VOL. 11, NO. 19, OCTOBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

A SCOPE ON MICROALGAE AS POTENTIAL SOURCE OF BIOFUEL

Samar A. El-Mekkawi[1], Ola. A. El-Ardy[1], N. N. El-Ibiari[1], Nabil. M. Abdelmonem[2], Ahmed H. Elahwany[2] and Ibrahim M. Ismail[3]
[1]Department of Chemical Engineering and Pilot Plant, National Research Centre, Dokki, Egypt
[2]Department of Chemical Engineering, Cairo University, Egypt
[3]Renewable Energy Engineering, Zewail City of Science and Technology, Giza, Egypt
E-Mail: samarelmekkawi@hotmail.com

ABSTRACT

Biofuel is expected to have a role in creating a renewable, practical and environmentally intact source of energy. Biomass is converted into biofuels either via: chemical, thermo chemical, or biochemical processes. The choice of conversion process and feedstock depends on the desired product and the form of energy. The potentiality of microalgae as a biofuel source is high comparing to other sorts of biomass. However there are several basics needed for the development of this trend. Firstly, the suitable microalgae strain. Secondly, the type of cultivation system that is agreeable to the environmental consideration and ideal for energy conservation. Finally, the physical and chemical factors affect the cultivation of microalgae. Greenhouse gas emissions and energy utilization potential are pertinent to biofuel production. Life cycle assessment of biofuel production from microalgae proposes them to be preferable to fossil fuel. However; the algal technologies need more improvements to be attractive economically.

Keywords: biodiesel, biofuel, cultivation systems, fatty acids, microalgae, photo bioreactor, triacylglycerides.

1. INTRODUCTION

Egypt has been run across an energy crisis in recent decades. The peak of production was over 900'000 bbl/day in 1999s [1]. The out-put start to turn down as oil fields aged. In 2013 Egypt's total oil production was 714'000 bbl/day while the consumption was 757'000 bbl/day. Local oil consumption increased by 30% more than last decade [2]. Oil consumption has been increased due to industrial development and population growth. One of Egypt's affronts is to satisfy the local need for fuel production among the decline of national out-put.

Fossil fuels, the major form of energy, are indeed unsustainable because of depleting supplies and their contribution to the accumulation of carbon dioxide in the environment. Egypt Climate Change Report [3] arranged by Egyptian Environmental Affair Agency stated that Egyptian dependence on fossil fuel represents 92% of the energy sector. In 2010, the recorded emission value was 275 metric tonne CO_2 equivalent sharing 0.60 % of global emissions [4].

Environmental and economic sustainability issue is enriched by renewable fuel. Biofuel seem to be an adorable alternate energy source comparable with other sorts of renewable energy. Biofuel can be used in engines that use gasoline or diesel fuel after blending with petroleum fuel in different percentages [5],[6].

The use of B100 - based on 100% biodiesel- significantly reduces carbon oxides by 48.0 %, hydrocarbons by 67.0 % and particulate emissions by 47.0 %. With respects to nitrogen oxides NOx emissions that may increase by 10.0 %. Studies have shown small variations compared to B20 - based on 20.0 % biodiesel- the change in emissions are directionally the same but smaller while NOx emissions decrease by 2.0 % [7]. Overall the scarcity of sulphur in biodiesel allows NOx purification technologies that were not viable with higher sulphur contents. Nevertheless the decreasing of the regulated emissions, biodiesel decreases the non-regulated emissions such as polycyclic aromatic hydrocarbon (PAH) by 80.0 %, nitrated PAHs by 90.0 % and ozone generating hydrocarbons by 50.0 %. These components have been identified as potential cancer causing compounds [8]. The United States Environmental Production Agency EPA mentioned that emissions diverge with the type of biodiesel source such as soybean, rapeseed, and animal fats [7].

2. BIOFUEL

Biofuel is indicated to liquid or gaseous fuels that are produced from biomass. The main distinction between biofuel and petroleum feed stocks is their oxygen constituents. Biofuel have oxygen constituents ranging from 10.0 % to 45.0 % whereas petroleum fuels have basically none. Thus; the chemical properties of biofuel and petroleum are contradicted. All biofuel have inferior sulphur levels and many of them have low nitrogen levels [9]. Liquid biofuel being considered world over fall into: bio-alcohols, biodiesel, and bio-synthetic oils [10].

The technically conversion options for biomass into biofuel can be categorized into three basic methods: chemical, thermochemical and biochemical conversion Figure-1. The desired product and the form of energy are the main factors that influence the choice of conversion process.

2.1 Biochemical conversion

Biochemical processes includes fermentation, anaerobic digestion and bio-photolysis. Large scale fermentation is used in many countries to produce ethanol from sugar crops, starch crops and cellulosic crops. The most used feedstock is corn since it contains 60 - 70 % starch [11]. Fermentation process simply is based on converting starch of the biomass into alcohol using

ARPN Journal of Engineering and Applied Sciences

enzymes or using mechanical means as ultrasonic or mechanical shear.

Research recorded significant amounts of sugar in microalgae that can be utilized as feed stock for bio-alcohol production [12], [13], [14]. Microalgae like *Chlorella, Dunaliella, Chlamydomonas, Scenedesmus, Spirulina* are known to comprise considerable quantities of starch and glycogen could be utilized as raw materials for production of ethanol Table-1.

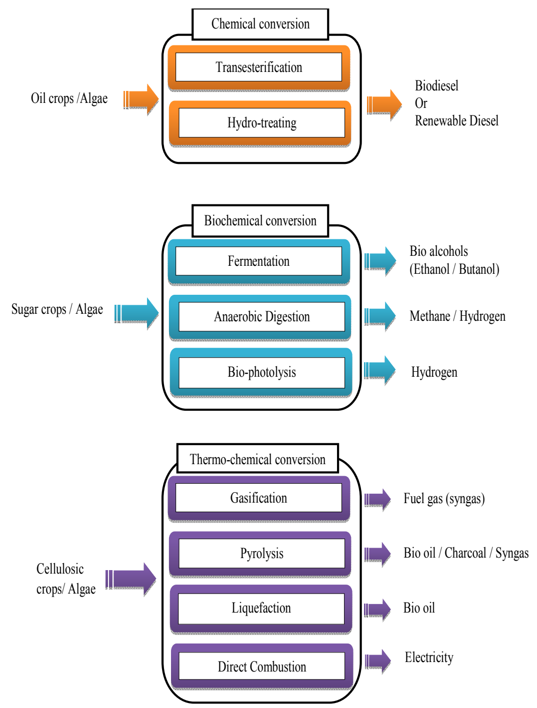

Figure-1. Technically conversion options for biomass into biofuel.

