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Algal Biorefinery: a Road towards Energy Independence and Sustainable Future

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Abstract – *The most important renewable resource on this planet is biomass. As the value of biomass content is related to the chemical and physical properties of large molecules, the challenges for the future are to be found in a combination of the biological, physical and chemical sciences, to replicate an oil refinery with a biorefinery thus replacing finite non-renewable fossil resources with biorenewable biomass resources for the production of food, feed, fertilizer, fuel, energy, medicinal products, industrial chemical and related consumer product through the use of clean and green bioprocess technologies. Algal biorefineries offer significant potential for future supply of oils, protein, and carbohydrates for fuels and chemicals without impacting food supplies. The residual biomass from biodiesel production processes can be used potentially as animal and fisheries feed and after anaerobic digestion can be used as fertilizers in the form of compost. Even it could solve the problem of huge carbon emission from thermal power plant by recycling the carbon. The simple, direct method of greenhouse gas (GHG) mitigation is the removal of CO_2 from stack gases, followed by long term sequestration of CO_2 by microalgae ponds. Thus the microalgal biodiesel projects can qualify as clean development mechanism (CDM) projects and bring in additional income through the sale of certified emission reductions (CER). Microalgal biorefinery concept could become a highly distributed source of fuel oil, energy, feed, fertilizer and medicinal metabolites and perhaps make this world pollution free and leap towards sustainable development.*

***Keywords**: Algae, Biodiesel, Biomass, Biorefinery, Carbon Sequestration, Fuel*

I. Introduction

A need of sustainable energy resources currently threatens the survival of an increasingly globalized world economy. Continued use of petroleum-based fuels is now widely recognized as unsustainable because of depleting supplies and contribution of these fuels to pollute the environment. Steady increases in the price of raw materials such as crude oil are forecast, due to rising demand from developing countries and escalating scarcity of reserves. Also, the increasing accumulation of CO_2 in the atmosphere and its impact on climate change has provided a significant driver for change. Amid growing concern, global agreements to limit greenhouse gas (GHGs) emissions have been formed such as the Kyoto Protocol. Directly resulting from such agreements, many developed countries have adopted 'cap-and-trade' carbon trading schemes in efforts to curb emissions. Thus projects which capture CO_2 and prevent it being released into the atmosphere will play a significant role in combating climate change. While the 20^{th} century saw the emergence and establishment of an organic chemical manufacturing industry based on petroleum refining, the 21^{st} century will see the development of a new organics industry based on biomass refining. In both scenarios the driver is energy. The enormous demand for petroleum as a cheap, single-use fuel gave chemical manufacturing a large volume, low cost and continuous supply of hydrocarbons from which the petrochemical industry was built; chemical and engineering technology for cracking, separating, rearranging, polymerizing and functionalizing allowed us to take complex mixtures of simple chemicals and transform them into a multitude of higher value molecules with a seemingly never-ending range of applications from high volume, low cost plastics to small volume but highly expensive drugs. We are now at the beginning of an era where new, renewable sources of energy are sought with increasing vigor; biomass, renewable carbon, is guaranteed a place in the new energy portfolio for the foreseeable future [1]-[3].

II. World's Fuel Scenario

Over 1.5 trillion barrels of oil equivalent have been produced since Edwin Drake drilled the world's first oil well in 1859. The world will need that same amount to meet demand in the next 25 years alone. The International Energy Agency (IEA) has reported in the reference scenario that the world's primary energy need is projected to grow by 55% between 2008 and 2030, at an average annual rate of 1.8 % per year. Demand reaches 17.7 billion tonnes of oil equivalent, compared with 12.4 billion tonnes in 2008. Energy and Capital have reported that, by 2025, the world's demand for oil will shoot 60%, while production capacity would be thrown back to 1985 levels. According to the Energy Information Agency (EIA) report, petroleum consumption falls by 90,000 barrels per day in 2008-2009. China's annual oil consumption growth rate is of 7.5% and India's of 5.5% and both are expected to take quantum leap over the next decade [4]. If the governments around the world stick to current policies, the world will need almost 60% more energy in 2030 than today, of this 45% will be accounted by China and India together. Transportation is one of the fastest growing sectors using 27% of the primary energy. At the present staggering rates of consumption, the world fossil oil reserve will be exhausted in less than 45 years [10].

