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2. Bioenergy from Algae -A Biorefinery Approach

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Abstract:

Algae are potential sources of bioenergy like biodiesel, bio-alcohol, biochar, biohydrogen, biogas, hydrocarbon etc. Algae are possible to be cultivated round the year in industrial wastewater, domestic waste water, and even in sea water with or without dilution. Cultivation of algae in industrial effluents is useful in reducing nutrient load and safe release to the environment. Contrastingly, the algal biomass is harvested for converting into bioenergy. Industrial emission of carbon-di-oxide (CO_2) and flue gas can be captured and applied for cultivation of algae for biofuel production, which is useful in reducing global carbon footprint. Biomass can be enhanced by the different simple growth media/physical parameters optimization techniques, vitamins/hormones supplementations, myxotrophic cultivation, co-cultivation with other microorganisms corresponding bacteria, yeasts, fungi etc. Significant quantity of triacylglycerols intended for biodiesel production can be derived, while the other left over major fractions like carbohydrate/proteins can likewise be utilized for bioenergy conversion.

While oil crude can be derived by "pyrolysis" of dry algal biomass, cost of biomass drying can be reduced by extracting oil crude from wet biomass by "hydrothermal liquefaction". Fuel gas can be obtained by "gasification" of carbon rich biomass. In a biofuel industry, the co-products can also be generated like pigments, biolubricants, bioplastics, cosmetics, biofertilizers etc. It is worthwhile to study the algal bioenergy production with cascading prospects of co-product development in algal biorefinery leading to socio-economic upliftment. Additionally, this chapter emphases on "zero waste" technology to minimize the waste generation during biofuel production enhancing the commercial viability of the algal biofuel industry.

2.1 Introduction:

2.1.1 Algae and Cyanobacteria (Blue Green Algae):

Algae are considered as primitive, oxygenic, eukaryotic, photosynthetic thallophytes with the forms of microscopic single cell (unicellular) to giant macroscopic kelps (multicellular). Cyanobacteria or 'blue green algae' are prokaryotic, oxygenic, photosynthetic, diazotrophic, mostly microscopic, however macroscopic colonies are quite conspicuous. Initially, both algae and cyanobacteria were classified after their morphological similarity and physiological properties like reserve food materials and pigments. However, with recent advances, molecular classification based on different gene sequences along with morphological and physiological attributes (polyphasic approach) are acceptable. These microorganisms colonize with the availability of moisture, with highly adaptive ability in very harsh conditions of hot springs and highly saline (>100ppt) salt pans. Microalgae/cyanobacteria are having the great potential in carbon sequestration, waste water treatment and useful resources for pharmaceuticals, and a wide range of value-added products like antioxidants, food, feed, polysaccharides (cellular and extracellular), proteins, lipids (polyunsaturated fatty acids), pigments, bioactive compounds, vitamins, cosmetics, biofertilizers etc. (Khan et al., 2018; Thajuddin & Subramanian, 2005). Explicit to species, microalgae/cyanobacteria are having high metabolic adaptations, grow in optimal conditions of pH, temperature, salinity in low/high nutrient (inorganic/organic) conditions, autotrophic/heterotrophic mode, waste water in natural day light conditions /fluorescent light/ 'Light emitting diode' (LED) without much sophisticated facilities. Biofuels attained from microalgae/cyanobacteria are sustainable and renewable.

