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Renewable Energy Production by Microalgae; A review

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ABSTRACT

Biofuels are the up and coming alternative to exhaustible, inenvironmentally and unsafe fossil fuels. Microalgae as a source of biofuels have been widely studied for biodiesel/biogas/biohydrogen/biochar/bioelectricity production and has been gathering much contemplation right away. Increasing in energy demand and in greenhouse gas emission makes it important to develop alternative energy carriers that are renewable, clean and environmentally friendly. The use of arable land for biofuels in some cases has been associated with food insecurities and increased greenhouse gases caused by indirect land use change effects. Microalgae can grow on land not suitable for agriculture and would alleviate these concerns**.** The high lipid and mineral contents of microalgae render it beneficial for the production of biofuels and value-added products. On the other hand, result in to the reducing pollution and protecting the environment, because as a result of generating electricity in fuel cells or mechanical force in blast engines, the only output is water vapor. This review focuses on the current scenario and future prospects of microalgae aimed at biofuel production and the technologies available for converting the biomass produced into biofuel are analyzed. The goal of this work was to give a comprehensive review on biofuel production from microalgae biomass.

1. Introduction

Microalgae are unicellular and multicellular photosynthetic microorganisms that grow rapidly and have highly efficiencient, and their biomass production is 50 times higher than that of fast-growing terrestrial plants [1]. Microalgae are eukaryotic organisms found in almost all ecosystems and are well adapted to a wide range of environmental pressures such as cold, heat, drought, salinity, light oxidation, UV radiation, anaerobic conditions and osmotic pressure [2]. They have low nutritional needs, high growth rate and the ability to accumulate or secrete the right metabolites, which is the main reasons for their biotechnology in the near future [2].

Microalgae have been suggested as good candidates for fuel production because of their higher photosynthetic property, efficiency, higher biomass production, and faster growth compared to other energy crops. Algae contain protein, carbohydrates and lipids. Lipids can be processed to biodiesel, carbohydrates to be ethanol and H_2, and proteins as raw material for biofertilizer. There are many ways to convert the oil and fats into biodiesel, namely transesterification, esterification, blending, micro emulsion and pyrolysis, but transesterification and esterification are the most commonly used methods. Other important factor in biodiesel production is fatty acids (FA) type, and its amount. There are three main type of the FA that can be present in a triglyceride, i.e., saturated, mono-unsaturated and poly-unsaturated with two or three double bonds. The cetane number (CN), kinematic viscosity, density and heating value of biodiesel can be predicted from the FA composition [3].

Microalgae cells are able to convert and store energy instead of using it for growth. Thus, microalgae biomass can be considered as new systems for the production of biofuels that potentially replace fossil fuels due to the renewability, stability and short growth cycle of algae. Biofuels are not only suitable for replacing fossil fuels, but also reduce the concentration of carbon dioxide in the atmosphere [2].

Microalgae are located at the bottom of the aquatic food chain and, as photosynthetic organisms, capture carbon dioxide and water and convert them into organic compounds (such as triglycerides) or electron acceptors (such as molecular hydrogen) with the help of sunlight, which eventually accumulate or precipitate [2].

The lipid and biomass content of microalgae can reach over 80% and 7.3 grams per liter per day of biomass dry weight makes them an ideal candidate for biofuel [4] and lipids can be extracted for biodiesel production from microalgal biomass [5], while the residual/leftover biomass can converted into different liquid and gases biofuel including bio-alcohols through fermentation [6], bio-H_2 through dark fermentation [7], and bio-CH_4 via anaerobic co-digestion [8].

The different microalgae cultivation systems consist of: Open system, Closed system (Photobioreactor), Algal turf scrubber (ATS), Hybrid cultivation system (HCS). The most common methods of harvesting microalgae are gravitational deposition, flocculation, centrifugation, filtration and micro-screening, flotation and electrophoresis technologies. The choice of technology for harvesting depends on the properties of the microalgae [9].

2. Microalgal Biofuels Production

Several characteristics that make microalgae suitable for energy recovery. These include: (i) absence of competition with food supply, (ii) high productivity with reduced cultivation areas (oil yield of about 70% by weight of dried biomass, with area requirement of just 0.1 m^2/year per kg extracted), (iii) growth possibility on areas not suitable for other crops, without subtraction of soil from food crops cultivation, (iv) production in most types of water (fresh, brackish and waste water), with minimal or positive impact on water resources use [10].

The adverse impact of fossil fuel combustion products on the environment and its depletion as non-renewable energy has accelerated the pace of energy transformation in various countries [11, 12, 13].

Among the various types of biomass, algal biomass is highly considered for biofuel production due to higher lipid and sugar content in algal biomass [7, 14, 15]. Microalgal biomass has the potential for production of a broad range of biofuel through different routes. Microalgal biomass can be transformed into biodiesel through the transesterification of lipid [16], bioethanol, bioH_2 through the fermentation of carbohydrates [7, 17], while bio-CH_4 via co-digestion [18].