Renewable and carbon neutral biofuel are necessary for environmental and economic sustainability. Biofuels such as biodiesel and bioethanol have been proposed as possible alternative renewable fuels. Unfortunately biofuel produced from oil crop, waste cooking oil and animal fats are not able to replace fossil fuel. The viability of the first generation biofuels production is however questionable because of the conflict with food supply. Production of biofuel using microalgae biomass appears to be a viable alternative and algal biorefinery approach give us a feasible economy and endow with fuel for sustainable future.

III. Biorefinery Concept

The biorefinery concept is analogous to today's petroleum refinery, which produce multiple fuels and products from petroleum. A Biorefinery is collection of processes that utilizes a renewable biological source to produce an end product, that is a zero-waste producing, and whereby each component of the renewable biological or bio-based source, or a product there from, is converted or utilized in a manner to add value, and hence sustainability to the plant. By producing multiple products, a biorefinery takes advantage of the various components in biomass and their intermediates therefore maximizing the value derived from the biomass feedstock. Algal biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and value added chemicals from algal biomass. Algal biorefinery could, for example, produce one or several low volume, but high value, chemical or nutraceutical products and a low value, but high volume liquid transportation fuel such as biodiesel or bioethanol. At the same time generating electricity and process heat, through combined heat and power (CHP) technology, for its own use and perhaps enough for sale of electricity to the local utility. Multidisciplinary collaborative research program has emerged in order to develop innovative technologies for the economical and sustainable production of biofuels and other bioproducts from microalgae. Fast growing microalgae are efficient converters of solar energy and carbon dioxide, thereby producing many times the biomass per unit area of land when compared to terrestrial plants. These photosynthetic microorganisms have great potential to be the solution to the growing energy and environmental challenges, as a more efficient method for bioenergy production and a practical and environmentally responsible method for carbon dioxide sequestration [4].

IV. Algae as Best Feedstock for Biorefinery

Algae having ability to synthesize triacylglycerols (TAGs) consider as a second generation feedstock for production of biofuels. The potential value of microalgal photosynthesis to produce biofuels is widely recognized [4]–[7].

The advantages of microalgae over any other biomass as a source of transportation biofuels are numerous:

1. Microalgae synthesize and accumulate large quantities of neutral lipids/oil (20–50% dry cell weight) and grow at high rates (e.g. 1–3 doublings per day).
2. Oil yield per area of microalgae cultures could greatly exceed the yield of best oilseed crops.
3. Microalgae can be cultivated in saline/brackish water/coastal seawater on non arable land, and do not compete for resources with conventional agriculture.
4. Microalgae tolerate marginal lands (e.g. desert, arid- and semi-arid lands) that are not suitable for conventional agriculture.
5. Microalgae utilize nitrogen and phosphorus from a variety of wastewater sources (e.g. agricultural run-off, concentrated animal feed operations, and industrial and municipal wastewaters), providing the additional benefit of wastewater bioremediation.
6. Microalgae sequester carbon dioxide from flue gases emitted from fossil fuel-fired power plants and other sources, thereby reducing emissions of a major greenhouse gas. 1 kg of algal biomass requiring about 1.8 kg of CO_2 [9].
7. Microalgae produce value-added co-products or by-products (e.g. biopolymers, proteins, polysaccharides, pigments, animal feed and fertilizer) and do not need herbicide and pesticide.
8. Microalgae grow in suitable culture vessels (photo-bioreactors) throughout the year with higher annual biomass productivity on an area basis.

The oil productivity of many microalgae exceeds the best producing oil crops.

Microalgae are photosynthetic microorganism which converts sunlight, water and CO_2 to sugars, from which macromolecules, such as lipids and triacylglycerols (TAGs) can be obtained. These TAGs are the promising and sustainable feedstock for biodiesel production [4]. However, cultivating algae only for biodiesel is not economically viable in the current environment because it provides higher costs when comparing with conventional fuels [8]. There are four stages involved in microalgal biodiesel production system includes cultivation, dewatering, extraction and transesterification. Each of the stages requires higher energy that need to be consumed thus contributes in higher production cost. Microalgal biorefinery approach can be used to reduce the cost of making microalgal biodiesel. Microalgal-based carbon sequestration technologies cover the cost of carbon capture and sequestration. The general concept of the proposed system is illustrated in (see Fig. 1).

