Role of Microalgae in Sustainable Energy and Environment

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Abstract. The fast-growing global population is pressing the requirement of energy leading to the extensive use of fossil fuels globally which tends to their exhaustion, alongside the environmental pollution. The need of a third-generation fuel which is viably sustainable has increased and for that microalgae are standing out among various other competitors. Microalgae may be prokaryotic, like cyanobacteria or eukaryotic, like green algae. They are highly efficient in converting solar energy into biomass and can be cultivated in a wide range of conditions. Microalgae are the sources of biofuels, bioactive medicinal products, and food supplements. They have an outstanding photosynthetic efficiency and biomass productivity with high contents of fatty acids, polysaccharides, and proteins. Biofuels derived from microalgae have immense potential for carbon dioxide (CO$_2$) sequestration, whereby 1 kg of algal biomass may fix $1.8$ kg of CO$_2$. Microalgae are termed as 'living biorefinery' because they can produce a wide range of green chemicals like biopesticides and biofertilizers. Keeping in mind the severe impacts of chemical fertilizers, sustainable agricultural system is opting for biofertilizers and biopesticides. Biopesticides help prevents the attack of pathogenic fungus and soil borne diseases without causing any harm to plants and environment. The remarkable features of biofertilizers include enhanced crop productivity per area; reduced amount of energy consumption and contamination of soil and water; and increased soil fertility. Biofuels derived from microalgae are of various kinds including Biochar (solid); bioethanol, biodiesel, and vegetable oil (liquid); bio hydrogen and bio syngas (gaseous). Some of the pros of bioethanol obtained from microalgae are high octane number, minimal production of greenhouse gases, and the exclusive biofuel which can directly be used in automotive industry. This paper will provide an insight on the viability and feasibility of microalgal biomass in the production of biofuels and other bioactive compounds with the constraints and challenges faced in commercializing these products. This review shall elaborate on the potential of microalgae as a sustainable solution for future energy crises and environmental deterioration.

1. Introduction

The increasing depletion of fossil-based fuels and their deleterious impacts to the environment caused by the emissions of greenhouse gases like CO$_2$ have led to the shift in generating energy from renewable sources. It will reduce the dependency on fossil fuels and the severe problems associated with environmental pollution. This critical juncture led to the advent of biofuels which are renewable, nontoxic, and ecofriendly fuel produced from various feedstocks. Amid these feedstocks microalgae is having immense potential to replace fossil fuels and play a vital role for energy security and to obviate global environmental problems, ultimately leading towards their sustainability [1].

Microalgae for their cultivation need light as an energy source to convert the absorbed water and CO$_2$ into biomass through photosynthesis [2]. The requirement of major nutrients is fulfilled by nitrogen and phosphorus, which are 10-20% of the algae biomass. The growth is supplemented by the presence of some macro (Na, Mg, Ca, and K) and micro nutrients (Mo, Mn, B, Co, Fe, and Zn) [3]. The oils contained in microalgae have similar physico-chemical properties as that of vegetable oils hence they are rich raw materials in the production of biofuels. Figure 1 shows the efficacy of microalgae in the production of biofuels and biofertilizers.
Chisti, 2007 [3] predicted that microalgae have the potential and capacity to meet the global oil requirement. Microalgae do not compete for land with crops used for food production. As shown in Table 1 (column 4), the cultivation of microalgae does not require a large area of land compared to other plant sources.