The use of algal biomass for bio fuels production has many advantages, namely: algal bio-mass can be produced all over the year and have a rapid growth capability, it grows in aqueous media, but it requires less water than terrestrial crops, it can be grown in brackish water on non-arable land, algae cultivation does not need herbicides or pesticides application and the nutrients for algae growth (mainly nitrogen and phosphorus) can be obtained from wastewater, thus as the algae grow, water effluent from agro-industrial sectors are treated. Algae growth does not compete with food production and it improves air quality due to CO_2 bio-fixation, as 1 kg of dry algal biomass uses around 1.83 kg of CO_2. Many species of microalgae have oil content between 20 and 50% dry weight and by changing the growth conditions the oil yield may increase significantly. The thermochemical processes developed for biomass energetic valorization may be also used for algal biomass, having in mind the specificities of this type of biomass. Thermochemical processes are usually divided into dry or conventional and wet or new hydrothermal processes that operate under sub or supercritical conditions [3]. A conceptual model for integrated microalgal biomass and biofuel (biomethane, biodiesel, biohydrogen, and biogas) production is shown in Figure 1 [19].

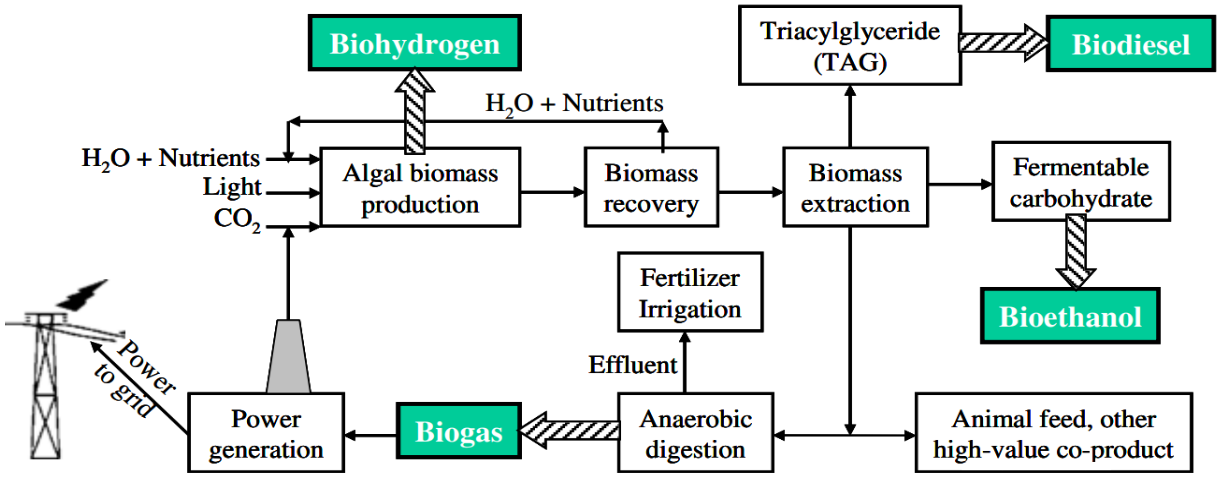

Figure 1. A conceptual model for integrated microalgal biomass and biofuel production.

2.1. Biodiesel

The biodiesel production should involve cell disruption, extraction, and transesterification of the oil to biodiesel. There are several methods for the effective extraction of lipids from microalgae, including autoclave, microwave, sonic and 10% NaCl solution to identify the most effective method of cell degradation [20].

The rapid increasing in the concentration of carbon dioxide in the atmosphere along with the depletion of fossil fuel reserves has led to an increase in attention to renewable fuels. Due to the high biomass production of microalgae, rapid lipid storage in their cells and the ability to survive in saline water have been identified as important food storage for industrial biodiesel production [21]. Among the microalgae that are potentially used as biodiesel biofuels, Chlorelea is the most considered due to its ability to adapt to heterotrophic and phototrophic breeding conditions [4]. Microalgae is able to produce a considerable quantity of lipids in the range of ~5000 to 100,000 L/hector/day, while microalgal derived biodiesel have a high energy content (39 to 41 KJ/g). Table 1 shows oil content of certain microalgae suitable for biodiesel production [19].

Table 1. Oil content of certain microalgae suitable for biodiesel production.