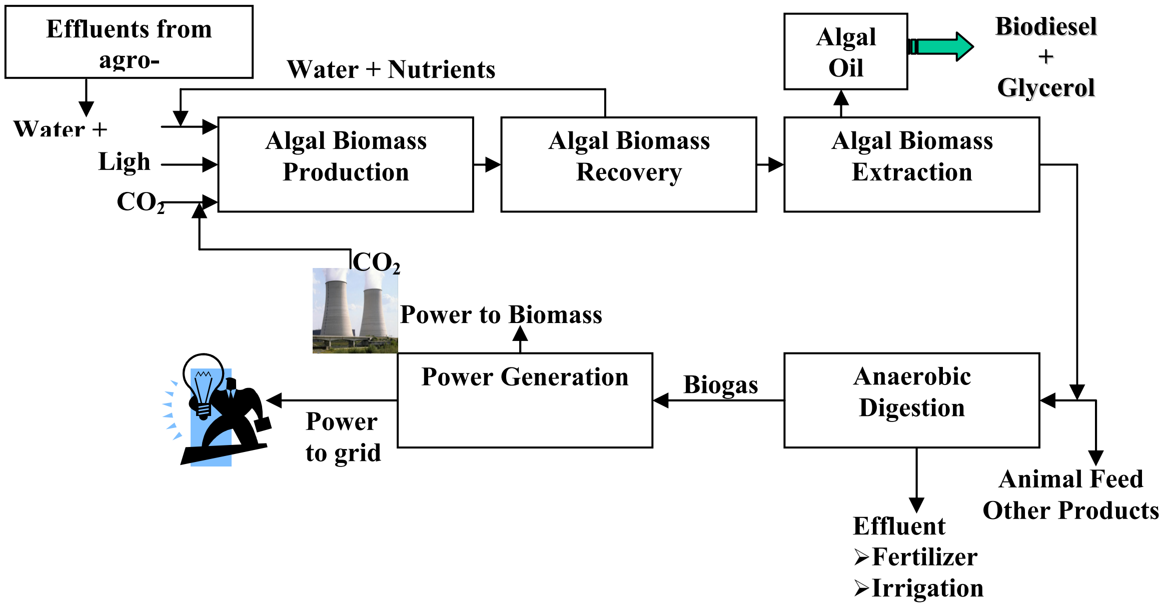

Fig. 1. A conceptual process of Algal Biorefinery for better economy

V. Microalgal Biomass Production

Conventional open pond algal production systems are very old and now some recent closed photobioreactors have been developed for continuous and increased biomass production. The vast bulk of microalgae cultivated today are grown in open ponds. Open ponds can be built and operated very economically and hence offer many advantages as long as the species for cultivation can be maintained. Producing microalgal biomass is generally more costly than growing crops. To minimize expense, biodiesel production must rely on freely available sunlight, despite daily and seasonal variations in light levels which are easily available in India. In open pond method, fresh culture medium is fed at a constant rate and the same quantity of microalgal broth is withdrawn continuously. Feeding ceases during the night, but the mixing of broth continue to prevent settling of the biomass [11]. There are three potential and very common methods of large-scale production of microalgae:

- ***Open ponds/ Raceway ponds***

Open ponds have a variety of shapes and sizes but the most commonly used design is the raceway pond. It is a closed loop of rectangular grid with recirculation channel. They usually operate at water depths of 15–20 cm, as at these depths biomass concentrations of 1 g dry weight/L and productivities of 60-100 mg/L/day can be obtained [12]. There is a paddlewheel, which mix and circulate the algal biomass as shown in figure 2. Flow is guided around bends by baffles positioned in the flow channel. Raceway channels are built in concrete or compacted earth, it can be of different length and diameter and generally lined with white plastic. During daylight, the culture is fed continuously in front of the paddlewheel where the flow begins. Broth is harvested behind the paddlewheel, on completion of the circulation loop. The paddlewheel operates all the time to prevent sedimentation. The main disadvantage of open systems is that by being open to the atmosphere, they loose water by evaporation at a rate similar to land crops and are also susceptible to contamination by unwanted species. In practice open ponds are usually reported to be dominated by two to six species with a range of evolutionary advantages; rapid growth, resistance to predators, tolerance to high levels of dissolved oxygen, etc.

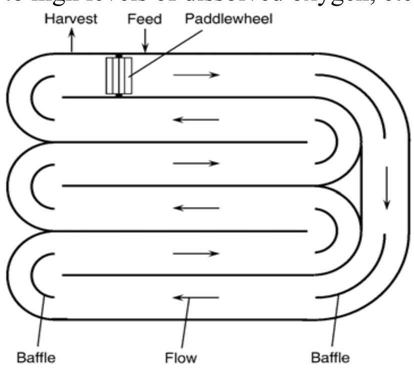

Fig. 2. A Raceway Pond

Raceways are perceived to be less expensive than photobioreactors, because they cost less to build and operate. Economically, open pond system of biomass production is 10 time less costly in comparison to photobioreactors [13]. Although raceways are low-cost, they have a low biomass productivity compared with photobioreactors. There is need to approve the raceway pond system of biomass culture to achieve high and sustained growth rates and oil yields that is essential to developing an algal-based biofuel industry.

