1 to 39 billion within a few years (Basso et al. 2011). Carbohydrates like agar, starch, cellulose, and glycogen which can be easily transformed to fermentable sugars for production of bioethanol are present in high amount in microalgae.

4.4 The Growth of Algae for Biomass Production

The growth of algae is influence by several factors like carbon source, nutrient source, light and optimum temperature has major impact. Major nutrients like phosphate, nitrate, and carbohydrate and trace nutrients like zinc, cobalt, molybdenum, and manganese are necessary for desired growth. For cultivation, some additional parameters which also play important role are proper mixing in the photoreactor, optimal pH, uptake of CO_2, and removal of O_2 in equal amount. These parameters need be controlled and coordinated properly to achieve desired algal biomass production. Among all these, the temperature is the most significant and sensitive factor for large-scale production, and optimal growth temperatures for the growth are in range of 20–30 °C (Dragone et al. 2010). Increase in temperature results in decrease in algal cell volume, and frequent variation in temperature significantly decreases the algal lipid production. The major advantages of microalga for biomass and energy production are its very short doubling time; it easily grows in any aquariums; for its growth, cheap media can be used (including wastewater); its ability to utilize CO_2 as it grows; helps in cleaning of the environment; it can be grown in a non-arable land on a large scale, and on small scale can be grown in our own houses; it has great potential of competency for food vs. fuel; and is considered as tough competitors for biofuel production.

4.5 Environmental Impacts on Biofuel Production

For the production of biofuel, microalga is an option, but it requires large-scale production of microalgae, having large multiple impact on environment with consumption of energy. Such limitation could limit system design and operation of microalgae biomass production (Fig. 4.1).

4.5.1 Impact of Light

As algae is a photosynthetic organism and requires proper intensity of light for its growth and development, at proper light intensity, only biosynthesis of appropriate biomass takes place. Mostly, algae require only 90–100 μmol of light intensity for photosynthesis to run dark reaction properly. So, cultivation of microalgae in open pond system requires constant monitoring of light intensity for proper biomass production (Carvalho 2010). Naturally, algae form only a few mm layers and do not shade each other remarkably. But during mass cultivation of shading, it is definitely a problem. So, mixing of cultivated microalgae is required to bring each cell on the surface of the pool to get illuminated regularly. Algae can harvest best under flashing light effect in which cell is illuminated with very high light intensities for short time duration, which has been efficiently used completely in darkness (Panjiar et al. 2017).

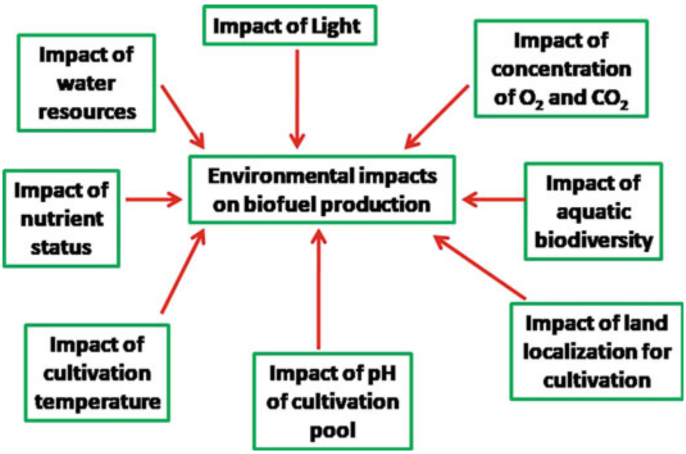

Fig. 4.1 Various environmental impacts on biofuel production by mass cultivation of microalgae

4.5.2 Impact of Concentration of O_2 and CO_2

As algae are photosynthetic microorganisms, they constantly require CO_2 for the production of biomass. At the same time, photosynthesis results in production of O_2 which gradually accumulates in the cultivating pond and inhibits the enzyme RUBISCO. RUBISCO is the main enzyme for the dark reaction of the photosynthesis and has more affinity for O_2. So, to achieve fast and efficient growth of algae, it requires external supply of CO_2 to the culture, which has been coupled with removal of O_2. As the O_2 produced during light reaction has inhibitory effect on photosynthesis, proper gaseous exchange is achieved by aeration of the cultivation pond, which also helps in proper mixing of culture component due to turbulence of air bubbles. This turbulence helps microalgae to assess required amount of CO_2 and nutrient due to proper mixing of substance, thus enhances mass transfer rates.