2.1.2 Bioenergy from Algae/ Cyanobacteria:

The biofuels from algae/cyanobacteria are third generation, replacing lignocellulosic biomass, reducing competition with food and increasing economic sustainability. With more environmental sustainability, as a fourth generation, algae with potency are cultivated in the vicinity of industries under flue gas containing carbon dioxide (6-8%). With reduced lignocellulosic constraints, algal biomass follows quick conversion to biofuels (Table 1). Contrasting with higher energy crops, algae cultivation is plausible in non-arable lands or wastelands, saline sea water, waste water with round the year production of raw material (biomass) for the 'biofuel industry'. Macroalgae (seaweeds) do have seasonal impact on biomass production, however can be cultivated in coastal areas, without the requirement of freshwater. With reduced pollutants emissions (CO_2, SOx and NOx) to the environment, biofuels reduce 'global warming' and 'carbon footprint' as well. In an estimate (2018), the global 'greenhouse gas' released was 58 $GtCO_2eq$, of which 20 $GtCO_2eq$ (20%) was contributed by the energy part (Lamb et al., 2021). With global recognition, microalgae can convert solar radiation (9-10%) to biomass with the yield of $77g/m^2/d$ turning around 280 ton/ha/year (Khan et al., 2018). A large number of microalgal cells like *Chlorella vulgaris*, *Chlorococcum humicola*, *Scenedesmus quadricauda*, *Botryococcus braunii* are capable of accumulating lipids, and are explored for biodiesel production (Baldev, 2021; Borah, 2020; Hirano et al., 2019; Kafil et al., 2022). The microalga from chlorophyceae, *Botryococcus* sp. is recognized to accrue greater amount of lipid, producing 25-75% of hydrocarbon, which is having similar properties like petroleum crude oil. Botryococcene (C34) is a triterpene, and a major hydrocarbon from *Botryococcus* sp. Botryococcene is processed by hydrocracking to produce octane, and can be further used as petrol and kerosene. Cyanobacteria accumulate less lipid in their cells compare to other groups of algae, however are rich in carbohydrates (cellular and extracellular). Carbohydrates like starch (cyanophycean starch for cyanobacteria/blue green algae) is the major food reserve in the class chlorophyceae, and can be converted to bio-alcohols on fermentation. Wet biomass can be subjected to 'hydrothermal liquefaction' (HTL), and oil crude is accomplished, while gaseous fuels can be generated by pyrolysis, gasification and anaerobic fermentation. On the contrary, the surplus biomass on extraction of lipid, opulent in carbohydrates, proteins etc. is processed directly to biofuel or 'value-added products'. Therefore, it is worthwhile to study on mass production of algae/cyanobacteria in photobioreactors, diverse technologies appertaining to sustainable industrial bioenergy production integrated to a biorefinery approach leading to socio-economic benefit.

Table 2.1: Biofuel Derived from Algae and Cyanobacteria

Class	Name of the species	Macromolecule/Process	Biofuel	References
Cyanophyceae	*Anabaena planctonica*	Anaerobic digestion	Methane	Mendez et al. (2015)
	Anabaena variabilis	Photolysis	Bio-hydrogen	He et al. (2012)
	Borzia trilocularis	Anaerobic digestion	Methane	Mendez et al. (2015)
	Arthrospira platensis	Hydrothermal liquefaction	Bio-crude	Duan et al. (2018)
Chlorophyceae	*Botryococcus braunii*	Lipid	Biodiesel	Hirano et al. (2019)
	Botryococcus braunii	Pyrolysis	Bio-crude	Lee et al. (2020)
	Chlorella vulgaris	Lipid	Biodiesel	Baldev et al. (2021)
	Chlorella vulgaris	Pyrolysis	Bio-crude	Lee et al. (2020)
	Chlorella vulgaris	Anaerobic fermentation	Biobutanol	Wang et al. (2015)
	Chlorella protothecoides	Photolysis	Bio-hydrogen	He et al. (2012)
	Chlamydomonas reinhardtii	Pyrolysis	Bio-crude	Lee et al. (2020)
	Chlorococcum humicola	Lipid	Biodiesel	Borah et al. (2020)
	Dunaliella apiculata,	Photolysis	Bio-hydrogen	He et al. (2012)
	Scenedesmus quadricauda	Lipid	Biodiesel	Kafil et al. (2022)

Class	Name of the species	Macromolecule/Process	Biofuel	References
	Nannochloropsis sp.,	Photolysis	Bio-hydrogen	He et al. (2012)
	Nannochloropsis oceanica	Hydrothermal liquefaction	Bio-crude	Duan et al. (2018)
	Ulva lactuca	Anaerobic fermentation	Biobutanol	Potts et al. (2012)
Phaeophyceae	*Laminaria japonica*	Pyrolysis	Bio-crude	Lee et al. (2020)
Rhodophyceae	*Kappaphycus* sp.	Pyrolysis	Bio-crude	Lee et al. (2020)
	Gracilaria eucheumoides	Hydrothermal liquefaction	Bio-crude	Duan et al. (2018)

2.2 Production of Raw Material-Biomass for Bioenergy:

Biomass improves on optimizing requisite 'physico-chemical parameters' for the growth of algae. For more productivity, accuracy and reproducibility, optimization process can be carried out by 'response surface methodology' (RSM) or in different software like matrix laboratory (MATLAB). For cultivation of algae, the utmost significant nutrients are N, P and C. Algae can be cultivated in both autotrophic and mixotrophic (autotrophy+heterotrophy) conditions. The ability of algae to grow in organic media enhances the biomass and cost effectiveness. Biomass is improved in a controlled environment like closed photobioreactors and in open photobioreactors like raceway ponds.