**Table 1. Dominance of microalgae among other feedstocks [4].**

| SNo | Plant Source            | Oil composition by wt. in biomass (%) | Oil Productivity (l oil/ha/year) | Land Use (m² year/kg biodiesel) | Biodiesel productivity (kg biodiesel/ha/year) |
|-----|-------------------------|--------------------------------------|---------------------------------|--------------------------------|-----------------------------------------------|
| 1   | Corn/Maize              | 44                                   | 172                             | 66                             | 152                                           |
| 2   | Soybean                 | 18                                   | 636                             | 18                             | 562                                           |
| 3   | Jatropha                | 28                                   | 741                             | 15                             | 656                                           |
| 4   | Canola/Rapeseed        | 41                                   | 974                             | 12                             | 862                                           |
| 5   | Sunflower               | 40                                   | 1070                            | 11                             | 946                                           |
| 6   | Castor                  | 48                                   | 1307                            | 9                              | 1156                                          |
| 7   | Palm oil                | 36                                   | 5366                            | 2                              | 4747                                          |
| 8   | Microalgae (low oil content) | 30                           | 58,700                          | 0.2                             | 51,927                                        |
| 9   | Microalgae (medium oil content) | 50                           | 97,800                          | 0.1                             | 86,515                                        |
| 10  | Microalgae (high oil content) | 70                           | 136,900                         | 0.1                             | 121,104                                       |

Various other advantages of microalgae highlighting its role in sustainability are summarized below:
Microalgae are having the capability to fix CO₂ in the atmosphere and its biomass can be efficient in the bio-fixation of waste CO₂, thereby playing a vital role in the reduction of the major contributor of global warming and greenhouse effect (1 kg of dry algal biomass may fix about 1.8 kg of CO₂) [5].

Microalgae can be grown round the year. The harvesting of microalgae is cost incentive as compared to other crops and they can be grown independently without affecting the human food chain thus eradicating food versus fuel feud [6].

Microalgae can be grown in several environments that are unsuited for growing other crops, such as fresh, brackish, or salt water or non-arable lands. Moreover, they can be cultivated in open ponds and photobioreactors (PBRs). Therefore because of this significant and non-selective growth, microalgae can be produced at superior rate (yield/hectare) without disturbing the ecology [7].

Microalgae can be cultivated using wastewater providing dual advantage of wastewater treatment and biomass production. Sea water is a viable alternative for the bulk cultivation of microalgae, which will reduce the cost of production and reduce the global consumption of fresh water. Since, sea water is a good source of nutrients and may enhance the productivity of microalgae biomass [8].

Microalgae forms a stable and efficient biological system to utilize the solar energy and produce organic compounds. Microalgae have the potential of transforming 9–10% of sunlight into biomass with a theoretical yield of about 280 ton/ha/year [9]. Microalgae biomass is used to obtain many beneficial products (co/by) like biofuels, bio-pesticides, biopolymers, carbohydrates, proteins and biofertilizers etc [10].

Generally, microalgae double their biomass within a day but exponential growth results in doubling of biomass in just 3-4 hours [4]. On an average microalga have oils in the range of 20 to 50% by weight of dry biomass, but sometimes even higher productivities can be obtained by varying the growth factors [3].

The subsequent sections of the paper will encompass the applications of microalgal biomass in sustainable agriculture and biofuels followed by the challenges and how they can be tackled in making these products economically, efficiently and commercially viable.

2. Application of Microalgae in Agriculture
To match the rising food demand, reliability on agricultural system is increasing and consequently on the usage of agrochemicals. Agrochemicals consists of two groups of compounds: pesticides and fertilisers. Synthetic/conventional pesticides being inhibitors to pests and toxic to pathogenic contaminants to plant crops are having some serious and adverse impacts on humans, animals and environment [11]. Fertilizers are used to enhance the growth of seeds or plants and enrichment of soil by providing essential nutrients like nitrogen, potassium and phosphate but they are also responsible for causing environmental pollution [12].

2.1. Biopesticides
Plant crops are always at risk due to the existence of pests. Hence, pesticides are used to protect the crops from pests. As the demand of safe and healthy food is increasing, while environment is facing serious problems due to synthetic pesticides; this led to the development of research on biopesticides. Biopesticides are natural or derivatives of living organisms and are biodegradable and environmentally sustainable having less or no negative impact on humans, animals, and environment [13]. According to their origin, they can be classified into biochemical biopesticides {plant growth regulators (PGR) & pheromones}, botanical biopesticides (phenolics & terpenes) and microbial biopesticides (microalgae) [14].