4.5.3 Impact of Water Resources

A consistent, continuous low cost water supply is necessary for the cultivation of microalgae for biofuel production. Although there is large volume of water present on the earth and microalgae are able to grow in marine as well as freshwater, but for the cultivation of microalgae is require well define boundary of the water body used for the growth. The water level and temperature of the cultivating pool need to be maintained, as open environment results in water loss due to evaporation (Teter et al. 2018). So, freshwater needs to be added at uniform time difference to maintain water at constant condition, but it is costly and energy demanding. For efficient growth of microalgae, continuous addition of oxygen in the water is also necessary; this is achieved by pumping, and significant amount of energy produced by the algae is consumed in it. So, the location with reduced pumping due to natural tidal flows is the choice location to feed cultivation pond. The distance to the water source is also an important factor in locating the cultivation site. Microalgae have the potential to grow in wastewater as well, but it required pretreatment to remove contaminant and growth-inhibiting components, such as metabolites of dead algae, inorganic and organic chemicals, etc. Pretreatment and recycling of water could raise the energy demand and cost of the process.

4.5.4 Impact of Cultivation Temperature

Temperature is one of the important factors for the growth of microalgae and very sensitive parameter for large-scale production, especially as open pool cultivation. Continuous variation in environmental temperature is normal phenomenon, but for the cultivation of microalgae such variation is not desirable. Increase in temperature significantly results in decrease in algal cell volume; all the enzymes of the photosynthetic dark reaction perform well within narrow range of temperature variation. Such variation in cultivation temperature remarkably reduced the lipid synthesis efficiency of the algae, which has direct effect on production of energy (Kassem and Çamur 2017). The optimum growth temperature for microalgae is in the range of 20–30 °C. But, during summer, when the light intensity increased, it caused increase of cultivation pool temperature. At the same time, during winter or evening, low light intensity results in reduced cultivation pool temperature, and both conditions remarkably reduced the microalgae biomass production. Even increase in temperature by few degrees can lead to the mass death of the microalgae.

4.5.5 Impact of pH of Cultivation Pool

The pH is another important physical parameter, which has direct effect on microalgae. Alkaline condition is desirable for the growth of microalgae, while acidic condition has highly deleterious effect on the growth of microalgae. Under alkaline conditions, microalgae photosynthetic rate gets increased many folds and yields additional biomass, as it enhanced the ability of microalgae to capture the CO_2 from the atmosphere. With increase in the rate of photosynthesis, gradual accumulation of OH^- ions takes place, which gradually changes the pH of the cultivation pool from basic to acidic. The change in pH from basic to acidic also altered the permeability of the algal cell and effects the transportation of important minerals and ions, necessary for the growth of algal biomass (Agasteswar et al. 2017). Acidic pH also results in hydronium forms of the inorganic salt and amalgamation of the inorganic salts, while cultivation of specific algae strains having ability to grow at extreme pH has the advantage to overcome the contamination.

4.5.6 Impact of Nutrient Status

Large-scale production of algae requires sufficient amount of nutrient for fast biomass production, which is directly proportional to the energy production. There are large number of elements like N, O_2, C, H_2, K, Ca, Mg, Fe, P, and S which are the main mineral nutrients for the growth of microalgae, and trace minerals are also required. Among these, the mineral nutrients like O_2, H_2, and carbon are directly obtained from atmosphere, and mineral nutrients like K, P, and N are essential for the growth of microalgae. Nitrogen and phosphorus are more important as they participate in lipid production and are necessary to maintain high growth rate. Nitrogen and phosphorus are most essential elements for the microalgae cultivation as they are necessary for formation of amino acid, DNA, RNA, etc., for growth, cell division, and other biochemical functions (Jha 2017). Potassium is also an essential element as it maintains membrane permeability of the microalgae for the efficient growth. So, to get good yield of biomass and lipid accumulation, all these nutrients need to be supplied in proper proportion (Elsayed et al. 2017). Mass cultivation of microalgae requires nutrients supplement, primarily nitrogen, phosphorus, and potassium, which can be supplied in the form of dry algae powder (Hein and Leemans 2012). Supply of recycled nutrients from the wastewater has the potential to reduce the cost, but it will enhance the rate of contamination.