2.2.1 Closed-Photobioreactors:

The first photobioreactor (PBR) was shaped up in 1940s (Johnson et al., 2018). Closed photobioreactors are intended to cultivate microalgae/cyanobacteria for a precisely controlled environment, minimum contamination and critical monitoring of growth. The controlled parameters could be pH, light (better surface area illumination, duration, type and intensity), temperature, O_2, CO_2 etc. Although, a high operating cost exists, a closed structure provides better mixing of nutrients, increased metabolic efficiency, and also suitable for the growth of genetically engineered microalgae/cyanobacteria (Fabris et al., 2020). It is essential for biomass applicable in nutraceuticals or pharmaceuticals, which requires axenic conditions. To achieve the maximum efficiency in biomass production, different PBR systems are designed.

Tubular photobioreactors are transparent long tubes, arranged in different geometric positions (horizontal/vertical/ helix) for efficient utilization of sunlight, and attached with pumps for mixing the biomass (Tan et al., 2020). However, these photobioreactors are poor in mass transfer. The efficiency pertaining to 'mass transfer' is improved by the vertical photobioreactors. These are vertical column attached with the spargers allowing mixing of O_2 along with CO_2. These bioreactors are not efficient in capturing light, and useful only in experimental studies (Tan et al., 2020). The 'bubble column' forms are rather simple in mixing with the bubbles of gases like CO_2, whereas in air-lift PBRs, baffles separate the column into two parts where air is mixed released by the 'sparger' placed at the lowest. To overcome the dark internal portion of these types of photobioreactors, annular photobioreactors were developed within the inward space. 'Flat-plate PBRs' are commercially feasible, having better surface illumination, and the gases are mixed with spargers at the bottom. 'Continuous flat plate PBRs' attached in series provide more productivity and product quality (Vargas et al., 2017). Nevertheless, all photobioreactors require a proper mixing system with controlled air flow for a dense biomass to reduce other microbial competitors, adherence to the surfaces allowing maximum illumination and transparency. Apart from these conventional types of PBRs, some specialized PBRs are also constructed for quality product development like integrated open tanks -plate panels, closed vessels-plate panels. A solid state PBR was constructed specifically for the pigment production from cyanobacteria (Léonard et al., 2010). Even the buildings are also used for the PBRs like Penthouse Roof PBR and PBR Façade (Koller, 2015). Floating horizontal photobioreactors are made of plastics, and tested for a marine alga *Nannochloris atomus* in a protype unit of 65L (Dogaris et al., 2015). The mixing was achieved by flowing of water.

2.2.2 Open-Photobioreactors:

Although, 'closed PBRs' are more productive and useful in maintaining quality, maximum biomass (>80%) production is achieved by open PBR systems industrially. A 'raceway pond' is a cost effective open PBR with less energy requirement, capital cost, operating cost than closed PBRs (Borowitzka & Vonshak, 2017). This is suitable for a comprehensive biomass generation with high commercial applicability (Fig. 1). Cultivation of *Chlorella vulgaris* in an open raceway PBR was found to have biomass productivity of 31mg/L/d in a cost-effective medium of urea (NH_2CONH_2), superphosphate ($Ca(H_2PO_4)_2$) and potash (KCl) with a reasonable lipid productivity of 25% (Baldev et al., 2018). High rate open ponds (HRAP) is one of the advances to the conventional open raceways, where more complex conformations and baffle systems, applied for better mixing and illumination to cells (Craggs et al., 2014). Industrially, thin layer cultures are often beneficial for biomass production reaching up to 80–100t of dry biomass/ha (Doucha & Lívanský 2015). 'Algae turf scrubbers' (ATS) facilitates attached algal growth in open cultivation. However, the productivity of open PBRs is limited by uncontrollable parameters like pH, rainfall, light intensity, temperature, and water evaporation, intervention by insects, birds' faeces and contamination due to other microorganisms.