Microalgae	Oil content (% dry wt)	Reference
B. braunii	25–75	Chisti 2007 [62]
Chlorella emersonii	63	Illman et al. 2000 [63]
Chlorella minutissima	57	Illman et al. 2000
C. vulgaris	56.6	Liu et al. 2007
C. vulgaris	40	Illman et al. 2000
C. protothecoides	23	Illman et al. 2000
Chlorella sorokiniana	22	Illman et al. 2000
C. cohnii	20	Chisti 2007
Cylindrotheca sp.	16–37	Chisti 2007
D. primolecta	23	Chisti 2007
Isochrysis sp.	25–33	Chisti 2007
M. salina	>20	Chisti 2007
Monodus subterraneus	39.3	Khozin-Goldberg et al. 2006 [64]
Nannochloris sp.	20–35	Chisti 2007
Nannochloropsis sp.	31–68	Chisti 2007
N. oleoabundans	54	Metting 1996 [65]
N. oleoabundans	35–54	Chisti 2007
Nitzschia laevis	69.1	Chen et al. 2008b
Nitzschia sp.	45–47	Chisti 2007
Parietochloris incise	62	Solovchenko et al. 2009 [66]
P. tricornutum	20–30	Chisti 2007
Schizochytrium sp.	50–77	Chisti 2007
T. sueica	15–23	Chisti 2007
Chlorella sp.	28–32	Chisti 2007

Biodiesel can be produced by direct transesterification with heterogenous/homogenous catalyst or via in-situ(trans)esterification of the microalgal lipids [22].

High lipid efficiency of dominant and rapidly growing algae is one of the main preconditions for commercial production of bio-gasoline from microalgae lipid. Although large amounts of algal biomass are produced under optimal growth conditions, they are relatively low in lipids, while species with high lipids are typically slow-growing. Major advances in this area can be made by inducing lipid biosynthesis, for example, through environmental pressures. There has been a wide range of studies to identify and develop efficient lipid induction techniques in microalgae such as nutrient stress (eg, nitrogen or phosphorus deficiency), osmotic stress, radiation, pH, temperature, heavy metals and other chemicals. In addition, several genetic methods have been developed to increase triglyceride production and inductance [23].

Growth stress conditions can often be used to increase natural lipid formation. This stress was either due to the use of nutrient-deficient breeding cultivation or the addition of excess salt to nutrient-rich cultivation. It seems that the combination of nutrient deficiency and salt enrichment increases lipid formation in *Isochrysis sp.*, but this condition reduces lipid in *Dunaliella salina*. Interestingly, the amount of free glycerol for *Dunaliella sp*. seems to be quite high. *Botryococcus braunii* produces relatively high lipid content in each set of different growth conditions, but the highest value was 54.2% (DW) in nutrient deficiency conditions [3]. Nannochloropis, which grows in nitrogen-deficient cultivations, can increase lipid levels from 28% to more than 50%. Lipid production indicates that a maximum of 150 mg/L per day is achieved when cellular nitrogen reaches 5 to 6%. However, in this study, the initial concentration of nitrogen in the breeding medium reached more than 25 mg/l [3].

Microchloropsis salina (*Monallantus salina*) is able to produce 72% of lipids in nitrogen deficiency conditions. To produce lipids, the percentage of them in microalgae is less important than maximizing growth rate. The result is that nitrogen-deficient cultivation increases lipid production compared to cultures with sufficient nitrogen. High light environments have more lipids than low light environments. In addition, the amount of lipids in culture and lipid production rates indicate that higher amounts of lipids are produced under conditions of sufficient nitrogen and high light, due to greater biomass growth [24].

2.2. Biogas

In the biogas production model, it is assumed that the inflows to the AD are derived from five process steps. These include the vinasse, a by-product in ethanol production; the primary sludge from the wastewater primary treatment stage; the algae residues (lipid-extracted algae (LEA) and the undisrupted algae) from the oil extraction step; the filtered algae in the harvesting section; and crude glycerol, a by-product from the transesterification step in the biodiesel production.

The vinasse from the ethanol production factory was one of the components with a high mass flow rate. Considering the molasses-based distillery effluent, vinasse, as the main component in the anaerobic digestion, the following four reactor configurations were implemented on a commercial scale: a continuous stirred-tank reactor (CSTR), an upflow anaerobic sludge blanket (UASB) reactor, a fixed film/media digester (or anaerobic filter, AF), and a thermophilic digester. The most successful configurations today are the UASB and CSTR reactors. The UASB reactors are used for the treatment of a wide range of industrial wastewaters (from low-to-high-strength wastewater) including vinasse. UASB reactors are being encouraged because of their several advantages including plain design, uncomplicated construction and maintenance, low construction and operating costs, low sludge production, robustness in terms of chemical oxygen demand (COD) removal efficiency and wide applicability, less CO_2 emissions due to less energy requirement, as well as quick biomass recovery [25].

co-digestion of microalgae biomass and primary sludge (PS) enhances 65% CH_4 productivity as well as microcontaminants removal efficiency achieved up to 90%.

During the AcoD process, the produced biogas contains CH_4 (50–65%) and CO_2 (40– 50%) and traces amount of H_2SO_4, N_2O, which need separated from the methane [26]. Therefore, innovative and sustainable biogas upgrading technologies are immediately required. However, there are several traditional upgrading technologies (chemical adsorption, membrane separation, and pressure swing adsorption) available, which demand a high cost [27]. Recently, microalgae-based biogas upgrading are under investigation to avoid the major disadvantages of conventional biogas upgrading [28].

2.3. Biohydrogen

The need to safeguard our planet by reducing carbon dioxide emissions has led to a significant development of research in the field of alternative energy sources. Hydrogen has proved to be the most promising molecule, as a fuel, due to its low environmental impact. Even if various methods already exist for producing hydrogen, most of them are not sustainable [29].