4.5.7 Impact of Land Localization for Cultivation

Cultivation of microalgae requires large land area generally has competition for land for food production. So, use of marginal land for the cultivation is good option, but topology and soil porosity/permeability are important factors and affect the growth of microalgae. Cultivation land should be neither shaded nor fully open as it directly affects the temperature of cultivation pond. At the same time, cultivation pond needs to be established in pollution-free environment, as matter and poisonous gas have direct effect on growth of algae (Gasparatos et al. 2018). The most suitable locations are warm countries close to the equator or in low-latitude regions, where least variation of temperature takes place.

4.5.8 Impact of Aquatic Biodiversity

For energy production, mass cultivation of microalgae is required known as "regulated eutrophication," which required custom harvesting and sufficient supply of air. However, regulated eutrophication also has remarkable risk to the biodiversity. Mass cultivation of microalgae regularly causes decomposition of dead algal biomass, which consumes dissolved oxygen causing asphyxiation for its own growth and for other aerobic aquatic organisms. Absence of oxygen is cause for death of aquatic organisms, which results in water turbidity and toxicity due to degradation of dead organism. In absence of oxygen during anaerobic condition, there are production of methane and other greenhouse gases, responsible for global warming. Due to emission of such gases, there are bad odorous in the surrounding environment. Accidental release of water from cultivation pond into the surrounding area or specifically near large water body can lead to large-scale eutrophication and ultimately loss of large number of aquatic organisms. This impact is directly proportional to the amount of leaking and quality of the receiving water body. But it has positive impact also if the algae production is integrated with the treatment of water bodies already suffering from excess nutrient.

4.6 Constrain in Algal Production Technology

The objective for production of microalgal biofuel is inspired by the motivation to replace the existing conventional nonrenewable source of energy with renewable one, as a cheap and eco-friendly approach. But practically there are several limitations in mass scale production of biofuel by microalgae (Fig. 4.2).

4.6.1 Strain Selection

The first and the main issue in microalgal production technology is selection of specific correct strain of microalgae as per the requirement. So, screening and selection of such microalgae strain is quite tedious and requires lot of screening in hope to find specific strain that can work efficiently and give desirable product. There are many species of microalgae with high potential for production technology, but till date very less numbers of families has been evaluated and there is lack of phenotypic information. So, it is need of hour to characterize genetic diversity of microalgae for its domestication and wild species as well as identification of potential strain, protection of improved strains, and conservation of precious germplasm (Allen et al. 2018). Also, conservation of genetic diversity is necessary for genetic basis for various breeding programs for the development of new strain having high potential in different production systems or climates. Selection of precise germplasm for future use requires genetic and phenotypic characterization. Lack of phenotypic information is most hindering factor for genetic improvement of algal strain (Venteris et al. 2014). There are numerous species of microalgae with high potential for genetical engineering, but are in early stages of development. The working conditions of

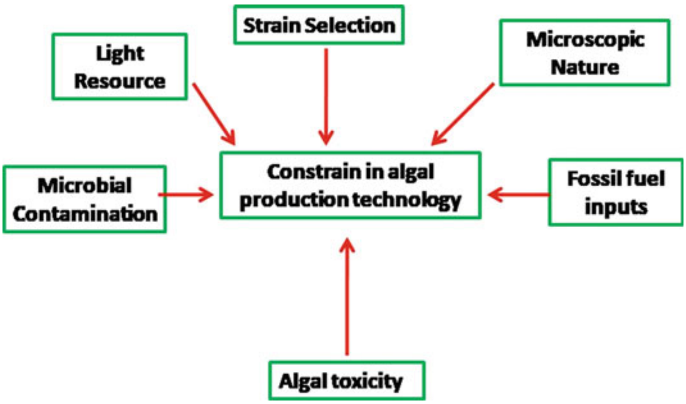

Fig. 4.2 Various constrains on biofuel production by mass cultivation of microalgae

specific system constraints must be considered for each strain to narrow the list down to a group that can be used on a mass production.