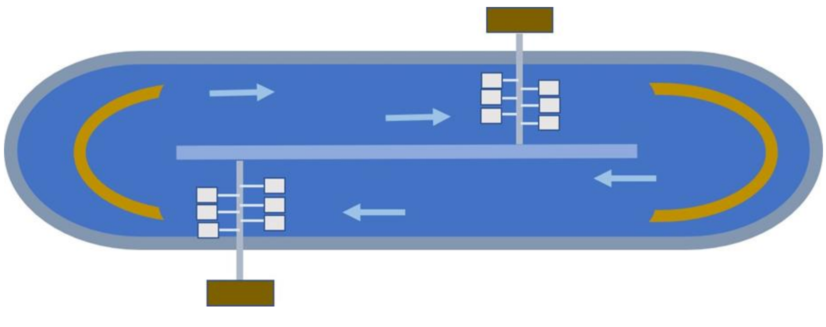

Figure 2.1: A Raceway Pond for Microalgae/Cyanobacteria Cultivation

2.2.3 Cultivation in Waste Water:

Microalgae/cyanobacteria can be cultivated in wastewater from aquaculture wastewater, domestic sewage water, slaughterhouse industry, distillery effluent, textile industry, pharmaceutical waste water, agro-industrial wastewater etc. (Aziz et al., 2019; Borah et al., 2020; Kalavathi et al., 2001; Sarmah & Rout, 2018; Shahid et al., 2020). A raceway pond is more effective in treating waste water with biomass production (Fig. 2). A tubular PBR was integrated with a facility treating waste water. Three microalgae viz. *Scenedesmus obliquus*, *Chlorella vulgaris*, along with a microalgal consortium were cultivated (Gouveia et al., 2016). The consortium had highest productivity (0.9 g/L·d) with the highest elimination of nitrogen (98%), phosphorus (100%) together with COD (64%). *Chlorococcum humicola* on cultivation in textile effluent (100%), produced biomass with growth rate 0.24/d, and an efficient elimination of nitrate (100%) and phosphate (94%) were obtained in 3 days (Borah et al., 2020). Kalavathi et al. (2001) reported degradation of the recalcitrant pigment present in ‘distillery effluent’ by *Oscillatoria boryana* ‘BDU 92181’.

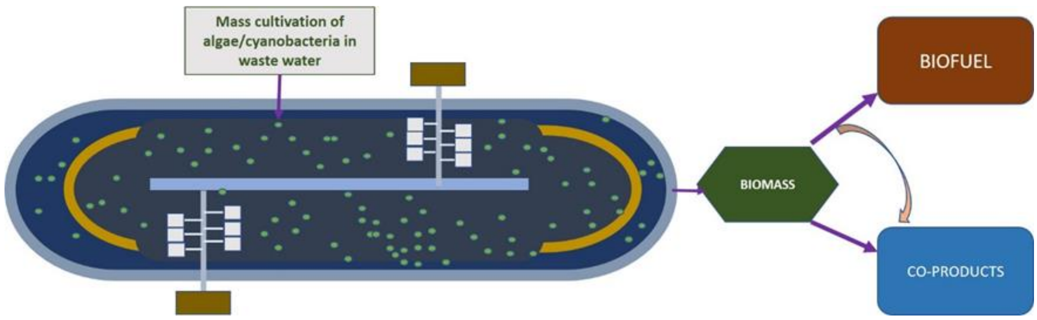

Figure 2.2: Cultivation of Microalgae/Cyanobacteria in Waste Water for Product and Co-Product Development

2.3 Technology for Bioenergy Production:

For production of bioenergy, algal/cyanobacterial strains ought to have high rate of growth, easy to harvest with greater accumulation potential of desired macromolecules. Potential strains are isolated, or can be engineered to give a better yield of proteins, polysaccharides, lipids, hydrocarbons etc.

2.3.1 Biodiesel Production:

Lipids can be storage or structural. Biodiesel or ‘fatty acid methyl esters’ (FAME) is derived by triacylglycerol transesterification, which are neutral storage lipids. To make biomass rich in lipid different strategies like optimization of physico-chemical characteristics and starvation of important nutrients can be adopted. Genetic improvements in lipid accumulation can be achieved by modulating metabolic pathways like competing pathways blocking, enhancing biomass while in stress, microRNA and pyramiding genes (Sharma et al., 2018). Lipid is extracted and transesterified into FAME by an acid or a base catalyst. Also, in one-pot transesterification, biomass is subjected to direct FAME, while lipid is in the cells. In a conventional FAME production, the ‘molar ratio’ optimization of methanol, temperature, duration of reaction, catalyst characteristics and concentration are important for maximum conversion into FAME. Recently, in green technology, nano catalytic approach is amongst the efficient methods of conversion to biodiesel. The nano catalyst 'Ca $(OCH_3)_2$' was found to yield 99% of FAME with only slight decline (96%) in consecutive cycles (Teo et al., 2016). The compositional characteristics pertaining to fatty acids is also important for a quality FAME. A quality biodiesel requires to have a composition of 5 (C16:1):4 (C18:1):1 (C14:0) of fatty acids (Prabandono & Amin, 2015; Schenk et al., 2008). The biodiesel from microalgae is comparable to the standards like 'EN 14214' and 'ASTM D6751'. Baldev et al. (2018) presented engine test on different blends of biodiesel pertaining to *Chlorella vulgaris,* showed lesser emission of pollutants (hydrocarbons/NOx /CO) compared to commercial biodiesel.