Hydrogen as the cleanest source of energy is a promising alternative to conventional fossil fuels. Among different technologies for hydrogen production, photosynthetic microorganism, such as microalgae, has a great potential to produce hydrogen, by using only water and sunlight, as both clean and cheap sources. Microalgal biohydrogen photoproduction: scaling up challenges and the ways forward [30].

Many algal species show potential to produce hydrogen under certain conditions. Nonetheless, certain technical barriers like developing low-energy methods to harvest microalgal cells, difficulties in continuously producing biomass at a large scale, the presence of invasive species in large-scale ponds, low light penetrance in dense microalgal cultures, and the lack of cost-effective bioenergy carrier extraction techniques, are required to overcome before using microalgae as an economically viable biofuel feedstock [31].

Microalgal hydrogen production is made possible by biological processes directly or indirectly, depending on sunlight, or by fermentation processes and thermochemical technologies for biomass conversion (Figure 2)[29].

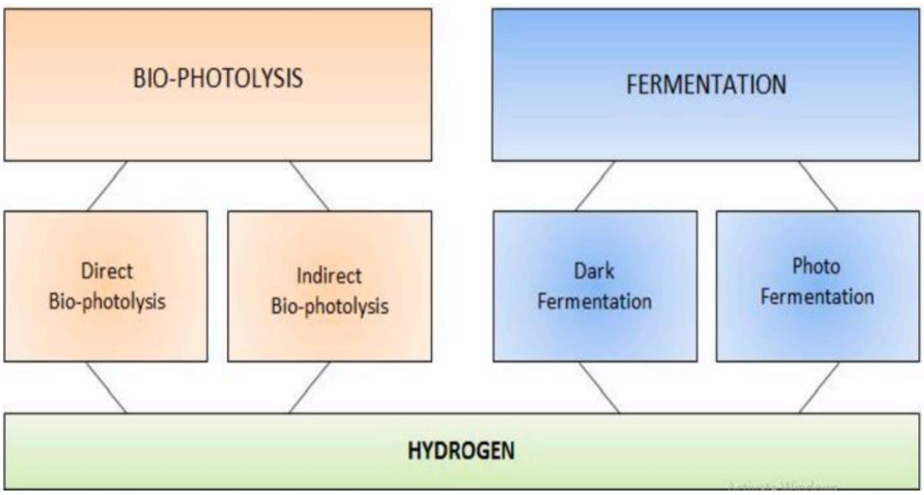

Figure 2. Hydrogen production processes in microalgae.

A large number of unicellular, filamentous, fresh water, and marine cyanobacterial species and strains have been produced large quantity of hydrogen. *Gloeocapsa alpicola*, *Anabaena variabilis*, *Anabaena azollae*, *Arthrospira (Spirulina) platensis*, *Anabaena cylindrica*, Cyanothece, *Nostoc muscorum*, etc. has been produced a high quantity of hydrogen gas. *Anabaena sp.* is produced extraordinarily significant amount of hydrogen. Among them nitrogenstarved cells of *A. cylindrica* produces highest amount of hydrogen (30 ml H_2/lit/h) [19].

Microalgae can produce biohydrogen naturally by light or its biomass can be used as a raw material for fermented biohydrogen.

The pivotal process of microalgal metabolism consists of oxygenic photosynthesis and complex redox reactions that take place at the level of the thylakoid membranes in chloroplasts through two successive phases. During the first light-depending reactions, ATP and reduced NADH, and NADPH, are generated to be involved in the next dark reactions where the atmospheric CO_2 is fixed by a RuBiSco (ribulose-1,5-bisphosphate carboxylase/oxygenase) enzyme to ultimately generate energy rich-carbohydrate stores. Specifically, during the light phase, an electron transport chain is generated along with photosystems II (PSII) via the plastoquinone (PQ) pool, cytochrome b6f complex (Cyt b_6f) and photosystems I (PSI) due to the light energy received as photosystems are associated with light-harvesting complexes I and II (LHC I and LHCII), consisting of numerous photoreceptive pigments. These electrons through PSI leave the electron transport chain and reach the final acceptor ferredoxin (Fd) [32]. In anoxic conditions, Fd is able to address electrons to the hydrogenase enzyme.

This kind of enzyme catalyzes a reversible reaction in which hydrogen can also be split into electrons and protons [29]:

$2H^+ + e^- \leftrightarrow H_2$

In direct photolysis, there is a dissociation of water into hydrogen and oxygen in the presence of light, that is, $H_2O \rightarrow H_2 + ½O_2$. Green microalgae can use light to carry out photosynthesis as they possess chlorophyll a and the photosynthetic systems: Photosystem (PS) II and Photosystem (PS) I, respectively. Disadvantages are the enzyme hydrogenase is very sensitive to oxygen so when a certain amount of oxygen is present, will inhibit hydrogenase activity and will stop it from producing hydrogen. Also, it requires high intensity of light. The advantages include tenfold more solar conversion in green microalgae.