4.6.2 Light Resource

Microalgae production system driven by photosynthesis based on cell factory directly depends on light/solar source. Sunlight intensity varies across the globe, so maximum solar to chemical energy conversion potential also varies. Therefore, the low solar light region has to use artificial light source for the efficient microalgal production system, to conquer the restrictions posed by the low competence of photosynthesis. For microalgal production system, first and cheap light option is natural sunlight only, as sunlight is critical to autotrophic growth of algae. But there is regular fluctuation in quality and intensity in natural sunlight at daily, regionally, and seasonally. Like any photosynthetic organism, the chlorophylls of microalgae also show best light absorption at around 440 and 680 nm wavelengths (Schuurmans et al. 2015). The bottom of the water column received reduced light intensity due to inhibitive property of light by the surface layer, so there is insufficient light intensity for photosynthesis (Barry et al. 2015). For 24 h functioning of microalgae production system, an artificial lighting system is necessary. So, light is one of the main constraining factors of productivity and growth of microalgae even in presence of sufficient nutrition and suitable temperature.

4.6.3 Microscopic Nature

Microalgae production system uses microalgal strains typically 3–20 μm and grows in low concentrations, so harvesting in typically less than 2 g algae/L in conventional way is very difficult. Microalgae have negatively charged surfaces to form stable suspensions, and separations from suspension add more difficulty in its harvesting. Not only that, many microalgae cell walls are very sensitive and get damaged during separation process like centrifugation which can result in leaching of the cell contents. Several method of harvesting has been used as centrifugation, flocculation, foam fractionation, ultrasonic separation, and membrane filtration, which finally increase the cost of algal biomass. Most common and efficient method of harvesting is filtration with the help of cellulose membrane, but the membrane tends to become clogged and needs application of filter to draw liquid through it. Although filtration is simple, it is highly time consuming (Khan et al. 2018). With regard to time, centrifugation appears more suitable, but it is highly energy intensive, and for large-scale production, it is not very suitable. Other option is flotation using gas bubble the algae suspension, creating a froth of algae that can be skimmed off.

4.6.4 Microbial Contamination

The isolation and identification of microalgae in lab of unialgal and pure species is possible. But during mass cultivation there is always chance of contamination of algae with lower metazoan and other aquatic organisms (Lian et al. 2018). One of the main sources of contamination is bacteria, which inhibit the growth of microalgae due to secretion of toxic substance, which interferes with algal metabolism. But bacteria from plant growth promoting group have positive effect on the growth of microalgae (Jha, 2019a, b, c). Such growth promoting bacteria have the ability to produce growth promoting beneficial biomolecules, but till date these beneficial biomolecules are unknown (Kumar et al. 2019; Rastegari et al. 2019b, c; Yadav et al. 2019).

4.6.5 Fossil Fuel Inputs

Every step of mass cultivation of microalgae requires energy as for mixing, harvesting, aeration, etc. Microalgae are temperature-sensitive organism, and for efficient production, it required controlled temperature to maintain high productivity. Maintenance of temperature demands both cooling and heating, which require input of energy either in the form of electricity or fossil fuel. Microalgae production system optimization is a means to minimize energy demand (Cotton et al. 2015). Even production system efficiency has been enhanced by integrating options as using waste heat from power generation/direct heat for the process like to dry the algae.

4.6.6 Algal Toxicity

The most important perspective of biofuels production is production of co-products, which have been used by the human and are safe. Many species of microalgae at certain stage of its lifecycle may produce toxins. These toxins have been produced by the microalgae to protect itself and compete with its competitor or to reduce competition. Such toxin may be simple as some gas or complex as physiologically active biomolecules (Marc 2012). Toxin production is strain and species specific and also depends on cultivation/environmental conditions. The prediction of presence or absence of toxin production ability of particular microalgae is quite difficult.