2.3.2 Bio-Alcohol Production:

Carbohydrates of microalgae/cyanobacteria have the significant application in bio-alcohol production on fermentation. More than 80% of carbohydrates are reported from the microalgae like *Scenedesmus* and *Chlorella* (Ellis et al., 2012). Microalgae sugars are easily fermentable due to the presence of digestible starch. The rich carbohydrate-rhamnose from macroalgae like *Ulva lactuca* can be anaerobically converted into butanol (van der Wal et al., 2013).

Industrially, ethanol production is more than the biobutanol. Lakatos et al. (2019) mentioned the methods available for microalgal carbohydrate conversion into bioethanol are biomass fermentation while pre-treated, reserved carbohydrate 'dark' fermentation and CO_2 to bioethanol direct fermentation. However, biomass fermentation is more in practice industrially. The fermentation is mostly carried out by *Saccharomyces* sp. (yeast) and *Zymomonas* sp. (bacteria). The most universal method for biobutanol production is 'Acetone, Butanol, Ethanol' (ABE) fermentation with the anaerobic bacterium *Clostridium acetobutylicum*. The other potential bacteria for fermentation are *Clostridium saccharobutylicum*, *C. saccharoperbutylacetonicum*, *C. beijerinckii*, *Butyribacterium methylotrophicum* etc. The intracellular pathway of *Clostridia* sp. can be categorized into three phases of solventogenesis, acidogenesis and gases. Butanol production occurs at solventogenesis phase. The acetic acid or butyric acids in acidogenesis phase reduces the pH and produces a stress which further retards the butanol production.

Butanol is more preferable biofuel appertaining to the high energy efficiency than ethanol, however, the product separation in ABE formation is less effective for its low concentration amongst other solvents. The techniques available to overcome the difficulties are, pervaporation, vacuum fermentation, perstraction, gas stripping etc. (Karimi et al., 2015). Butanol applied in 100% is plausible in present day motor engines without modification or can be mixed with gasoline. Butanol addition enhances the quality of 'brake specific fuel consumption' (BSFC), torque, power, release of pollutants like NOx and CO_2 (Saraswat & Chauhan, 2020). Butanol has other advantages over ethanol like higher safety than gasoline, more mileage, difficult to ignite but with cleaner flame, combustible but not explosive with less robust flame, water immiscible, easy transport through existing pipelines, less emission in hydrocarbon, CO and nitrogen oxides, low Reidvapor pressure (low evaporation), less hygroscopic, less corrosive etc.

2.3.3 Bioenergy from Protein:

Algae/cyanobacterial biomass is rich in protein, mostly ranging 40-50%. The cyanobacterium *Spirulina platensis* contains proteins more than 60% of dry weight. Adding to the carbohydrates and lipids, protein biomaterials are also increasing attention in biofuel aspect. Typically, proteins accumulate faster than lipids or carbohydrates in cells, and can also be used as a C-source in generation of biofuel. Genetically, by re-routing nitrogen flux in the bacterium *Escherichia coli*, the amino acids side chains and backbone of protease treated algal biomass could be converted to bio-alcohols (C2; C4; C5), adding to nitrogen recycling (Mielenz, 2011). Choi et al. (2014) presented a typical conversion of protein rich biomass into biofuel in metabolically engineered bacterium *Bacillus subtilis* involves protein biomass-polypeptides-pyruvate-acetolactate-2-ketoacids-aldehyde-biofuels.