There is two step processes during Indirect photolysis, firstly there is a splitting of water molecules in the presence of sunlight and protons and oxygen is formed. Secondly carbon dioxide fixation occurs storage carbohydrate is being produced, followed by the production of hydrogen gas by hydrogenase.

$$12H_2O + 6CO_2 + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$
$$C_6H_{12}O_6 + 12H_2O + \text{light energy} \rightarrow 12H_2 + 6CO_2$$

Blue-green algae (cyanobacteria) are promising microorganisms for this. Advantages are hydrogen evolution is separated from oxygen evolution. It can also produce relatively higher hydrogen yields. Furthermore, by-products can be efficiently converted to hydrogen. Disadvantages are like significant adenosine triphosphate (ATP) requirement of nitrogenase. Also, this requires continuous light source which is difficult for large scale processes [31]. Furthermore, genetic modification in the bio-H_2ase gene can increase the resistance ability of the hydrogenase enzyme. A different genetic approach used for enhancement of bio-H_2 production in microalgae such as (i) overexpression of PSII gene, cytochrome b_6f, hemA, and lba gene, translational repressor NAB1 protein; (ii) knockout of light-harvesting gene, IFR1 protein, OEE_2 gene; (iii) cloning of pyruvate oxidase gene, DT hydA gene; (iv) antisense transformation of sulp/sulp2 gene or amino acid substitution; (v) insertion of GAL4 gene, CRY1, and CRY2 gene, VP 16 and other light inducible system can enhance the bioH_2 production in microalgae (Figure 3) [7].

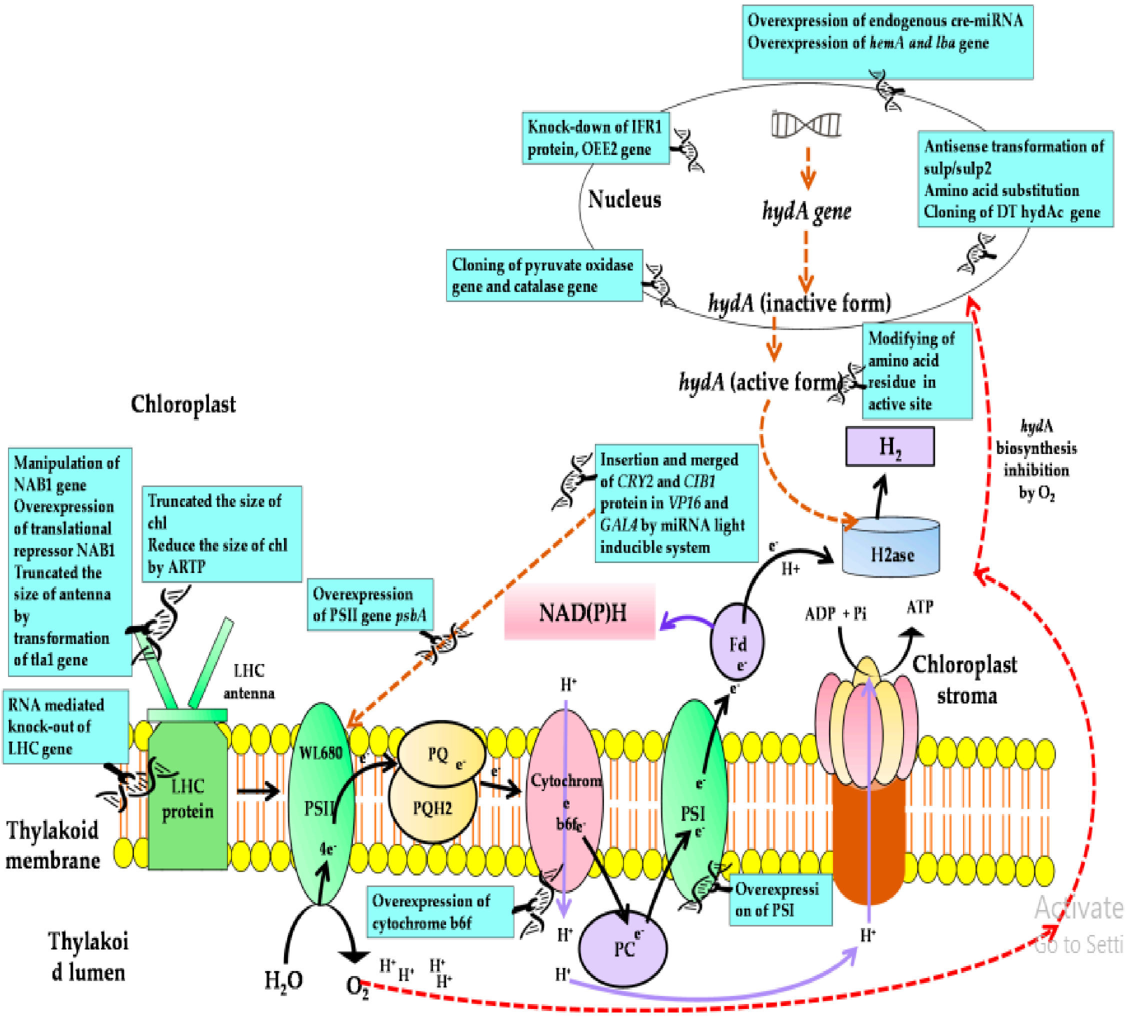

Figure 3. A different genetic approach used for enhancement of bio-H_2 production in microalgae.