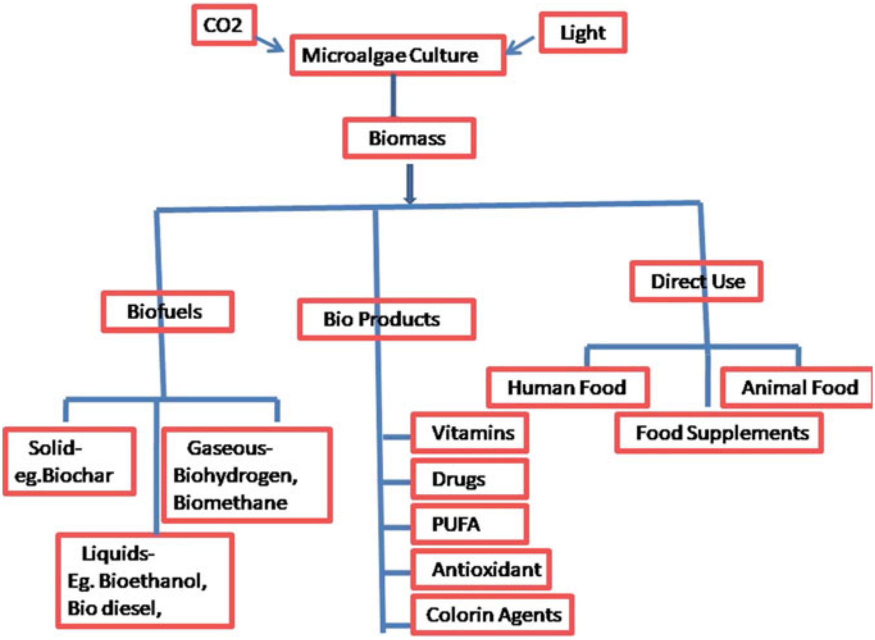

Fig. 4.3 Various applications of biofuel produced by mass cultivation of microalgae

4.7 Applications of Microalgae

The microalgae have been used by the humans from many decades ago, and nowadays there are varieties of commercial as well as industrial applications of the algae. With biofuel, microalgae also produce many important products like polyunsaturated fatty acids, pigments, natural colorants for cosmetics, antioxidants, pharmaceuticals, proteins and carbohydrates, and too many other products (Fig. 4.3). Microalgae also produce variety of animal feed, biohydrogen, biofertilizer, stabilizers, bioelectricity, and essential food supplement (Kour et al. 2019b; Yadav et al. 2017, 2020). Microalgae efficiently contribute in wastewater treatment pollution control and reduce greenhouse gases (Pienkos and Darzins 2009). The genetic modification of the microalgal genes can be a pathway to get new potential products.

4.8 Conclusion and Future Perspectives

With industrialization, the consumption of fossil fuel increased at the highest level, which resulted in increase in atmospheric CO_2 at an alarmingly situation as well as cause atmospheric pollution and depletion of ozone layer. And now fossil fuel reserves are at the wedge of depletion, and for continuous function of industries, there is requirement of alternative source of fuel. This is possible by shifting on renewable energy source as production of biofuel from microalgae, where continuous carbon fixation and long-term biomass production for production of biofuel. For efficient production of biofuel, selection of specific species with good fatty acid profile is important. The future challenge in this field is improvement through the genetic engineering techniques in the lipid profiles of important microalgal strains, having high lipid productivity.

For the mass scale production of biofuel, microalgae are used which definitely have several environmental benefits when compared to other energy sources. Wastewater treatment during the microalgae cultivation and production of various food and pharmaceutical compounds are certain important benefits of microalgae. Microalgae can provide a lower cost alternative to wastewater treatment, which reduces the demand of chemical use as well as reduce the energy input (Stephens et al. 2010). For biofuel production, large-scale production of microalgae is required, which utilized large amount of atmospheric CO_2 and burning of biofuel at the same time which resulted in more impartial level of CO_2 emissions when compared to fossil fuel. This will result in reduced contribution of CO_2 to environment responsible for global climate change.