Table-1. Some algal sources for bioethanol production.

Algal species	% starch	Ref.
Chlamydomonas reinhardtii	53.00	[15]
Chlorella vulgaris	12.00 -17.00	[16]
Chlorococcum Sp.	26.00	[17]
Scenedesmus obliquus	23.70	[17]
Oscillatoriaus sp.	19.30	[17]
Phormidium angustissimum	28.50	[17]
Spirulina fusiformis	37.30 - 56.10	[18]

Microalgae accommodate cellulose which can also be fermented to bioethanol [19], while the solid residue can be used as cattle-feed [20]. Generally bioalcohol are used as a petrol additive or substitute; however alcohols can be readily ignited by hot surface. Thus the pre-ignition and knocking in engines that use alcohol makes them more dangerous than other engines [21].

The second category of biochemical conversion is anaerobic digestion. The bio-wastes can be digested with bacteria into CH_4 and CO_2 mixture called biogas [22]. Algal biomass can be used for biogas production. However ammonia is evolved due to the existence of nitrogen in algal cells that cause digestion inhibition [23], the more ammonia evolved the more digestion inhibition. The rate of digestion and biogas production is based on several factors as temperature and pH. Anaerobic bacteria withstand temperatures varying from temperatures less than freezing up to 58 °C. The best temperature conditions to grow are about 37 °C for mesophilic and 55 °C for thermophilic, while the best condition of pH ranging from 6.6 to 7.6 [24]. Anaerobic digestion of carbohydrates produces hydrogen and carbon dioxide [25]. Bio-hydrogen production can be also synthesized from mixed culture of photosynthetic anaerobic bacteria [26].

Another hydrogen production process is called biophotolysis. This process is based on evolution of hydrogen using cyan bacteria and algae. The reaction is identical to electrolysis including splitting of water into oxygen and hydrogen [27]. Pigments absorb light energy that enthuse the released electrons from water oxidation while part of light energy is stored in hydrogen gas that is evolved in so called direct biophotolysis process. There is another process called indirect biophotolysis. It is based on formation of carbohydrates followed by dark fermentation in which hydrogen is released [28].

2.2 Thermo chemical conversion

Thermochemical conversion describes the thermal decomposition of biomass by different processes such as gasification, pyrolysis, thermochemical liquefaction, and direct combustion. Generally in gasification process, the biomass is partially oxidized into a combustible gas mixture at high temperature (873 - 1073°C). This mixture is known as syngas and consists of CO, CO_2, H_2, N_2 and CH_4[29]. Gas turbines and gas engines use syngas as a fuel. This kind of fuel can be treated by denitrogenation to produce methane - rich fuel and nitrogen can be converted into ammonia fertilizer [30].

Biomass can be converted into syngas, bio-oil, and charcoal via pyrolysis at range of temperature from moderate to high temperature (350-700 °C) in the absence of air. Flash pyrolysis seems to be applicable technique for sufficient production of liquid fuels [29]. However there are technical challenges in pyrolysis oil structure. The oil produced using this process has several defects as acidity, and instability beside the formed dissolved water and solids particulate precipitant. Therefore, the processed oil requires upgrading dehydrogenation and catalytic cracking to reduce oxygen content [31]. Pyrolysis of algal biomass has achieved promising outcomes. However the yield of bio oil from pyrolysis increases with temperature up to 477°C, while the yield of charcoal decreases with increasing temperature. The yield of gaseous products of both processes increases with increasing temperature from 302 to 602 °C [31].

Liquid fuel can be synthesized from wet algal biomass via thermochemical liquefaction at temperature ranging from 273 to 350°C and pressure ranging from 5 to 20 MPa assisted by a catalyst in the existence of hydrogen. The process utilizes high amount of water in sub-critical conditions to break down biomass materials into smaller molecules own higher energy density [20], [32].

Biomass can be utilized as bio fuel directly via direct combustion. Burning biomass in the presence of air at temperature above 873°C is only viable when moisture content < 50.0 % of dry weight [20].Research on coal/algae co-firing revealed that significant reduction of Greenhouse Gas (GHG) emissions. Nevertheless the life cycle assessment (LCA) demonstrate that lower net values for SOx, NOx, particulate, CO_2, and CH_4; the fossil fuel consumption is decreased due to direct injection of flue gas into the algal ponds [33].

2.3Chemical conversion

The oil crops are considered suitable feedstock for renewable diesel and biodiesel. Renewable diesel consists mainly of paraffinic hydrocarbons, designated R100. The extracted oil from such crops can be chemically converted to renewable diesel via hydro-treating process. In this process, feedstock is reacted with hydrogen under elevated temperature and pressure in the presence of catalyst to remove sulphur, oxygen and nitrogen and convert triglycerides molecules into paraffinic hydrocarbon [34].

Transesterification is chemical process that converts triglycerides to methyl ester and glycerol as by product. Industrial process use excess amount of methanol to ensure irreversible reaction. This process is catalyzed by acid, alkali or enzymes [35]. Alkali catalyzed reaction is more rapid than the acid catalyzed reaction by about 4000 times [36], [37]. The main drawback of alkali catalysed reaction is the capability of free fatty acid saponification. For the sake of limit yield loss due to saponification reactions, oil should include least possible free fatty acids. Biodiesel is recovered by consequence washing with water to get rid of glycerol and methanol [38].

Recently the dominant feed stock used in Southeast Asia is palm oil. Rape seed is used in Europe and soybean is used in United States. While animal fats and used cooking oil provide powerful markets for biodiesel in many sites [39]. Vegetable oils have wide commercial investments as biodiesel feed stocks include camelina, canola, coconut, corn, jatropha, and safflower [40].

Oltra [9] and Huang *et al.* [41] contributions[9] revealed that the potentiality of microalgae as a source of biodiesel is comparable to other oil crops, and other microorganisms as bacteria oils and oleaginous yeast. Table-2 exhibits a comparison of different sources for the oil production.

3. MICROALGAE

Algae belong to plant kingdom. Algae are divided into macroalgae as seaweed of size over 50 µm that are classified as Eukaryotic, and microalgae that are divided into Prokaryotic blue-green algae (cyan bacteria) and Eukaryotic algae of size up to 50 µm .

The eukaryotic microalgae cell possesses a true membrane surrounding nucleus. Eukaryotic nucleus contains the main part of chromosomes and nucleolus. On the contrary, the DNA of prokaryotic cell exists free in cytoplasm and is not surrounded by a membrane. Moreover the membrane of eukaryotic cell is surrounding the constituents of the cell that are called organelles. These organelles are: Golgi body, mitochondria, endoplasmic reticulum, vacuoles, centrioles and plastids. On the other hand the prokaryotes have no membrane bounded organelles [42].