2.4. Bioelectricity

One energy from aquatic herbs which is potential to be developed, eco-friendly, and competitive is microalgae. The potency of microalgae development is important in the future since microalgae have preeminence as food material, supplement, biodiesel, and bioethanol. It can also be utilized as the electricity producer. Microalgae-Microbial Fuel Cell (MMFC) technology utilizes the result of microalgae photosynthesis as an oxygen in the cathode with the tapioca wastewater as the anode to produce bioelectricity. The power density value was calculated based on the influence of the wide of electrode surface and the membrane circle. The wide of the electrode surface and the membrane circle was calculated by following equation:

$$P = V x I \quad (1)$$

where P is power density (W), I is Current (A), and V is Voltage (V).

Power density can be influenced by the wide of electrode surface and membrane, so the equation is:

$$P = V \times t / A_{Total} \quad (2)$$

Tools that are used in MMFC technology are based on modified. MMFC tools design is based on the microbial fuel cell research, namely electrode and membrane usage type of substrate, the reactor design [33].

Microbial fuel cell is a technology that utilizes microbes to produce energy in the form of electricity. Microbes convert various kinds of organic compounds into CO_2, water, and energy. Recently, one of MFC technologies developed is MMFC (Microalgae Microbial Fuel Cell) technology. MMFC is an alternative that be used as a source of electricity generator through hydrolysis and fermentation of microalgae in one process unit. MMFC consists of an anode and cathode that connected through a load (usually a resistor). Anode chamber is containing microorganism cultures that catalyses the composition of organic materials into electrons and protons. Power will be produced by the reduction of oxygen or other compounds at the cathode chamber. On the operation of MFC, electrogene which will produce CO_2. Microalgae in the cathode chamber use CO_2 as a carbon source for growth [34].

These are the greenest and most sustainable types of fuel cells, and undoubtedly represent the future of energy production. MFCs can be double-chambered, with separated anodes and cathodes, or single-chambered, having the electrodes in the same container

[35]. In both cases, they exploit microorganisms and their metabolism to produce the fuel necessary for the fuel cell to function. Most MFCs are mixed, using anode bacterial cultures for hydrogen production and cathode microalgae strains for oxygen supply [36]. However, prototypes of fuel cells that work only with algal strains are in development [37]. MFCs have significant environmental benefits. Thanks to the biological processes underlying their functioning, they can combine energy production with other functions, such as bioremediation activities [38, 39]. It also bypasses the hydrogen storage limitation, since hydrogen is produced and utilized almost at the same time in the anodic chamber. However, this technology is not yet widely applied due to high costs and ineffective yields, which require further study for improvement [40]. Some recent investigation suggested that the integration of MB-MFCs system with microalgal based bioH_2 production are a cost-effective approach for wastewater treatment and bioH_2 production. In this system, wastewater is used as nutrient rich substrates for bacterial growth, the bacteria oxidize the substrates and generates H+ and e−, the e− moves towards the anode, and is then transferred to the cathode where electron flow generates a bioelectric current. Then, H+ moves towards cathode through the proton membrane exchanger and reacts with O_2 (which are produced during microalgal respiration) and forms H_2O. In algal cells, direct photolysis occurs, which produces bioH_2, furthermore, produced algal biomass during this treatment process can be utilized for fermentative bioH_2 production [41]. Table 2 shows the different microalgae strains utilized for bioelectricity generation [42]. Moreover, advance approaches are integrated for advancement of MB-MFC, while its large scale realization need to be demonstrated for real-world application and commercialization [43]. Although, single MB-MFC process is ineffective to generate the power of different commercial implementation; therefore, it can be integrated with AD technology.

Table 2. Different microalgae used for bioelectricity generation.

Microalgae	Cathode	Anode	Power Density
Chlorella vulfaris; Ulva lactuca	Graphite fiber brush	Air cathode with platinum (Pt) catalyst	980.0 mW/m^2
Chlorella vulgaris	Carbon fiber brushes	Carbon felt containing Pt catalyst	187.0 mW/m^2
	Toray carbon cloth	Toray carbon cloth	13.5 mW/m^2
	Graphite felt	Carbon fiber cloth	2572.8 mW/m^2
	Carbon felt	Carbon felt	24.4 mW/m^2
	Carbon felt	Carbon fiber cloth	2485.3 mW/m^3
	Carbon fiber brushes	Carbon cloth	5600.0 mW/m^3
	Graphite rod	Graphite rod	0.95 mW/m^2
	Carbon felt	Carbon fiber cloth	3720.0 mW/m^3
Chlorella sp.	Graphite carbon	Graphite carbon	3.35 mW/m^2
Lagoon (algae culture)	Plain carbon cloths	Plain carbon cloths	11.5 mW/m^2
Laminaria saccharina	Graphite felt	Graphite felt	250.0 Mw/m^2
Mixed algae culture	Carbon fiber brush	Carbon cloth coated with platinum	30.0 mW/m^2
Scenedesmus obliquus	Toraycarbon paper	Toray carbon paper	102.0 mW/m^2
Synechococcus leopoliensis	Black acrylic	Carbon fiber veil	42.5 mW/m^3