2.1.1. Analogy between Synthetic and Biopesticides
Currently, restrictions are imposed on the use of many synthetic pesticides such as organochlorines, organophosphates etc which favoured the demand and use of biopesticides. Since synthetic pesticides have advantages over biopesticides such as low production cost, greater yield but the biopesticides developed recently are more effective, easier to use, more economical and have a longer shelf life [15]. Table 2 shows comparison between synthetic and biopesticide.

| SNo | Synthetic pesticides                                                                 | Biopesticides                                                                 |
|-----|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| 1   | There affect is not specific since only 5% reaches target organisms and it harms non  | They affect only the specific organisms (target pests) [17].                 |
|     | target species like bees, fishes etc [16].                                             |                                                                              |
| 2   | Exposure can cause serious diseases in humans (Parkinson’s disease, neurotoxicity,   | Some species of Algae require extra precautions in usage as they possess toxicity|
|     | endocrine disruptions) [18]. Leaching through soil can cause groundwater pollution    | like Chrysanthemum spp., Gracilaria coronopifolia, Microcystis aeruginosa etc  |
|     | [19].                                                                                  | [20].                                                                        |
| 3   | Low cost of production and higher yield make their use predominant in agriculture[21].| High cost of production and lower yield make their usage exclusively in organic |
|     |                                                                                       | agriculture[22].                                                             |
| 4   | Non-biodegradable and act as a source of pollution for crops and other organisms by   | Biodegradable, ensures food security and protects natural environment [15].   |
|     | inculcating toxic effects in them [23].                                               |                                                                              |

2.1.2. Sustainability of Microalgae as Biopesticide

Microalgae are considered as ‘living biorefinery’ because of their potential to produce a range of green chemicals while converting CO\textsubscript{2} and water to oxygen during photosynthetic process. Microalgae is converted to primary metabolites (carbohydrates, lipids and proteins) and secondary metabolites (terpenes, fatty acids, esters, phenolic compounds, steroids, triglycerides) which can be utilized to produce the biopesticides and biofertilizers which are coined as green chemicals [24].

- Microalgae have the capability to mitigate the greenhouse gases generated from thermal plants. During the culture of Synechococcus nidulans the intermittent addition of CO\textsubscript{2}, SO\textsubscript{2}, NO and ash catalysed the production of protein enriched biomass and achieved bio-fixing efficiency of 55% for CO\textsubscript{2}, for assays with injections of 10% CO\textsubscript{2}, 60 ppm SO\textsubscript{2}, 100 ppm NO and 40 ppm ash [25].
- *Chlorella sp.* was used for nutrient removal from crop runoff in wastewater treatment plant; the removal of nitrogen and phosphorus was about 80.5% while the removal of heavy metals varied from 56.5% to 100% [26].
- Since the recycling of nutrients favours the sustainable cultivation of Microalgae, therefore Rosa et al. 2015 [27] cultivated *Spirulina* sp. LEB 18 by recycling of culture medium achieved increase in biomass productivity and carbohydrates by 31.4% and 96.5% respectively, found to be potent in the control of pathogens.
- Chen et al. 2017 [28] studied nutrient recycling from liquefaction process for *chlorella vulgaris* which produced high levels of organic nitrogen and phosphates.
- Microalgae has the capability to produce phytohormones which are the derivatives of isoprenoids. Phytohormones affects the growth and productivity of microalgae and helps to stabilise various metabolic pathways to produce biomolecules (carbohydrates, Proteins and lipids). Hence microalgae culture does not require any synthetic growth catalyst to increase the biomass yield unlike other Agri-systems [29].
Herbicidal compounds derived from Scytonea hofmannii has been patented, but not yet commercialized [30].