- ***Closed bioreactors***

Closed bioreactors support up to fivefold higher productivity with respect to reactor volume and consequently have a smaller "footprint" on a yield basis. Besides saving water, energy and chemicals, closed bioreactors have many other advantages which are increasingly making them the reactor of choice for biofuel production, as their costs are reduced [14]. Closed bioreactors permit essentially single-species culture of microalgae for prolonged durations. Most closed bioreactors are designed as tubular reactors, plate reactors, or bubble column reactors. Other less common designs like semi-hollow-spheres have been reported to run successfully.

The most common type of closed bioreactor is tubular photobioreactor. Tubular photobioreactor consists of an array of straight transparent tubes that are usually made of plastic or glass. The solar collector tubes are generally 0.1 meter diameter or less in diameter because light does not penetrate too deeply in the dense culture broth that is necessary for ensuring a high biomass productivity of the photobioreactor. Microalgal broth is circulated from a reservoir (i.e. the degassing column in Fig. 3) to the solar collector and back to the reservoir [5].

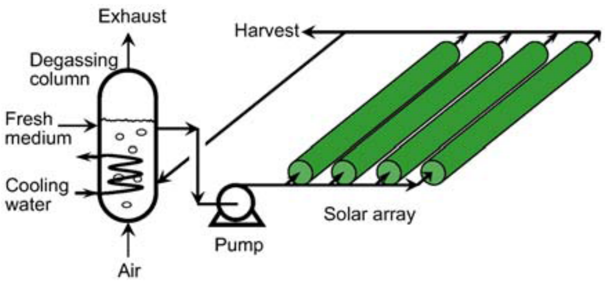

Fig. 3. A tubular photobioreactor with parallel run horizontal tubes

- ***Hybrid systems***

In this case both open ponds as well as closed bioreactor system used in combination to get the better results. Open ponds are a very proficient and lucrative method of cultivating algae, but they become contaminated with superfluous species very quickly. A combination of both systems is probably the most logical choice for cost-effective cultivation of high yielding strains for biofuels. Open ponds are inoculated with a desired strain that was invariably cultivated in a bioreactor, whether it be as simple as a plastic bag or a high tech fiber optic bioreactor. Importantly, the size of the inoculums needs to be large enough for the desired species to establish in the open system before an unwanted species. Therefore to minimize contamination issues, cleaning or flushing the ponds should be part of the aquaculture routine, and as such, open ponds can be considered as batch cultures. This process has been demonstrated by Aquasearch (Hawaii, USA) cultivating *Haematococcus pluvialis* for the production of astaxanthin. Half of the Aquasearch facility was devoted to photobioreactors and half to open ponds. *H. pluvialis* is grown continuously in photobioreactors under nutrient sufficient conditions and then a portion is transferred to nutrient-limited open ponds to induce astaxanthin production [14].

VI. Products of Algal Biorefinery

The main components of algal biomass are protein, carbohydrate, lipids and valuable compounds. Algal proteins comprise all the 20 amino acids and constitute up to 50% of dry weight in growing cultures. Algae could be the good source of ethanol as its storage products are ά-(1-4)-glucans, β-(1-3)-glucans, fructans, sugar and glycerol while the cellulose content is very low in the algae. The lipids of the algae can be classified in two groups namely storage lipids and membrane lipids. Storage lipids are mainly TAGs and add up to 50% of dry weight. These TAGs could be extractable from the wet biomass with the help of organic solvent and further utilize as biodiesel after transesterification. Up to 40% of membrane lipids are polyunsaturated fatty acids (PUFAs) such as α-linolenic, eicosapentaenoic and docosaesaenoic acids, belongs to the ω-3 groups. We could also get the valuable compounds from the algal biorefinery such as pigments, antioxidants, essential fatty acids, vitamins, sterols, anti-fungal microbial, anti-viral toxins etc. A list of valuable compounds from algal biomass is given in Table I. An assortment of scenario for exploitation of algal biomass in an algal refinery is given in Fig. 4. After extraction of TAGs and valuable components the residual biomass of algae is subjected to anaerobic digestion for biogas generation.