References

Agasteswar V, Sridhar V, Brahmaiah P, Sasidhar V (2017) Cultivation of microalgae at extreme alkaline pH conditions: a novel approach for biofuel production. ACS Sustain Chem Eng 5(8):7284–7294

Allen J, Unlu S, Demirel Y (2018) Integration of biology, ecology and engineering for sustainable algal-based biofuel and bioproduct biorefinery. Bioresour Bioprocess 5:47

Barry AN, Starkenburg SR, Sayre RT (2015) Strategies for optimizing algal biology for enhanced biomass production. Front Energy Res 3:1

Basso LC, Basso TO, Rocha SN (2011) Recent developments and prospects in biofuel production. In: Bernardes MA (ed), pp 85–100

Carvalho AP (2010) Light requirements in microalgal photobioreactors. Springer, Berlin

Cotton CAR, Douglass JS, De Causmaecker S, Brinkert K, Cardona T, Fantuzzi A et al (2015) Photosynthetic constraints on fuel from microbes. Front Bioeng Biotechnol 3:36

Dragone G, Fernandes B, Vicente A, Teixeira JA (2010) Third generation biofuels from microalgae, current research, technology and education. Appl Microbiol Biotechnol 2:1355–1366

Elsayed KNM, Kolesnikova TA, NokeA, Klöck G(2017) Imaging the accumulated intracellular microalgal lipids as a response to temperature stress. 3 Biotech 7:41

Enamal MK, Enamala S, Chavali M, Donepudi J, Yadavalli R, Kolapalli B et al (2018) Production of biofuels from microalgae - A review on cultivation, harvesting, lipid extraction, and numerous applications of microalgae. Renew Sust Energ Rev 94:49–68

Gardner-Dale DA, Bradley IM, Guest JS (2017) Infuence of solids residence time and carbon storage on nitrogen and phosphorus recovery by microalgae across diel cycles. Water Res 121:231–239

Gasparatos A, von Maltitz G, Johnson F (2018) Survey of local impacts of biofuel crop production and adoption of ethanol stoves in southern Africa. Sci Data 5:180186

Hein L, Leemans R (2012) The impact of first-generation biofuels on the depletion of the global phosphorus reserve. Ambio 41:341–349

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc Natl Acad Sci (USA) 103:11206–11210

Jha Y (2017) Potassium mobilizing bacteria: enhance potassium intake in paddy to regulate membrane permeability and accumulate carbohydrates under salinity stress. Brazil J Biol Sci 4:333–344

Jha Y (2019) Endophytic bacteria as a modern tool for sustainable crop management under stress. In: Giri B, Prasad R, Wu QS, Varma A (eds) Biofertilizers for sustainable agriculture and environment. Soil biology, vol 55: Springer, Cham, pp 203–223

Jha Y (2019) Mineral mobilizing bacteria mediated regulation of secondary metabolites for proper photosynthesis in maize under stress. In: Ahmad P, Abass MA, Alyemeni MN, Alam P (eds) Photosynthesis, productivity and environmental stress, John Wiley & Sons Ltd, pp 197-293

Jha Y (2019) Regulation of water status, chlorophyll content, sugar, and photosynthesis in maize under salinity by mineral mobilizing bacteria. In: Ahmad P, Abass MA, Alyemeni MN, Alam P (eds) Photosynthesis, productivity and environmental stress, John Wiley & Sons Ltd, pp 75–95

Kassem Y, Çamur H (2017) A laboratory study of the effects of wide range temperature on the properties of biodiesel produced from various waste vegetable oils. Waste Biomass Valorization 8:1995–2007

Khan MI, Shin JH, Kim JD (2018) The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Microb Cell Fact 17:36

Kour D, Rana KL, Yadav N, Yadav AN, Rastegari AA, Singh C et al (2019a) Technologies for biofuel production: current development, challenges, and future prospects. In: Rastegari AA, Yadav AN, Gupta A (eds) Prospects of renewable bioprocessing in future energy systems. Springer International Publishing, Cham, pp 1–50. https://doi.org/10.1007/978-3-030-14463-0_1

Kour D, Rana KL, Yadav N, Yadav AN, Singh J, Rastegari AA et al. (2019b) Agriculturally and industrially important fungi: current developments and potential biotechnological applications. In: Yadav AN, Singh S, Mishra S, Gupta A (eds) Recent advancement in white biotechnology through fungi, Volume 2: Perspective for value-added products and environments. Springer International Publishing, Cham, pp 1–64. https://doi.org/10.1007/978-3-030-14846-1_1