Table-2. Comparison of different sources for the oil production.

Kind of organism	Perfection	Imperfection
Micro-algae	-Fatty acid configuration is akin to most vegetable oils. - Oil content is up to 85% for some species in definite conditions. -Short time growth cycle.	-Fuel value of micro-algae lipid is less than diesel fuel. - Cultivation cost is greater than the most currently crop oils.
Bacteria	-Rapid growth rate	-Produce complicated lipids.
Yeasts	-Exist abundantly in nature. -Sufficient oil content. -Short growth cycle. -Ability to grow in harsh conditions.	-Cultivation cost is higher than the common currently crop oils.
Waste oil	-Low cost	-Contain high free fatty acids

Microalgae have different forms of cell organization. Cells may be arranged in colonies or in filamentous form. Other species may exist unicellular. Most of the unicellular prokaryotic cells are non-motile but they appear to be sliding or floating. Microalgae survive in various environmental conditions. They grow in fresh water, brackish, marine or hyper-saline. Microalgae endure an extent of temperatures and pH, and nutrient variability [43].

4. THE CHEMICAL COMPOSITION OF MICROALGAE

The chemical compositions of algae strains are different from strain to strain and from culture technique to another. This depends on cultivation factors as temperature, lightning, pH value, CO_2 supply, aeration rate, mixing velocity, and nutrient composition etc. For the sake of desired composition and sufficient algal biomass, specific cultivation conditions should be applied. These parameters could be physical as irradiance, population density, light, and dark growth; or chemical as nutrient proportions. Microalgae consist mainly of protein, carbohydrates, lipids, vitamins, and pigments.

4.1 Protein

Microalgae species is considered untraditional source of protein referring to the high constituents of amino acids. Most nutritional researches on protein concentration as a component of microalgae are based on evaluating the existing of crude protein. The results revealed that microalgae are potential for human and animal nutrition as supplements [44].

4.2 Carbohydrates

Carbohydrates are the major constituents of algae. Microalgal carbohydrates are exist in the form of cellulose, starch, sugars, and other polysaccharides [11], [17], [19].

4.3 Lipids

Microalgae main constituents are similar to higher plants. Lipids and fatty acids are parts of these components. Their existence depends on their function. Sorts of lipids exist in membranes for supporting and increase elasticity of the membrane. Other sorts of lipids with specific composition are interiors and function as storage products. The main mission of interior lipids is providing the cell by energy necessary for metabolism.

Lipids are commonly classified as polar and non-polar lipids. Most polar lipids exist in cell membrane as phospholipids and glycolipids. The non-polar lipids found mainly in the interior part of the cell. These non-polar lipids include triglycerides (TAG) and free fatty acids (FFA) [45]. The lipid content varies from strain to other. The average content is ranging from 1 to 40% of algae dry weight. Changing the cultivation conditions may increase the lipid content of some strains up to 85% of the dry weight [46].

The major quantities of carbon chains in lipid have carbon numbers ranging from C12 to C22. Shorter chain lengths exist in small quantities. While chains of carbon number less than C6 are considered free fatty acids. The moderate chain lengths C12 to C22 are suitable for biodiesel production. These carbon chains may be either saturated or unsaturated [47].

Lipid composition of algae can diverge quantitatively and/or qualitatively by altering culture conditions. Biodiesel production and fatty acid profile of the lipid are so relevant, since biodiesel properties depend upon lipid composition [48].

Saturated fatty acids award biodiesel high oxidative stability and higher cetane number. The imperfection of saturated fatty acids is the poor low-temperature properties of them. Biodiesel produced from feed stocks that contain high concentrations of poly unsaturated fatty acids have positive cold-flow properties. While, the unsaturated fatty acids are vulnerable to oxidation, and tend to be unstable for long time period of storage [49].

4.4 Vitamins

Microalgae are considered a valuable source of almost all important vitamins. Wide range of vitamins as A, B1, B2, B12, C, E, nicotinate, biotin, folic acid, or pantothenic acid exist in several species of microalgae [50]. The amount of vitamins contained in microalgae may vary by the variation of cultivation conditions. Vitamins are very sensitive to heat. Thus; vitamins instability should be taken into consideration at harvesting, drying and extraction steps.

4.5 Pigments

The microalgae color represents an indication of the pigments content. The most common pigment in all microalgae is chlorophyll that is necessary for photosynthesis. However any pigment may exist individual or combined with other types of pigments. As vitamins, pigments production is influenced by cultivation conditions. All pigments are sensitive to high temperature. Thus; mild conditions should be applied during drying and extraction.

4.5.1 Chlorophyll

The responsible pigment that absorbs light energy is chlorophyll (a) that exists in all algae. Chlorophyll (a) exists individually in Cyanobacteria and the Rhodophyta. Other taxonomy of microalgae Chlorophyta and Euglenophyta contain chlorophyll (b) in addition to chlorophyll (a). Marin algae and fresh water diatoms contain additional chlorophylls of the form (c), (d), and (e). Chlorophyll amount is ranging from 0.5 to 1.5% of algae dry weight [51].

4.5.2 Carotenoids

Carotenoids pigment exists in wide range of algae. Red algae are rich in carotenoid, while marine algae contains considerable amount of this pigment. The rest taxonomies contain significant proportion of carotenoid. In spite of some carotenoids like β-carotene, neoxanthine and violaxanthine exist in wide range taxonomy, other carotenoids are rare [52].

Carotenoids have color ranging from yellow to red. They are used widely in pharmaceuticals and medical purpose. Carotenoids are divided into two categories:

a) Oxygen-free hydrocarbons as carotenes.
b) Oxygenated derivates as the xanthophylls with ketonic, acetylene, carboxylic, hydroxy, or epoxy groups.

4.5.3Phycobiliproteins

Phycobiliproteins are deep-colored water-soluble proteinaceous accessory pigments. There are two categories of phycobiliproteins, phycoerythrobilins and phyco-cyanobilins. The phycoerythrins are divided into three different types depends on their spectrum absorption: C-phycoerythrin that exist in cyan bacteria and in Rhodophyceae, and R-phycoerythrin and B-phycoerythrin that exist in Rhodophyceae[52].

5. FACTORS AFFECTING FATTY ACID COMPOSITION

Actually algae store small quantities of triacylglycerides TAG under ordinary cultivation conditions. Optimizing the TAG content occur by modifying the growth conditions. The adjustment of the parameters of cultivation depends mainly on the desired constituents to be maximized. The stress properties may be physically or chemically [53].