Polontalo et al. (2021) studied the performance of the MMFC system based on the influence of yeast (8 g L^{-1} and 4 g L^{-1}), “Batik wastewater” concentration (50 % and 100 %), and graphite electrodes (1:1 and 2:2). The MMFC system was carried out by filling anode chamber with “Batik” wastewater and the cathode with C. vulgaris. MMFC simulation was operated for 7 d. Concentration of 100 % “Batik” wastewater and 2:2 number of electrodes gave the best result in MMFC with voltage 0.115 Volt, algae absorbance 0.666. The COD decreased from 824 mg L^{-1} to 752 mg L^{-1} after the MMFC. The addition of 8 g L^{-1} yeast gave the optimum of bioelectricity production reached 0.322

Volt and the microalgae grew until the absorbance reached 1.031.

2.5. Biochar

Biochar is a carbon-rich charcoal made up by thermal decomposition (pyrolysis, hydrothermal liquefaction, and torrefaction) of different organic biomass under low oxygen and high temperature [44].

Pyrolysis is the thermal degradation of biomass in the absence of oxygen, resulting in the production of liquid (bio oil) and solid (biochar) residues, and gaseous products (pygas), effectively transforming wastes into valuable products [45].

Depending on heating velocity and residence time of the process, pyrolysis can be broadly classified as slow (conventional), or fast. Slow pyrolysis maximises solid fraction (biochar) production, and occurs at long residence times and slow heating rates, while liquid and gaseous energy-rich products (bio-oil or pygas) fractions are increased during fast pyrolysis [46]. An increase of pyrolysis temperature generally maximizes the gaseous fraction, minimizing the solid yield [47].

Properties of the solid residue (biochar) also vary in terms of carbon content and composition. Concerning energetic aspects, bio-oil and biochar could be used as fuels, meeting increasing needs for energy from non-fossil fuels sources [48].

However, biochar derived from sewage sludge generally presents high ash content and lower heating value, diminishing its energetic worth [49]. Biochar generally used as biofertilizer or absorbent for wastewater treatment, carbon sequester, etc. However, recent studies suggested that it can be used as a source of coal or coal fuel for the electricity generation [44].

High growth rate, cultivation ease, high lipid and low ash contents makes microalgae highly appealing, compared to other biomasses, with high yields in terms of both bio-oil and biochar [50], as determined with satisfactory results by numerous studies [51, 52, 53].

Microalgal biochar has lower carbon content than biochar from other feedstocks, lower surface area, and lower cation exchange capacity ,while pH, ash and nitrogen contents and extractable inorganic nutrients are high. These properties make it a useful additive to enhance soils characteristics and improve crop productivity, particularly for acidic soils [54]. Table 3 and 4 summarizes the fuel properties of different biochar derived from microalgal biomass and other biomass in dry and wet torrefaction, respectively [42].

Table 3. Fuel properties of different biochar derived from microalgal biomass.

Type of Biomass	t & T	Ultimate Analysis (wt%)				HHV (MJ/kg)	EY (%)
		C	H	N	O		
Chalamydomonas sp. JSC4 residue	15–60 min; 200–300 °C	51.6–72.6	7.2–4.4	4.0–6.4	37.2–16.5	17.6–24.8	74.3–99.8
Chlamydomonas sp. JSC4	30 min; 300 °C	63.6	5.01	6.0	25.4	–	–
Chlorella vulgaris ESP.31	15–60 min; 200–300 °C	49.1–65.3	7.9–5.1	5.0–6.7	38.0–22.9	17.9–25.2	–
Chlorella vulgaris ESP.31 by wet torrefaction	30 min; 170 °C	59.0	7.8	8.6	24.5	26.02	62.95
Scenedesmus obliquus CNW-N	60 min; 200–300 °C	36.9–39.3	5.5–3.6	6.5–7.3	28.2–23.2	–	–

Note: t & T: temperature and time duration; HHV: higher heating value; EY: energy yield.

Table 4. Fuel properties of different biochar derived from other biomass.