2.2. Biofertilizers

Biofertilizers are being under extensive research these days as they play a vital role in sustainable agriculture by enhancing the productivity of crops in an efficient and eco-friendly manner thereby reducing the deleterious effects of synthetic fertilizers [31]. Biofertilizers are classified by the microorganisms and the benefits achieved by their application: nitrogen-fixators; phosphates- and potassium solubilizing biofertilizers; phosphorus-mobilizing biofertilizers; and biofertilizers for secondary macronutrients, zinc- and iron solubilizers, plant-growth-promoting rhizobacteria (PGPR)(Figure 1), and compost [12]. In the band of biofertilizers eukaryotic microalgae, anoxygenic phototrophs and cyanobacteria are of prime significance because of their contribution in terms of soil fertility and yield of crops [32]. Cyanobacteria and eukaryotic green microalgae have unique performance in the mineralization, mobilization of organic and inorganic, macro and micronutrients, production of bioactive compounds, (polysaccharides, growth hormones, antimicrobial compounds, etc.) can improve the plant growth and thus makes them suitable to be used as biofertilizers [33].

Some of the salient features of biofertilizers are elaborated here:

- High yield per unit area can be obtained in a short duration of time and enhance soil fertility[34].
- Energy incentive, renewable and environmentally friendly solutions for modern agriculture[35].
- They are key components in integrated nutrient management (INM) and integrated plant nutrition system (IPNS), leading to sustainable economic development[36].
- They promote antagonism and biological control of Phyto-pathogenic organisms.
- Application of Nitrogen fixing cyanobacteria is coined as “Algalization” not only enriches soil & plant with N but also helps to overcome the use of chemical N fertilizer[37].
- A lot of microalgae and cyanobacteria are found to excrete extracellular polymeric substances (EPS) into their immediate living environment to form a biofilm. EPS supplements the content of organic carbon in soil, prevents soil erosion and helps to retain proper soil structure [38]. The inoculation of Chlorella spp. alone or in combination with vermiculite increased the stability of soil micro aggregates (0.25–0.050 mm) as compared to chemical fertilizer [39].
- Microalgae also play an important role in the production of growth hormones (cytokinins, jasmonic acid etc.) which can be utilized as bio stimulants in agriculture [40].

2.3. Challenges in Commercialisation of Microalgae in Agriculture

Enormous amounts of nutrients are needed for commercial agriculture, to fulfil this requirement in the form microalgal biofertilizers large amount of microalgae biomass is to be produced. Chemical fertilizers contain anhydrous ammonia which comprises of 82%N but microalgae biomass have 1-10% N; therefore about 15 times more microalgae material is needed to attain the same fertilization level [41]. The growing of microalgae provides nutrients and other useful compounds to the crops on a continuous basis and it needs to be evaluated in an appropriate way. It is also difficult to predict the actual dose and mode of application of biofertilizers. Studies are going on to make the microalgae cultivation and utilization of microalgae for biofertilizers economically viable.

However progressive development is going on for the commercialization of microalgae as biopesticide and biofertilizer [42]. Algae based biofertilizer products are in-market, which guarantee their effectiveness in the enhancement of plant productivity and soil fertility. Recently, Del Monte Fresh Produce Inc. had field trials with algae biofertilizers at Arizona’s raw desert. The algae fertilization helped in the reclamation of abandoned land, minimized fossil inputs, and increased the crop productivity[43].
3. **Biofuels from microalgae: A Sustainable milestone towards energy and environment**

The current focus is on microalgae as a feedstock for bioenergy production, as one of the most promising raw material to compensate and balance the ever-increasing demands for biofuels, food, feed, and valuable chemicals production. Bioethanol and biodiesel are becoming excellent fuel alternatives which can be produced from food crops, food and plant waste and microalgae [44]. US Renewable Fuels Standard (RFS) estimated to obtain 36 billion gallons of microalgae-based biofuels by the year 2022 [45]. The practical applicability of microalgae as a potential feedstock to produce biofuels is discussed in the introduction. Now the paper focuses about the expressive features (Table 3) of the biofuels and the challenges faced by the researchers in tapping the worth out of microalgae.