Nutrient starvation acts as chemical stimuli on microalgae cultivation. The most effective nutrients are nitrogen, phosphorous and sulphur. Lipid content may increase in some species when cultivated under nitrogen starvation. Remarkable, nitrogen limitation do not affect lipid composition of cyan bacteria[50]. There are other nutrients as silicon affects specific algal species as diatoms. The major physical stimuli are light intensity and temperature where saturated fatty acids increase with increasing temperature in many algae strains, as well as lipid content increases [54].

Light intensity effect is based upon algal species and strains. Poly unsaturated fatty acid are formed at low light intensity. On the contrary, massive light intensity modifies fatty acid composition and synthesizes further mono-unsaturated and saturated fatty acids [55]. The aging of the culture influences fatty acid composition [56]

Under stress, excess electrons are generated during the photosynthesis process causing over-production of reactive oxygen. In case of non stripping oxygen, photo inhibition occur [57].

6. THE MAIN TECHNOLOGIES USED FOR MICROALGAL BIOMASS PRODUCTION

Microalgae can be cultivated out door in open culture systems which are class into natural water as lakes, and lagoons and open ponds. Microalgae can also be cultivated in controlled closed culture systems called photo bioreactors (PBRs) in which a biological controlling is achieved. However, determination of high-value products from microalgae applicable in pharmacy and cosmetic seems to be viable. These products can be obtained as microalgae cultivated in closed photo bioreactor. This system make the control of contamination easier [58].

Open ponds comprise of circular ponds with a revolving spindle to blend the culture and prevent sedimentation. Open ponds may be built in concrete or compacted earth of depth (0.2-0.5) m, and may be lined with white plastic. The difficulty to control contamination refers to the difficulty to keep the cultivation parameters constant. Highly selective conditions are essential such as pH and /or salinity in order to retard microbial contamination, so as to guarantee dominance by the selected strain [60][60]. In view of these difficulties, the closed systems PBRs are used for sensitive strains or for high value-products. Figure 2 shows the world wide technologies being used for algae bio fuel production companies [6].

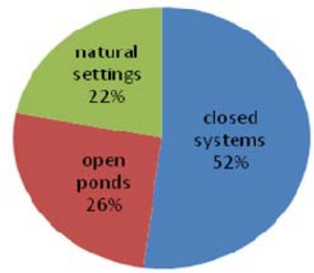

Figure-2. Worldwide technologies being used for algae bio fuel production companies.

7. GENERAL CONSIDERATION IN PBR DESIGN

7.1 Strain selection

Effective algal biotechnology relies on selecting the proper algae with related properties for certain culture conditions and desired products [61]. Fast growth encourages high biomass productivity, decrease the risk of contamination, increase yield per harvest and decrease cost [62].

Choose a species convenient to the biorefinery target by producing beneficial co-products contributes to both economic success and environmental sustainability. Nevertheless selecting species ease of harvesting reduce the cost, choosing big cell size, with specific gravity comparable to the medium and reliable auto-flocculation influence the process economics [63].

7.2 Light capturing distribution and utilization

An efficient PBR design should gather as much light as possible and spread it into the cultivation container avoiding light limitation that could occur at low light intensity or light saturation and photo-inhibition that occur when light intensity goes beyond a critical level; leading microalgae to die depending on light stress and the time of exposing to stress [64].

The visible light ranging from 400 to 700 nm is photo-synthetically active radiation. Rhyme of light/dark cycle affects the overall efficiency of solar energy capturing. Microalgae may be cultivated under flash light conditions. Cycle time might have negative effects on cell growth, but this negative effect can be eliminated by short cycle time, for example 10 s [65]. During that time, microalgae lose up to 42% of biomass produced during the daytime, so respiration during time should be minimized [66].

The transparency of PBR is an important design factor. The most selected materials used for PBR manufacture include glass, Plexiglas, polyvinyl chloride (PVC), acrylic-PVC, and most used is polyethylene. Glass is

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

strong and transparent but it is suitable for construction of small scale PBRs due to its high cost [67]. Selecting material surface has the ability to prevent the formation of bio-film is another important factor, since bio-film reduces light transmission through PBR[68].

As flat plate PBR and tubular PBR the greater surface/volume ratio, the greater light harvesting. Light attenuation is affected by high density microalgae cell. However improving mixing and limiting the length of light path are necessary for proper distribution of light [69].

7.3 CO_2/O_2balance and gas exchange

High concentration of dissolved oxygen DO is toxic to microalgal cells, since at high light intensity and high efficient photosynthesis; large amounts of oxygen radicals are produced and accumulated on the surface of the cell damaging the cytoplasmic membrane and other cellular components [70].

In phototrophic cultivation, CO_2 may be the limiting factor if CO_2 concentration is low or agitation is not enough. On the contrary high amount of dissolved CO_2 (dCO_2) is lowering culture pH. Gas stripping is necessary to achieve balance between DO and dCO_2. A consecrate space for gas exchange should be designed in photobioreactor. It is necessary to achieve proper mixing to permit mass transfer between gas and liquid phase inside photobioreactor and CO_2 enrichment and / or O_2 stripping improve the dCO_2/DO balance in algal culture [71].

7.4 Temperature

Temperature control is a significant challenge in PBR. In some cases, the temperature of media inside PBR becomes higher than the ambient temperature by 10-30 ºC. Increasing temperature relies on the dense of the culture, the depth of light path and the volume of PBR. Thus temperature is controlled by external cooling techniques as water spraying or submerging pipes in water ponds [54], [72].

7.5 pH

Microalgae withstand harsh conditions as high pH. However the proper cultivation restricted the optimum pH in the range of 7-9 for most algae species. Some species withstand different pH levels in more acid or basic ranges. Extreme pH causes culture collapse due to disruption of cellular processes [73].

7.6 Mixing

Mixing of microalgae culture is essential to avoid settling of algal cells. Moreover; the uniform distribution of substrates raises the equality of cell share. The proper mixing progress gas exchange, and facilitate uniform heat transfer. The choice of mixing method, either mechanically or using air pumping depends on the nature of the culture and the selected cultivation technique [74].

7.7 Sterility

High-value products require certain level of sterility during cultivation. Contamination by other organisms affects the quality and productivity of these products. Thus; for a desired product closed systems are recommended. Photo bioreactor cultivation faces serious problem of cleaning its walls. Culture usually stuck on the walls forming bio-film difficult to be cleaned and increase the chance of contamination [64], [70]. To increase the clean ability, the, internal surface of PBR should be smooth and the internal dimensions should be large enough to allow convenient cleaning [75].