Another important aspect of algal biorefinery is biofixation of carbon dioxide. Microalgae have the advantages of efficient photosynthesis superior to C4 plants (those plants that form four carbon stable intermediates in the photosynthetic process; generally associated with agricultural and large terrestrial plants), fast proliferation rates, wide tolerance to extreme environments, and potential for intensive cultures. These advantages promise high performance in the reduction of carbon dioxide. Therefore once harvested, microalgae can serve as a product to offset the costs that have been incurred.

VII. Conclusion

The rapidly escalating costs of petroleum and petrochemicals are likely to accelerate the shift towards chemical products derived from renewable, biological feedstocks. While biofuel from edible and non edible oil crops are being produced in increasing amounts as renewable biofuels, but their production in large quantities is not sustainable. Carbon neutral renewable liquid fuels are needed to eventually totally displace petroleum-derived transport fuels that contribute to global warming. An alternative is offered by microalgae but it appears that the production of microalgal biodiesel is not economically viable in current environment because it costs more than conventional fuels. Therefore, a new concept of algal biorefinery is required as an option to reduce the total production cost of microalgal biodiesel. Combination of wastewater treatment and microalgal CO_2 fixation provides additional economic incentives due to the savings from chemicals (the nutrients) and the environment benefits. It provides a pathway for removing nitrogen, phosphorus, and metal from wastewater, and producing algal biomass, which can further be exploited for biofuel production, without using freshwater. Use of the biorefinery concept and advances in raceway ponds engineering will further lower the cost of production.

TABLE I
LIST OF VALUABLE COMPOUNDS FROM THE MICROALGAE

Pigments /Carotenoid	Vitamins	Antioxidants	PUFAs	Pharmaceuticals/Others
ß-Carotene	A, B1, B6, B12, C, E	Superoxid Dismutase	DHA (C22:6)	Antifungal
Astaxanthin	Biotine	Polyphenols	EPA (C20:5)	Antimicrobial
Lutein	Riboflavin	Catalases	ARA (C20:4)	Antiviral
Zeaxanthin	Nicotinic acid	Tocopherols	GAL (C18:3)	Toxins
Canthaxanthin	Pantothenate	-	-	Amino acids, proteins
Chlorophyll	Folic acid	-	-	Sterols
Phycocyanin	-	-	-	MAAs as light protectant
Phycoerythrin	-	-	-	-
Fucoxanthin	-	-	-	-

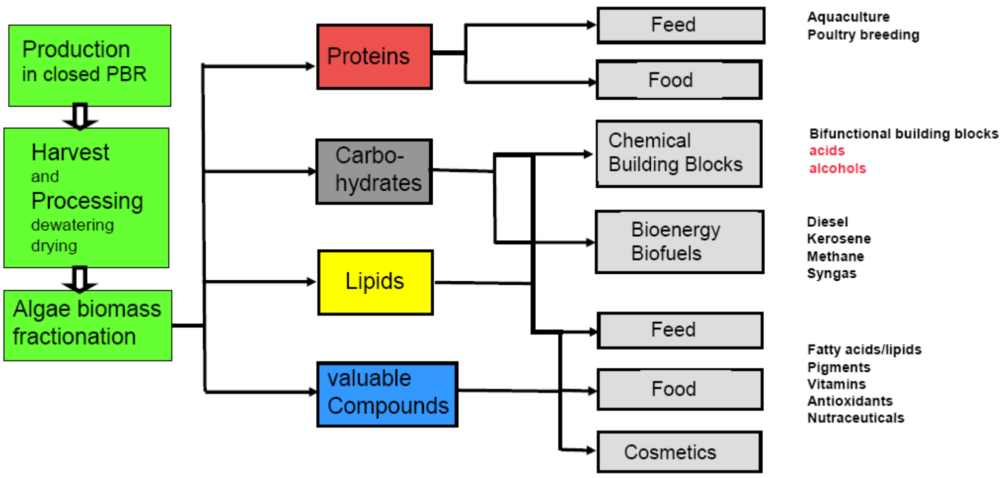

Fig. 4. Utilization of algal biomass in an Algal refinery

We can expect more and more biorefinery-type facilities where some combination of chemical, energy and food processing are used to add value to biomass feeds.

The more use we can make of food and bioenergy by-products to make chemicals, the lower the cost of those chemicals and the quicker we can expect their successful market entry.

It is vital to the future of sustainable chemical production that we employ only low environmental impact chemistry to convert these by-products into valuable chemicals and materials.

Therefore, in present scenario algal biorefinery is a way to link between energy, local environment and climate change and give us energy independence and sustainable future.

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