2.3.4 Biohydrogen Production:

Biohydrogen is known as the cleanest biofuel with efficient energy. However, the commercial application is restricted by the low production rate and less cost effectiveness. It has high calorific value (~122kJ/g) and heating efficiency (Goswami et al., 2021). Photosynthetic microorganisms like microalgae and cyanobacteria are capable of producing biohydrogen. A few microalgae/cyanobacteria producing H_2 are *Chlorella protothecoides*, *Nannochloropsis* sp., *Dunaliella apiculata*, *Anabaena variabilis*, *Nostoc muscorum*, *Spirulina platensis*, *Tetraselmis tetrathele* etc. (He et al., 2012). In direct photolysis of hydrogen production, initially photosystem II follows activation. A water molecule split into a proton (H^+), an electron (e^-) and O_2 by the act of enzyme H_2O -plastoquinone oxidoreductase. The electron moves from ferredoxin to [Fe-Fe]-hydrogenase to produce hydrogen. In indirect photolysis method, initially CO_2 is fixed into carbon storage products. In the following second step, biomolecule catabolism occurs via citric acid and glycolytic pathways. The electron is transferred to [Fe-Fe]-hydrogenase through plastoquinone, while liberating H_2. The most important enzymes involved in H_2 production are Hydrogenase ([Fe-Fe]-hydrogenase, [Ni-Fe]-hydrogenase) and Nitrogenase (dinitrogenase or Mo-Fe-nitrogenase). Hydrogen can also be released on fermentation of the biomass (dark/photo) methods by the microorganisms like *Citrobacter* sp., *Clostridium* sp., *Klebsiella* sp., *Thermotoga neapolitana*, *Caldicellulosirupto sachharokyticus* and *Enterobacter* sp. (Shobana et al., 2017; Xia et al., 2015). Hydrogen production can be improved by cultivating microalgae in nutrient deprived (magnesium, sulphate etc.) medium and also by mutagenesis.

2.3.5 Pyrolysis:

During pyrolysis large organics of the cells break down anaerobically to smaller molecules under high temperature and pressure resulting into crude oil, biochar and bio-syngas viz. hydrogen (H_2), CO, CO_2 etc. Initially the biomass gets dehydrated (80-150°C), and devolatilization (180-480℃) occurs with 70% degradation to release volatiles (Porphy and Forid, 2012). The devolatilization phase continues with decarboxylation, deoxygenation, and depolymerization. The solid components are formed during decomposition phase (500-800℃). The algal/cyanobacterial biomass is more preferrable over other higher plant biomass due to the absence of complex forms of carbohydrates like lignin. Conventional pyrolysis includes slow pyrolysis (mostly for biochar, 550 –950 °C; slow heating); intermediate pyrolysis (up to 500℃, 40-60% bio-oil); fast pyrolysis (850 – 1250 °C for 0.5 – 10 s; high bio-oil) and flash pyrolysis (> 1000 °C/s, less than 2s) with no solid products. To progress the pyrolysis efficiency of algal biomass, other methods are also employed like catalytic pyrolysis (reduces oxygenates and nitrogenates in biofuel); co-pyrolysis (more bio-oil) and hydropyrolysis for high bio-oil produce with biofuel 48 MJ/kg (Lee et al., 2020). The algae tested under pyrolysis are viz. *Chlamydomonas reinhardtii*, *Botryococcus braunii*, *Laminaria japonica*, *Kappaphycus* sp. etc.

2.3.6 Biogas/Biomethane:

Methane production can be improved by certain strategies like nitrogen starvation while biomass cultivation. In this process, C/N ratio together with efficiency in cell disintegration increases. Klassen et al. (2015) presented a 65% upsurge in biogas for *Chlamydomonas reinhardtii*. Mendez et al. (2015) reported, with increased anaerobic digestibility, cyanobacteria *Borzia trilocularis* and *Anabaena planctonica* produced methane '1.42-fold' higher than *Chlorella vulgaris*.

2.3.7 Hydrothermal Liquefaction:

Hydrothermal liquefaction (HTL), a thermochemical conversion is applied for algal biomass with moisture to biofuel. The technique is processed in medium temperature and high pressure (up to 25 MPa). Djandja et al. (2020) reported the yield of biocrude oil from algal biomass is dependent upon the species, reaction time, catalyst, temperature and the solvent used. At temperature 335℃ (solvent: methanol; time: 60min; catalyst: 5% weight of γ-Al2O3), *Chlorella vulgaris* yielded 39% of biocrude, while it declined to its lowest (26%) with solvent methanol (1) + water (1) subjected to similar conditions. The cyanobacterium *Spirulina* yielded 67% of crude oil with the solvent tetralin at 350℃ for 60 minutes with the catalyst Fe (CO) 5-S (Djandja et al., 2020). 'Hydrothermal carbonization' and 'hydrothermal gasification' are two processes which are used for biochar products and gasification (mostly CO_2) separately.