8. PHOTOBIOREACTOR CONFIGURATIONS

Photobioreactor function requires perfect light penetration through its walls. Thus; high ratio of illuminated surface area to volume is required [76]. Several configurations of PBR have been progressed in order to achieve high surface/volume. These configurations can be grouped in three basic types [77] flat plate, tubular and fermented PBR. The flat plat and tubular PBR are designed for high capture light ability. The fermented requires artificial interior illumination. Figure 3 shows the main categories of PBR.

Most common shapes of tubular PBR are air-lift bubble column, horizontal tubular reactor, and helical tubular reactor [78]. Their structure, supplies, features, and drawbacks are illustrated in Table-3.

Life cycle assessment (LCA) has to be performed to quantify actual energy inputs in the growth of the biomass including all the energy used to make nutrients, harvest, extract oil and conversion of biomass into specific sort of biofuel. The energy used to construct, operate and maintain photobioreactors has to be taken into consideration too. In that way; the optimum conditions of operating can be achieved accompanied with the most proper structure of algal oil, biomass, and biorefineries valued products.

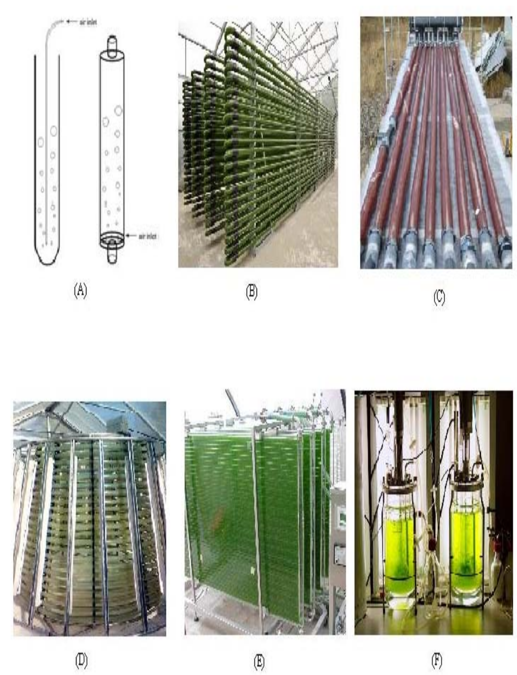

Figure-3. Main categories of photo bioreactors. (A) Air lift bubble column PBR. (B) Horizontal tubular PBR. (C) Near-Horizontal tubular PBR. (D) Helical tubular PBR. (E) Flat Plate PBR. (F) Fermenter PBR.

9. CONCLUSION AND FUTURE PROSPECTIVE

Biomass energy technologies use waste or plant matter to produce energy with a lower level of greenhouse gas emissions than fossil fuel sources. The technical conversion options for biomass into bio fuel either chemical, thermo chemical, or biochemical processes are selected according to the desired product and the required form of energy. The potential advantages of algae as feed stocks for biodiesel - as a sort of bio fuel- include their ability to synthesize and accumulate large quantities of neutral lipids 20-50% dry cell weight, and the high growth rate.

Microalgae may adapt to harsh environmental conditions, and produce value-added co-products as bioactive compounds that can be used as pharmaceutical compounds, health foods, and natural pigments. They may be cultivated in waste water using the existing nitrogen and phosphorous as nutrients; providing an additional benefit of waste water bio-remediation. Nevertheless they are able to utilize carbon dioxide from flue gases emitted from fossil fuel-fired power plants and other sources.

The choice of algal species is governed by the culture system used, resources available, location and prevailing environmental conditions, as well as the scope and aims of the individual project in question. In addition to the key indicator of lipid productivity, characteristics such as ease of cultivation, harvesting and the high-value co-products are vital to the success of any large scale algae culture.

Lipid contents, biomass, and lipid productivity are key characteristics for biodiesel production to ensure a cost effective and feasible process.

Table-3. Types of photo-bioreactor for microalgae biomass production.

Type of PBR	Structure	Supplies	Features	Drawbacks	Ref.
Tubular PBR Air-lift bubble column PBR	-Vertical transparent tubes. -Polyethylene bags	-Air compressor to insert air bubbles, while gas exchange takes place at the top vacant of the column -The tubes should be sprayed with water.	-Glass columns: high transparent and minimum fouling due to smooth surface -Plastic bags: low cost and good sterility start-up.	-Glass columns: high cost. -Plastic bags: difficult sterilization, difficult scaling up, and difficult disposal due to large quantities.	[79][80][81] [82], [83], [84]
Horizontal tubular	Parallel horizontal transparent tubes made of flexible plastic connected by PVC manifold.	-The tubes should be immersed or sprayed with water. -Need temperature controller	Can be scaled-up for high productivity.	The algal strain should tolerate high temperature like *spirulina*	[84], [85][86][87] [88]
Helical tubular	Flexible plastic tubes coiled in a circular frame work	-Gas exchange tower -Heat exchange system -Centrifugal pump to derive the broth through long tubes to the gas exchange tower	Out-door PBR with high productivity.	System is not suitable for all algal species due to damage cells by recirculation pump and fouling.	[89][90][91] [92]
Flat Plate	Narrow panels with bottom inlet air tubes	-Air compressor. -A closed system of water spraying to control temperature.	-Efficient use of sun light. -High surface area/ volume -High productivity. -No driving pumps.	High oxygen build-up due to high photo-synthetic rates.	[93], [94][95], [96][97]
Fermenter Type	Transparent fermented vessel use both sun light and artificial light	-Internal illumination system. -Internal mechanical stirrer. -Bottom inlet air tubes.	Operation parameters could be fully controlled.	-Low area/volume. -Poor sunlight harvesting efficiency.	[94], [95], [96]

Resistance to contamination, tolerance of operating conditions such as light, temperature, ionic strength and flue gas toxins, nutrient requirements, as well as ease of harvesting impact the success of large scale culture. However this information should be updated with respect to characterizing optimum growth conditions, measuring growth rates under different conditions e.g.; nitrogen deprivation that enhance lipid content, measuring lipid productivity under outdoor conditions (fluctuating temperatures and light intensities), determining the resilience of species by measuring the range of environmental conditions (e.g.; pH, temperature, nutrient levels, CO_2 levels, light.. etc) within which the algae remains productive and determining ease of algal cell harvesting. The evaluation of energy and emission balance for bio fuel production and use is essential to the identification of energy utilization and emissions reductions. Globally, LCA pilot scale studies are scarce as a consequence of a lack of multidisciplinary approach and insufficient novel technologies available in the public domain. Current research should aim to implement the algal biosynthetic strains in different environments and develop proper biotechnologies convenient to local strains.