### Table 3. Significance and challenges of Biofuels.

| SNo | Significance/Advantages | Challenges/Disadvantages |
|-----|-------------------------|---------------------------|
|     | **Bioethanol**          |                           |
| 1   | Microalgae possess high contents of different carbohydrates, such as glycogen, starch, agar, and cellulose, etc. which can be easily converted to fermentable sugars for bioethanol production [46]. | The primary areas which require optimization for the commercialization of algal bioethanol are, selection of the algal biomass, pre-treatment, and an efficient fermentation process [47]. |
| 2   | Major and cleanest biofuel used as transportation biofuel; high octane number prevents knocking; reduces ejection of greenhouse gases; can be used directly in automobiles or blended with gasoline [48]. | The most optimum method of harvesting, regardless of product specificity and microalgae species, has not been identified, since each technology has its own pros and cons [49]. |
| 3   | Global bioethanol production increased drastically from 1-39 billion litres within last few years. Out of which 75-80% is contributed by USA and Brazil [50]. | Algal biomass and carbohydrate productivity need to be improvised for economical and feasible production of bioethanol [51]. |
| 4   | Companies like Algenol, Sapphire Energy and Seambiotic etc. are involved in commercial scale production of bioethanol with output: 1 billion gallons/year costing at 85 cents/l [52]. | It is estimated that PBRs take up 47.4% of the equipment cost, and the power consumption accounts for 76.9% of the raw materials and utilities costs Therefore, this is a challenge to design a reactor to enhance the economic feasibility of optimizing the photo-bioreactors design [53]. |
| 5   | Some carbohydrates rich microalgae like *Chlamydomonas reinhardtii* and *Chlorella vulgaris* are potential for techno-economic analysis (TEA) of bioethanol production. TEA of bioethanol production from microalgae estimate suitability of the plant with respect to total investment, total cost ant total net profit [54]. | The potential of microalgae for bioethanol production can be tapped by improvement and optimization of each of the following: culturing algae and production of carbohydrate rich biomass; dewatering and harvesting of algal biomass; pre-treatment of biomass; ensuring maximum yielding fermentation [51]. |

### Biodiesel

| SNo | Significance/Advantages | Challenges/Disadvantages |
|-----|-------------------------|---------------------------|
| 1   | Microalgae can produce algal oil 58,700 L/hac from which 121,104 L/hac biodiesel can be produced [55]. | The infeasibility of algal biodiesel is due to the associated high operational, maintenance, harvesting and conversion cost [56]. |
| 2   | Microalgae species are favourable for the production of biodiesel because of its high lipids contents (50-80%) as in case of the *B. braunii* which contains up to 80% of oil in it biomass [4]. | Lipid yield depends on the species of microalgae as well as growth parameters. Sometimes lipid accumulation and growth of cells is contradictory, which effects the overall lipids productivity. Hence it is necessary to optimize the growth parameters [49]. |
| 3   | Biodiesel produced from microalgae has been found to have properties, such as density, viscosity, flash point, cold filter plugging point, solidifying point and heating value, similar to those of petroleum-derived diesel. Most of these parameters comply with the limits established by the American Society for Testing and Materials (ASTM) for biodiesel quality [57]. | Bio-oil extracted from microalgae in addition of containing triglycerides and fatty acids convertible into biodiesel, contains antioxidants and hydrocarbons that cannot be converted into biodiesel. The later have polarity and degree of saturation like the compounds of interest for biodiesel, making it difficult to extract them [58]. |
4. Conclusion
Microalgae are biorefineries, renewable, sustainable, and economically viable feedstock to produce biofuels and green agro-chemicals. Microalgae can be a sustainable solution for energy and environment as it contributes to the mitigation of CO₂, treatment of wastewaters and production of various bioactive compounds. Upgradation of algal biofuels, biopesticides and biofertilizers from lab scale to commercial level is possible by overcoming the associated challenges and limitations. In this review the extensive applications of microalgal biomass are incorporated which proves its potential as a future fuel playing a vital role in sustainable energy and environment.

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