Microalgae and Its Premises towards Sustainable Energy Development

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Abstract. This paper features the use of nature’s element as a tool to combat current global issues on environment. Through research works by TNB Research Sdn. Bhd. (TNBR), marine phototrophic microalgae is used in reducing CO2 emissions from its fossil-fuel based power plants using. The research program commenced in 2011 with the aim to develop capacity, capability and facilities in biological CO2 fixation. The research program focuses on improving and enhancing the CO2 fixation through four core measures; namely species selection, nutrient optimization, flue gas admission and photobioreactor (PBR) design and engineering. The measures lead to the migration and evolution of culture facilities from laboratory conditions to outdoor, from shake flasks to 6 x 250 liter pilot PBR facility at a live coal-fired power plant, from mono species to consortium of species. Increment of CO2 fixation rates is summarized with discussion on comparisons of other achievements reported elsewhere. A considerable amount of work on analysing the bioactive compound present in the algae – protein, amino acids, carbohydrate, lipid, fatty acids - and its encouraging results, as an impetus towards sustainable development, will also be shared. Premises and observations from various microalgae research works are collated and presented in a manner sufficient to highlight the eminent roles of this tiny creature to become our mentor in providing some solutions to our worldly problems.

1. Introduction

Any utility power company nowadays has to wrestle between secure, efficient and reliable supply of electricity with safety and environmentally benign choices of power generation, transmission and distribution technologies. These variables can be conveniently summarized into the equation of sustainable energy.

Sustainable energy, as to simplify its assessment, can be reduced into seven sustainability indicators. They are: (i) price of electricity, (ii) carbon dioxide (CO2) footprint, (iii) efficiency, (iv) availability, (v) land use, (vi) water use and (vii) social impact [1]. Tenaga Nasional Berhad (TNB) constantly strives to improve sustainability ranking of its energy delivery. The recent launch of Manjung 4 power station– a new 1,000MW coal-fired power plant utilizing ultra-supercritical boiler is one example of a more sustainable energy generation [2], as the technology is 5 % more efficient than
its subcritical counterparts [3]. This marks the simultaneous attempt to reduce coal consumption thus reducing the CO2 footprint, as well as maintaining electricity affordability by using cheap fuel source.

Apart from tackling the boiler efficiency to reduce coal consumption, TNB through its research arm subsidiary company, TNB Research Sdn. Bhd. (TNBR) is also embarking on reducing the CO2 in its power generation activities head-on i.e. through application of Carbon Capture and Utilization technologies. Gasification, amine-based absorption and physical adsorption [4], [5] are among the technologies that have been developed and demonstrated at TNBR’s 150 kWth Integrated Gasification Pilot Plant.

2. Microalgae research works at TNBR

Quite contrary to the above-mentioned CO2 capture technologies, another approach is through biological means using phototrophic microalgae. This approach is regarded to be more sustainable, due to its proven natural benign photosynthesis mechanism and being the fastest growing photosynthetic organisms [6]. Using this biological method, the CO2 is fixed bio-chemically into Cx-Hy-Oz compound, as a result of photosynthesis reaction that originates from CO2, water (H2O) and photon energy from the sun as the reactants. By mass ratio, approximately 2 tonnes of CO2 can be fixed by 1 ton of microalgae [7]. In positioning microalgae as the CO2 biological fixer from power plants, several research areas were identified, namely Species Selection, Culture Parameters Optimization, Nutrient Enhancement, and Photobioreactor (PBR) Design and Engineering. These areas have been identified as the concerted efforts in improving the biological fixation rates of microalgae, i.e. the amount of CO2 microalgae can fix per liter of culture per day of culture (g.CO2 per liter per day, g/L.day). It is not intended to detail out all methodologies in each of our projects from 2011 as they have been elaborated in other publications. Only pertinent highlights and results are presented.