ACKNOWLEDGEMENT

ARPN Journal of Engineering and Applied Sciences

The authors wish to thank Prof. Dr.Gamila Ali, Water Pollution Department, Environmental Research Division NRC, Prof. Dr.Guzine El-Diwani and Dr.Sanaa Abo El-Enin, Chemical engineering and Pilot Plant Department, Engineering Research Division, NRC. This work was supported in part by a grant from the project of STDF (Use of Egyptian National Resources to Produce Biodiesel for Jet Fuel Blends) for the financial support.

REFERENCES

[1] Egypt Energy Data, Statistics and Analysis - Oil, Gas, Electricity, Coal: Energy Information Administration [Internet]. 2012 [updated 2012 Jul 18; cited 2012 Nov 19]. Available from: http://www.eia.gov/cabs/egypt/full.html.

[2] BP Statistical Review of World Energy. 63rd edition [Internet]. June 2014. Available from: http://www.bp.com/statisticalreview.

[3] Egypt Climate Change. Egyptian Environmental Affair Agency. Ministry of State for Environmental Affairs [Internet] 2012. Available from: http://www.eeaa.gov.eg/ecc/climate.

[4] Egypt GHG emissions, reduction strategy. Mckinsey and company modernization program. Industrial Modernization Programme [Internet]. Jan 2012. Available from: http://www.imc-egypt.org.

[5] Sing A, Olsen S I. 2011. Critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. ApplEnerg. 88: 3548-3555.

[6] Singh J, Gu S. 2010. Commercialization potential of microalgae for biofuels production. Renew SustEnerg Rev. 14: 2596-2610.

[7] A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions-draft Technical Report. US EPA. October 2002; EPA420-P-02-011. Available from http://www.epa.gov.

[8] Biodiesel Emissions Overview. In: The Impact on California Air Quality [Internet]. 2004[cited 2012 Apr 16]. Available from: http://www.crimsonrenweable.com.

[9] Oltra C. 2011. Stakeholder perceptions of biofuels from microalgae. Energ Policy. 39: 1774-1781.

[10] Vasudevan P, Sharma S, Kumar A. 2005. Liquid fuel from biomass: an overwiew. J SciInd Res. 64: 822-31.

[11] Demirbas A. 2009. Fuel from Biomass. In: Biohydrogen: For Future Engine Fuel Demands. 12th ed. Springer.pp. 43-59.

[12] Huntley M, Redalje D G. 2007. CO2 Mitagation and renewable oil from photosynthetic microbes: A new appraisal. Mitigat Adapt Strat Global Change. 12: 573-608.

[13] Rosenberg J N, Oyler G A, Wilkinson L, Betenbaugh M J. 2008. A green light for engineered algae: Redirecting metabolism to fuel a biotechnology revolution. Biotechnology. 19: 430-436.

[14] Subhadra B, Edwards M. 2010. An integrated renewable energy park approach for algal bio fuel production in United States. Energy Policy. 38: 4897-4902.

[15] Kim M S, Bea k J S, Yun Y S, Sim S J, Park S, Kim S C. 2006. Hydrogen production from ClamydomonasReinjardtii biomass using a two-step conversion process: anaerobic conversion and photosynthetic fermentation. Int J Hydrogen Energy. 31: 812-816.

[16] Spolaore P, Joannis-Cassan C, Duran E, Isambert A. 2006. Review: Commercial application of microalgae. J BiosciBioeng. 101: 87-96.

[17] Rodjaroen S, Juntawong N, Mahakhant A, Miyamoto K. 2007. High biomass production and starch accumulation in native green algal strains and cyanobacterial strains of Thailand Kasetsart. J Nat Sci. 41: 570-575.

[18] Rafiqul I M, Hassan A, Sulebele G, Orosco C A, Roustaian P, Jalal K C A. 2003.Salt stress culture of blue-green algae Spirulinafusiformis. Pakistan J Biol Sci. 6: 648-650.

[19] Chen P, Min M, Chen Y, Wang L, Li Y, Chen Q, et al. 2009. Review of the biological and engineering aspects of algae to fuels approach. Int J AgricBiol Eng. 2: 1-30.

[20] McKendry P. 2002. Energy production from biomass (part 2): Conversion technologies. Bioresour Technol. 83: 47-54.

[21] Kim S, Dale B E. 2005. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. Biomass Bioenerg. 29: 426-439.

[22] Mussgnug J H, Klassen V, Schluter A, Kruse O. 2010. Microalgae as substrates for fermentative biogas production in a combined biorefinery concept. J Biotechnol. 150: 51-56.

[23] Demirbas A. 2010. Use of algae as bio fuel sources. Energ Convers Manage. 51: 2738-2749.

[24] Demirbas A. 2008. Biofuels sources, bio fuel policy, bio fuel economy and global bio fuel projections. Energ Convers Manage. 49: 2106-2116.

[25] Nath K, Das D. 2003. Hydrogen from biomass. Current Sci. 85: 265-271.

[26] Hallenbeck P C. 2011. Hydrogen Production by Cyanobacteria. In: Microbial technologies in advanced biofuels production. Springer.pp. 15-28.

[27] Carlozzi P, Buccioni A, Minieri S, Pushparaj B, Piccardi R, Ena A, etal. 2010. Production of bio-fuels (hydrogen and lipids) through a photofermentation process. Bioresource Technol. 101: 3115-3120.

[28] Takahashi P. 2007.Biophotolysis-based Hydrogen Production by Cyanobacteria and Green Microalgae In: Communicating Current Research and Educational Topics and Trends in Applied Microbiology. Mendez A-Vilas (Ed.).pp. 79-89.

[29] Clark J, Deswarte F. 2008. Introduction to chemicals from biomass. Wiley Series in Renewable Resources: John Willey and Sons.

[30] Minow T, Sawayama S. 1999. A novel microalgal system for energy production with nitrogen cycling. Fuel. 78(10): 1213-1225.

[31] Demirbas A. 2001. Biomass resources facilities and biomass conversion processing for fuels and chemicals. Energ Convers Manage. 42(11):1357-1378.

[32] Wahlen B D, Willis R M, Seefeldt L C. 2011. Biodiesel production by simultaneous extraction and conversion of total lipids from microalgae, cyan bacteria, and wild mixed-cultures. Bioresource Technol. 102: 2724-2730.

[33] Kadam K L. 2002. Environmental implications of power generation via coal-microalgae co-firing. Energy. 27: 905-922.

[34] Kalnes T, Marker T, Shonnard D R. 2007. Green diesel: A second generation bio fuel. Int J Chem React Eng. 5(1): DOI: 10.2202/1542-6580.1554.