2.4 Co-Product Development with Zero Waste Technology in Algal Biorefinery:

An integrated process of biorefinery for downstream processing is important in developing products/co-products, and reducing wastes (Figure 2.3). In this regard, the automation of the processes like cultivation, harvesting, growth and productivity monitoring should be considered. The industrial effluents and the flue gases released by the industries are used for algal/cyanobacterial growth in a biofuel industry. It is useful for reducing cultivation cost required for nutrients and freshwater requirement as well. In an integrated approach, biodiesel (188 tons/year) was produced along with co-products biogas (1,974,882 m^3/year) and biofertilizer (42 tons/year) with required electrical (1822.13 MWh/year) and thermal energy (3244.99 MWh/year) in large scale (Zewdie & Ali, 2020). Even a conventional oil petroleum refinery can be integrated with algal oil refinery (Andersson et al., 2020). The CO_2 released from the petroleum refineries is plausible to use for cultivating algal strains. The excess heat and hydrogen, which is produced by petroleum refineries can be applied in

HTL to generate biocrude oil. In the process, the generated gas can be turned into mechanical energy and electrical energy to run the industry. The potential avenues of a microalgal biofuel industry could be minimization of environmental wastes, realization of bioeconomy, resource recovery, high valued co-products, energy independence, reducing climate change, maximum utilization of biomass components, technically feasible, employment opportunities, cost-competitive etc. (Kumar & Singh, 2019). Bio-diesel would be coupled with co-products like nutraceuticals, fatty acids (emphasis on polyunsaturated), proteins, carbohydrates, pigments, biopolymer (polyhydroxybutyrate, biolubricants), and also the nutrients. The biofertilizer is developed from nutrients. The carbohydrates can undergo fermentation, pyrolysis or gasification for biofuel generation. The lipid productivity of *S. bijugatus* was reportedly 63mg/L/d, while the de-oiled biomass produced ethanol of 0.158g/g dw (Kumar & Singh, 2019). De-oiled protein rich biomass is utilized for feed for livestock, while on fermentation H_2 can be produced. Although, toxic substances from algae/cyanobacteria cause great hazard to plants, animals and environment, these products are having important antibacterial and antifungal characteristics. Khan et al. (2018) presented toxic substances from microalgae like *Nitzschia pungens* (domoic acid); *Gambierdiscus toxicus* (gambieric acids), *Amphidinium* sp. (Karatungiols) etc. which are poisonous to shellfish, antifungal and antimycotic agents. In a biorefinery, the zero-waste technology would be more effective if a cascading approach is adopted, where energy is produced only after all high valued products are produced.