Kumar S, Sharma S, Thakur S, Mishra T, Negi P, Mishra S et al (2019) Bioprospecting of microbes for biohydrogen production: Current status and future challenges. In: Molina G, Gupta VK, Singh BN, Gathergood N (eds) Bioprocessing for biomolecules production. Wiley, USA, pp 443–471

Lian J, Wijffels RH, Smidt H, Sipkema D (2018) The effect of the algal microbiome on industrial production of microalgae. Microb Biotechnol 11:806–818

Marc YM (2012) An overview of algae biofuel production and potential environmental impact. Environ Sci Technol 46:7073–7085

Panjiar N, Mishra S, Yadav AN, Verma P (2017) Functional foods from cyanobacteria: an emerging source for functional food products of pharmaceutical importance. In: Gupta VK, Treichel H, Shapaval VO, Oliveira LAd, Tuohy MG (eds) Microbial functional foods and nutraceuticals. John Wiley & Sons, USA, pp 21–37. https://doi.org/10.1002/9781119048961.ch2

Pienkos PT, Darzins A (2009) The promise and challenges of microalgal derived biofuels. Biofuels Bioprod Bioref 3:431–440

Rana KL, Kour D, Sheikh I, Yadav N, Yadav AN, Kumar V et al (2019) Biodiversity of endophytic fungi from diverse niches and their biotechnological applications. In: Singh BP (ed) Advances in endophytic fungal research: present status and future challenges. Springer International Publishing, Cham, pp 105–144. https://doi.org/10.1007/978-3-030-03589-1_6

Rastegari AA, Yadav AN, Gupta A (2019a) Prospects of renewable bioprocessing in future energy systems. Springer International Publishing, Cham

Rastegari AA, Yadav AN, Yadav N (2019b) Genetic Manipulation of secondary metabolites producers. In: Gupta VK, Pandey A (eds) New and future developments in microbial biotechnology and bioengineering. Elsevier, Amsterdam, pp 13–29. https://doi.org/10.1016/B978-0-444-63504-4.00002-5

Rastegari AA, Yadav AN, Yadav N, Tataei Sarshari N (2019c) Bioengineering of secondary metabolites. In: Gupta VK, Pandey A (eds) New and future developments in microbial biotechnology and bioengineering. Elsevier, Amsterdam, pp 55–68. https://doi.org/10.1016/B978-0-444-63504-4.00004-9

Rastegari AA, Yadav AN, Yadav N (2020) New and future developments in microbial biotechnology and bioengineering: trends of microbial biotechnology for sustainable agriculture and biomedicine systems: diversity and functional perspectives. Elsevier, Amsterdam

Schiermeier Q, Tollefson J, Scully T, Witze A, Morton O (2008) Electricity without carbon. Nature 454:816–823

Schuurmans RM, van Alphen P, Schuurmans JM, Matthijs HCP, Hellingwerf KJ (2015) Comparison of the photosynthetic yield of cyanobacteria and green algae: different methods give different answers. PLoS ONE 10(9):e0139061

Stephens E, Ross IL, King Z, Mussgnug JH, Kruse O, Posten C et al (2010) An economic and technical evaluation of microalgal biofuels. Nat Biotechnol 28:126–128

Teter J, Yeh S, Khanna M, Berndes G(2018) Water impacts of U.S.biofuels: Insights from an assessment combining economic and biophysical models. PLoS ONE 13: e0204298

Venteris ER, Wigmosta MS, Coleman AM, Skaggs RL (2014) Strain selection, biomass to biofuel conversion, and resource colocation have strong impacts on the economic performance of algae cultivation sites. Front Energy Res 2:37

Yadav AN, Kumar R, Kumar S, Kumar V, Sugitha T, Singh B et al (2017) Beneficial microbiomes: biodiversity and potential biotechnological applications for sustainable agriculture and human health. J Appl Biol Biotechnol 5:45–57

Yadav AN, Rastegari AA, Yadav N (2020) Microbiomes of extreme environments: biodiversity and biotechnological applications. CRC Press, Taylor & Francis, Boca Raton, USA

Yadav AN, Singh S, Mishra S, Gupta A (2019) Recent advancement in white biotechnology through fungi. Volume 2: Perspective for value-added products and environments. Springer International Publishing, Cham