[35] Vasudevan P T, Briggs M. 2008. Biodiesel production-current state of the art and challenges: Review. J IndMicrobiolBiotechnol. 35: 421-430.

[36] Keera S T, El-Sabagh S M, Taman A R. 2011.Transesterification of vegetable oil to biodiesel fuel using alkaline catalyst. Fuel. 90: 42-47.

[37] Yu J and Yucel S, Terzioglu P, Ozçimen D. 2012. Lipase applications in biodiesel production. Chapter 8. In: Zhen Fang editor. Biodiesel - Feedstocks, Production and Applications. In Tech Published.

[38] 2012. Production of Biodiesel from Algae in Selected Mediterranean Countries, Med-Algae. Project Reference Number: I-B/2.2/099.

[39] Investigation of biodistillates as potential blend stocks for transportation fuels. (June) 2009; CRC Report No. AVFL-17. Coordinating Research Council Inc.

[40] Li Y, Horsman M, Wu N, Lan C Q, Calero N D. 2008. Biofuels from Microalgae. Biotech Progress. 24: 815-820.

[41] Huang G, Chen F, Wei D, Zhang X, Chen G. 2010. Biodiesel production by microalgal biotechnology. ApplEnerg. 87: 38-46.

[42] Tomaselli L. 2004. The microalgal cells. Chapter 8. In: Richmond A. editor. Handbook of Microalgal Culture: Biotechnology and Applied Phycology. In Blackwell Publishing. DOI: 10.1002/9780470995280.ch1.

[43] HamedA F, Salem B, Abd El-Fatah H M. 2007. Floristic survey of blue-green algae/cyan bacteria in saline-alkaline lakes of Wadi El-Natrun (Egypt) by remote sensing application. J ApplSci Res. 3(6): 495-506.

[44] Bourges H., Sotomayor A., Mendoza E. and Chavez A. 1971. Utilization of alga Spirulina as a protein source. Nutr. Rep. Int. 4, 31-43.

[45] Fahy E, Subramaniam S, Murphy R C, Nishijima M, Raetz C R H, Shimizu T, et al. 2009. Update of the lipid maps comprehensive classification system for lipids. J Lipid Res. 50: S9-S14.

ARPN Journal of Engineering and Applied Sciences

[46] Chisti Y. 2007. Biodiesel from microalgae: research review paper. Biotechnol Adv. 25: 294-306.

[47] Menetrez M Y. 2012. An overview of algae bio fuel production and potential environmental impact. Environ Sci Technol. 46: 7073-7085.

[48] Huesemann M H, Van Wagenen J, Miller T, Chavis A, Hobbs S, Crowe B. 2013. A screening model to predict microalgae biomass growth in photo bioreactors and raceway ponds. BiotecholBioeng. 110(6): 1583-1594.

[49] Zendejas F J, Benke P I, Lane P D, Simmons B A, Lane T W. 2012. Characterization of the acylglycerols and resulting biodiesel derived from vegetable oil and microalgae (Thalassiosirapseudonana and Phaeodactylumtricornutum). BiotechnolBioeng. 109(5): 1146-1154.

[50] Becker, E.W. (ed.) 1994. Microalgae-Biotechnology and Microbiology. Cambridge University Press, Cambridge. Becker, E.W. (ed.) (1994) Microalgae-Biotechnology and Microbiology. Cambridge University Press, Cambridge.

[51] Maclachlan S, Zalik S. 1963. Plastid Structure, Chlorophyll Concentration, and Free Amino Acid Composition of a Chlorophyll Mutant of Barley. Canadian Journal of Botany. 41(7): 1053-1062, 10.1139/b63-088.

[52] Mulders K J M, Lamers P, Martens D E, Wijffels R H. 2014. Phototrophic Pigment Production with Microalgae: Biological Constraints and Opportunities. J. Phycol. 50, 229-242. Doi: 10.1111/Jpy.12173

[53] Widjaja A. 2009. Lipid production from microalgae as a promising candidate for biodiesel production. MakaraTeknologi. 13(1): 47.

[54] Sterner R W, Grover J P. 1998. Algal growth in warm temperate reservoirs: Kinetic examination of nitrogen, temperature, light, and other nutrients. Wat Res. 32(12): 3539-3548.

[55] Ogbonda K H, Aminigo R E, Abu G O. 2007. Influence of aeration and lighting on biomass production and protein biosynthesis in a Spirulina Sp. isolated from an oil-polluted brackish water marsh in The Niger Delta, Nigeria. African Journal of Biotechnology. 6(22): 2596-2600.

[56] Ahmed F, Li Y, Schenk P M. 2012. Algal biorefinery: Sustaiable production of biofuels and aquaculture feed. Chapter 3 In: Gordon R, Seckbach J editors. The Science of Algal Fuels: Phycology, Geology, Biophotonics, Genomics and Nanotechnology. Dordrecht; New York: Springer.

[57] Zhu X G, Long S P, Ort D R. 2008. What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? CurrOpinBiotechnol. 19:153-159.

[58] Pluz O. 2001.Photobioreactors: Production systems for phototrophic microorganisms. ApplMicrobiolBiotechnol. 57: 287-293.

[59] Thomas R, Cole J V. 2011. Engineering design of algal production systems. CFD Research Corporation. NFS-CMMI workshop.

[60] Radmann E M, Reinehr C O, Costa JAV. 2007. Optimization of the repeated batch cultivation of microalga SpirulinaPlatensis in open raceway ponds. Aquaculture. 265: 118-126.

[61] Rodolfi L, Zittelli G C, Bassi N, Padovani G, Biondi G, Tredici M R. 2009. Microalgae for oil: Strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photo bioreactor. BiotechnolBioeng. 102: 100-112.

[62] Griffiths M J, Harrison S T L. 2009. Lipid productivity as a key characteristic for choosing algal species for biodiesel production. J ApplPhycol. 21: 493-507.

[63] Ryan C. 2009. The promise of algae biofuels: Cultivation clean energy: Natural Resources Defense Council NRDC (US).

[64] Wang B, Lan C Q, Horsman M. 2012. Closed photo bioreactor for production of microalgal biomasses. Biotechnol Adv. 30(4):904-912.

[65] Grobbelaar J U, Nedbal L, Tichy V. 1996. Influence of high frequency light/dark fluctuations on photosynthetic characteristics of microalgae photoacclimated to different light intensities and implications for mass algal cultivation. J ApplPhycol. 8: 335-343.