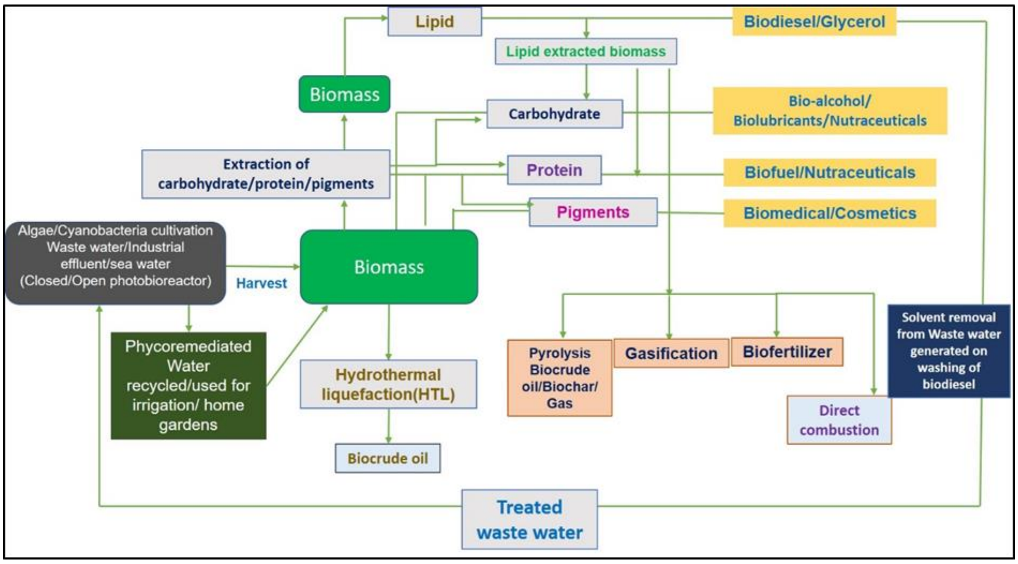

Figure 2.3: An Algal/Cyanobacterial Biorefinery Approach in Bioenergy

2.5 Socio-Economic Benefit:

The most often used socio-economic indicators are 'fossil energy return on investment' (EROI), 'return on investment' (ROI) and 'net present value' (NPV). Separately, other factors are external trade, resource conservation, external trade, social acceptability etc. (Maheshwari et al., 2021). A policy support targeting economic benefit gained by biofuel industry is needed. Biofuel production certainly reduces energy dependency, and increases economic sustainability. The technology can be transferred to the rural along with urban society for developing entrepreneurship. The deployment of the technology can be achieved by field-based trainings leading to self-sustainable modernized bioenergy production. Biofuel industry with biofertilizer production from biomass, integrating a biorefinery approach can provide economic benefit to the rural society. It can significantly increase employment generation (part time/full time/seasonal); entrepreneurship development; self-employment; impact on livelihood, poverty alleviation, women empowerment, and thereby socioeconomic upliftment (Figure 2.4). Also, environment sustainability can be attained by restoration of waste land, unproductive land, better environment and health improvement. Altogether, the beneficiaries (direct and indirect) are countryside marginal farmers, women together with children, poor households with low annual income, people with no livelihood opportunities, and the global scientific community. In China, on production of algae derived biofuel, an economic growth of 17.87 billion CNY was attained from 5.08 billion, creating jobs up to 104,000 (Yang et al., 2015). Although, it requires an expensive infrastructure, as algae are possible to cultivate in barren land, providing social well-being and food security as well.

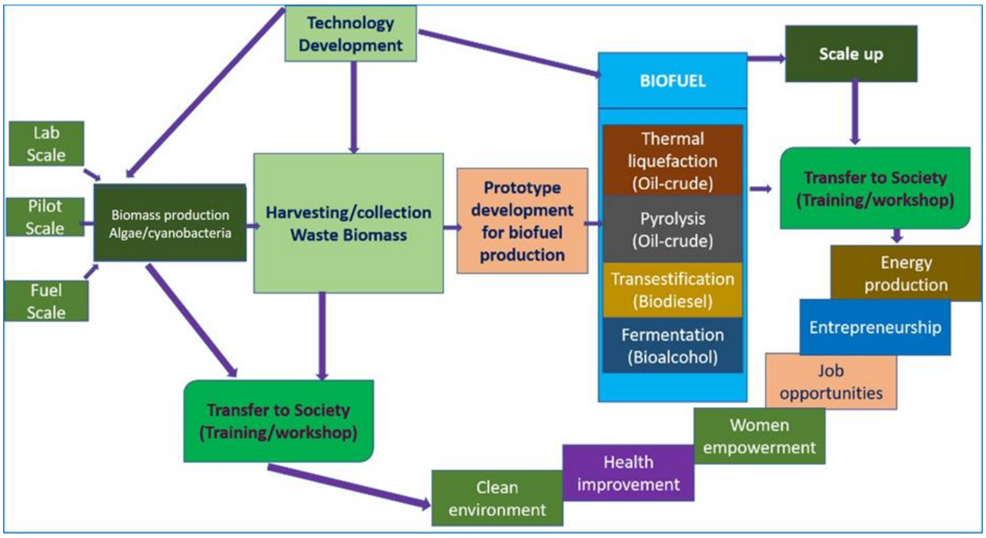

Figure 2.4: Socio-Economic Aspect from Biofuel Industry

2.6 Conclusion and Future Prospects:

Biofuel from algae /cyanobacteria is a green, clean and an efficient energy. It is a necessity for climate change, and a competent to fossil fuels. It reduces environmental pollution with more economic development (rural and urban). With the development of biomass energy sector, speedy economic growth, reduction in extreme poverty/hunger/malnutrition, and increase in job opportunities is possible. It also encourages women empowerment by gender equity, which could be achieved by generation of employment opportunities. Technology transfer to the society provides increased level of affluence, good health, and more life expectancy. The innovations in the technology will contribute to a sustainable bioenergy industry, GDP growth intensification, and socio-economic upliftment. Technologies pertaining to biofuel production from biomass (algae/cyanobacteria) have been improved than the past. However, more competent technologies for cultivation, harvesting, fuel conversion, separation, resource reusability are important in reducing negative energy balance. An integrated biorefinery approach with more innovation is indispensable for a sustainable bioenergy sector.

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