Type of Biomass	t & T	Ultimate Analysis (wt%)				HHV (MJ/kg)	EY (%)
		C	H	N	O		
Calophyllum inophyllum L	10 min; 260 °C	59.1	4.9	0.3	35.7	23.6	65.2
Energy sorghum	30 min; 275 °C	55.2	4.9	1.7	38.1	23.80	73
Humulud lupulud	10 min; 260 °C	60.5	6.0	2.7	30.8	25.3	38.5
Jatropha-seed residue	30 min; 300 °C	61.1	5.2	4.2	20.7	27.01	–
Waste bamboo chopsticks	40 min; 290 °C	55.5	5.4	0.2	38.3	23.04	–
Landfill food waste	40 min; 275 °C	61.2	5.8	3.4	29.6	26.15	77.2
Leucaena by microwave torrefaction	250 W	76.3	2.6	1.0	15.1	28.25	34.04
Leucaena by microwave torrefaction	250 W	80.3	2.8	1.1	15.9	29.72	36
Plumeria alba	10 min; 260 °C	60.7	6.8	0.6	31.9	25.7	45.7
Sewage sludge	400 W	66.8	2.3	2.7	28.3	13.21	19
Sunflower seed shell	60 min; 300 °C	69.5	5.3	0.5	24.6	27.6	–
Sweet sorghum bagasse	30 min; 300 °C	59.3	4.6	0.9	35.2	26.88	70

Note: t & T: temperature and time duration; HHV: higher heating value; EY: energy yield.

3. Challenges of Microalgal Biofuel Production and Future Perspectives

Third generation biofuels and high-value bioproducts produced from microalgal biomass have been considered promising long-term sustainable alternatives for energy and/or food production, potentially decreasing greenhouse gas emissions. Microalgae as a source of biofuels have been widely studied for bioethanol/biodiesel/biogas production [55].

Microalgae present positive impact also on carbon dioxide emissions, in fact they contain about 50% Cover dry weight derived mainly from atmospheric CO_2, therefore, production of 100 tons of microalgae allows fixation of about 183 tons of carbon dioxide [56].

A typical process for obtaining lipids from microalgae involves the following steps: cultivation in open ponds or photo-bioreactors followed by harvesting of algae using technologies like sedimentation, flocculation, filtration, centrifugation, etc. Depending on the process and conditions, primary harvesting concentrations in the range of 2–8 wt% solids are obtained [57]. This is generally followed by secondary harvesting using technologies like filtration or centrifugation. Algae concentrations after secondary harvesting are in the range of 20–27 wt %. Depending on specific technology chosen, feedstocks resulting from primary or secondary harvesting process steps are subject to lipid extraction. Most common methods for the extraction of lipids from microalgae include: solvent extraction, direct transesterification, and algae that secrete products directly into the growth medium (milking). Microalgae as a currently recognized bioenergy producing biomass, its liquid biofuels such as biodiesel and bioethanol have been widely studied [58].

However, there are several knowledge gaps and problems associated with biomass production and lower yield, high expenses, and lack in commercialization of algal bioprocess. To enhance the biomass productivity, high inputs of nitrogen source can be used to enhance the biomass productivity, while modern genetic engineering tools such as CRISPR-Cas9, TALEN, and ZFN-17 can be applied to alter the genome and metabolic pathways of microalgae to enhance the biomass productivity for biofuel production as well as synthesis of various bioactive compounds for various commercial applications. For the reduction of energy consumption during microalgae-based bio-fuel production, further strategies need to be explored. Therefore, several steps need to be integrated to achieve a sustainable low-cost bio-fuel production process [42].

4. Conclusions

Increasing industrialization, demographic expansion and expansion of the transportation and mobility sector worldwide, and especially in developing countries, are the cause of excessive conventional fossil fuels exploitation, leading not only to repeated energy shortages worldwide, but also to increasing global levels of greenhouse gases emissions [59].

Rapid industrial development, depletion of mineral oil reserves, and rise in atmospheric CO_2 require the development of carbon-neutral renewable alternatives. Biofuel production from microalgae is supposed to provide technical and economic feasibility that has the potential for CO_2 sequestration and is therefore, likely to get wide acceptance. Algal biofuels appear to be the only current renewable energy source that could meet the global demand for transport fuels [19].

Algae are one of the most primitive microorganisms on the Earth. They are small photosynthetic organisms that have an ability to completely replace the need of conventional fossil fuel for energy demand. They are robust microorganisms and can be grown in photo-bioreactors, open ponds, sewage or industrial waste without the need of arable land. Microalgal biomass can be converted to variety of biofuels via biochemical and thermochemical methods, they can also be used for the production of high value nutraceuticals at industrial scale [60].

Commercial production of microalgae biofuels remains a major constraint due to the higher cost of microalgae cultivation and biomass harvesting. Therefore, algal biomass should be investigated for potential application in various sectors, mainly marine industries and other sectors. By using microalgae biomass as an alternative raw material energy sources like biohydrogen, methane can be produced through fermentation and photosynthesis. Unlike solar energy, which has the disadvantages of low energy density, instability and difficulty in storage, biohydrogen and biogas are one of the novel ideal energy sources at present. The utilization of microalgae has various attractive prospects in their production due to its cost-effectiveness, renewable biomass and ease of scaling-up technology [61].

5. References

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