[66] Wilhelm C, Jakob T. 2011. From photons to biomass and biofuels evaluation of different strategies for the improvement of algal biotechnology based on

comparative energy balances. ApplMicrobiolBiotechnol. 92:909-919.

[67] Zittelli G C, Rodolfi L, Biondi N, Tredici M R. 2006. Productivity and photosynthetic efficiency of outdoor cultures of TetraselmisSuecica in annular columns. Aquaculture. 261: 932-943.

[68] Suh I S, Lee S B. 2003. A Light distribution model for an internally radiating photo bioreactor. BiotechnolBioeng. 82(2): 180-189.

[69] Zijffers J W F, Schippers K J, Zheng K, Janssen M, Tramper J, Wijffels R H. 2010. Maximum photosynthetic yield of green microalgae in photo bioreactors. Mar Biotechnol. 12:708-718.

[70] Zheng Y, Chen Z, Lu H, Zhang W. 2011. Optimization of carbon dioxide fixation and starch accumulation by TetraselmisSubcordiformis in a rectangular airlift photo bioreactor. African J Biotechnol. 10(10): 1888-1901.

[71] Kliphuis A M J, Martens D E, Janssen M, Wijffels R H. 2011. Effect of O_2:CO_2 ratio on the primary metabolism of ChlamydomonasReinhardtii. BiotechnolBioeng. 108: 2390-2402.

[72] Araujo S, Garcia V M. 2005. Growth and biochemical composition of the diatom Chaetoceros cf. WighamiiBrightwell under different temperature, salinity and carbon dioxide levels, protein, carbohydrates and lipids. Aquaculture. 246: 405-412.

[73] Hargreaves J W, Whitton B A. 1976. Effect of pH on growth of acid stream algae. Br Phycol J. 11: 215-223.

[74] Janssen M, Bresser L, Baijens T, Tramper J, Mur L R, Snel J F H, *et al.* 2000. Scale-up aspects of photo bioreactors: effects of mixing-induced light/dark cycles. J ApplPhycol. 12: 225-237.

[75] Posten C. 2009. Design principles of photo-bioreactors for cultivation of microalgae. Eng Life Sci. 9(3): 165-177.

[76] Sastre R, Csogor Z, Perner-Nochta I, Fleck-Schneider P, Posten C. 2007. Scale-down of microalgae cultivations in tubular photo bioreactors: A conceptual approach. J Biotechnol. 132: 127-133.

[77] Itoiz E S, Grunewald C F, Gasol C M, Garces E, Alacid E, Rossi S, *et al*. 2012. Energy balance and environmental impact analysis of marine microalgal biomass production for biodiesel generation in a photo bioreactor pilot plant. Biomass Bioenergy. 39: 324-335.

[78] Loubiere K, Olivo E, Bougaran G, Pruvost J, Robert R, Legrand J. 2009. A new photo bioreactor for continuous microalgal production in hatcheries based on external-loop airlift and swirling flow. BiotechnolBioeng. 102: 132-147.

[79] Arudchelvam Y, Nirmalakhandan N. 2012. Optimizing net energy gain in algal cultivation for biodiesel production. Bioresour Technol. 114: 294-302.

[80] Merchuk J C, Wu X. 2003. Modeling of photo bioreactors: Application to bubble column simulation. J ApplPhycol. 15: 163-169.

[81] Benemann J. 2008. 5th Annual World Congress on Industrial Biotechnology and Bioprocessing, Chicago, April 30. Open ponds and closed photo bioreactors-comparative economics.

[82] Lebeau T, Robert J M. 2003. Diatom cultivation and biotechnologically relevant products. Part I: Cultivation at various scales. ApplMicrobiolBiotechnol. 60: 612-623.

[83] Fernandez F G A, Camacho G, Perez J A S, Sevilla J M F, Grima E M. 1998.Modeling of biomass productivity in tubular photo bioreactors for microalgal cultures: Effects of dilution rate, tube diameter, and solar irradiance. BiotechnolBioeng. 58(6): 605-616.

[84] Wu L B, Song Y Z. 2009. Numerical investigation of flow characteristics and irradiance history in a novel photo bioreactor. African J Biotechnol. 8(18): 4672-4679.

[85] Ozkan A, Kinney K, Katz L, Berberoglu H. 2012. Reduction of water and energy requirement of algae cultivation using an algae biofilm photo bioreactor. Bioresour Technol. 114: 542-548.

[86] Briassoulis D, Panagakis P, Chionidis M, Tzenos D, Lalos A, Tsinos C, *et al*. 2010. An experimental helical-tubular photo bioreactor for continuous production of Nannochloropsis sp. Bioresour Technol. 101: 6768-6777.

[87] Mulumba N, Farag I H. 2012. Tubular photo bioreactor for microalgae biodiesel production. IJEST. 4(2): 703-709.

[88] Morita M, Watanabe Y, Okawa T, Saiki H. 2001. Photosynthetic productivity of conical helical tubular photo bioreactors incorporating Chlorella Sp. under various culture medium flow conditions. BiotechnolBioeng. 74(2):136-44.

[89] Jason L D, Carl L W. 2011. V-Trough photo bioreactor system and method of use. Patent US20110258920 A1.

[90] Hsieh C H, Wu W T. 2009. A novel photo bioreactor with transparent rectangular chambers for cultivation of microalgae. BiochemEng J. 46: 300-305.

[91] Sierra E, Acien F G, Fernandez J M, Garcia J L, Gonzalez G, Molina E. 2008. Characterization of a flat plate photo bioreactor for the production of microalgae. ChemEng J. 138: 136-147.

[92] Lee Y K, Ding S Y, Low C S, Chang Y C, Forday W L, Chew P C. 1995. Design and performance of α a-type tubular photo bioreactor for mass cultivation of microalgae. J ApplPhycol. 7: 47-51.

[93] El-Shishtawy R M A, Kawasaki S, Morimoto M. 1997. Biological H2production using a novel light-induced and diffused photoreactor. Biotechnol Tech. 11(6): 403-407.

[94] Xiong W, Li X, Xiang J, Wu Q. 2008. High-density fermentation of microalga chlorella protothecoides in bioreactor for microbio-diesel production. ApplMicrobiolBiotechnol. 78: 29-36.

[95] Borowitzka M A. 1999. Commercial production of microalgae: Ponds, tanks, tubes and fermenters. J Biotechnol. 70: 313-321.

[96] Ogbonna J C, Soejima T, Tanaka H. 1999.An integrated solar and artificial light system for internal illumination of photo bioreactors. J Biotechnol. 70: 289-297.

[97] Yang S T. 2011. Bioprocessing for value-added products from renewable resources: New technologies and applications. Elsevier Publishing.