2.1. Species Selection

The first attempt in identifying suitable microalgae species for the job was to sample, isolate and identify potential ones around the vicinity of a coal-fired power plant. Obviously, marine microalgae species were opted as most of thermal power plants are located by the sea shore, taking advantage of the abundance of sea water that is used for its steam condensation process. Sea water samples were taken from three different locations (North 4o 2.675’; East 100o 41.859’, North 4o 8.195’; East 100o 38.103’ and North 4o 9.435’; East 100o 37.079’) offshore of a coastal coal-fired power plant in Seri Manjung, Perak, Malaysia. The isolation was done through streak-plating technique on agar plates continued with serial dilutions until several dominant colonies thrived. Initial media was Conway and then switched to f/2 with artificial sea water [8]. CO2 fixation rate was determined by weighing the algal biomass weight daily and applying the mass ratio between the molecular weight of CO2 and biomass, which is 1.882 [7], [9]. Through population count, it was found that the marine species Isochrysis sp. was the dominant species there and possessed a higher CO2 fixation rate of 0.1 g/L/day, when compared experimentally to the other species – Tetraselmis sp. and Nannochloropsis Occulata - isolated at the same vicinity.

Next initiative is to further improving the fixation rate by simply trying out culturing a consortium of microalgae species. Search for the consortium of species is based on visual observation of the TNB Janamanjung’s (TNBJ’s) outfall water which appears greenish. Should there be any microalgae species survives in this water, it should be robust enough to withstand the turbulence, hydrodynamic stresses and acidity prevalent at this location, as a result of rigorous aeration and desulphurization process that took place in the upstream. It is further hunched by other reports stating that growth characteristics of microalgae species could be altered when two or more microalgae species were cultured together in the same culture medium [10]. Samples taken at the outfall were further analyzed, processed and through molecular identification revealed that it contains a dominant harmonious community of Chlorella sorokiniana, Chlorella pyrenadoisa and through morphological identification...
a diatom *Amphora sp.* [11]. These mixed species were later combined with the existing *Isochrysis sp.* at various volumetric proportions, to form a consortium, and through fixation rate experiment using actual flue gas from the power plant, a consortium consisted of 75% mixed species and 25% *Isochrysis sp.* yielded the best fixation rate [12].

2.2. *Culture parameter optimization*
Cultivating algae in photobioreactors requires conducive environment for microalgae growth. These include pH, temperature, amount of CO2 supplied, light intensity and suitable nutrient. In order to know the optimum culture parameter to give the maximum CO2 fixation rate, these parameters need to be optimized by statistical methods using Response Surface Method (RSM). As part of experimental design, pH was varied from 4 to 8 (by regulating needle valve admitting commercialized pure CO2 gas from a cylinder), temperature from 20 °C to 40 °C (by dedicated water cooler/heater and cooling/heating coil), CO2 flowrate from 0.05 liter per minute (lpm) to 0.25 lpm, and lighting from 500 lux to 2500 lux (from five Philips’ T5 cool daylight fluorescence bulbs and Skye’s PAR sensor). 21 runs were conducted altogether using a dual 10 L lab-scaled bubbling column photobioreactor. From the results of the experiments, the highest one recorded at 0.35 g/L.day. Through a 3-D surface plot, RSM then suggested that a higher rate can be achieved if temperature, pH, flowrate and lighting were set at 30 °C, pH 7.5, 0.15 lpm and 1500 lux respectively. Following the suggestion, another run was made to reveal a better fixation rate of 0.37 g/L.day, or a 5% improvement.

2.3. *Nutrient enhancement*
Using 6 x 250 liter air-lift bubbling column pilot PBR installed at the Sultan Azlan Shah 3 x 700 MW coal-fired power plant (TNBJ), *Isochrysis sp.* was cultured, using actual flue gas and sea water. Bearing in mind that actual flue gas from a coal-fired power plant can contain among others, gases like SO2, CO, NOx, unburned hydrocarbons, particulate matter, traces of fluorine and chlorine compounds [13], apart from CO2, thus, right formulation of nutrient is deemed crucial as to ensure optimum growth under these conditions. Using 240 variations of chemicals and their concentrations, formulation of new nutrient / media was carried out through statistical experiment, covering relevant constituents in macro and micronutrients. The new media formulation obtained was tested in several cases and was compared against the use of previous nutrient, the standard f/2. The test at TNBJ’s power plant was done in a 250 liter air-lift bubbling column type PBR, admitting up to 50 liter per minute CO2 from actual flue gas, through KNF’s diaphragm vacuum pump. The new media has demonstrated better algae growth, especially on actual flue gas. The improved specific growth rate (µ) and fixation rate were 0.2714 d⁻¹ and 0.72 g/(L.day) respectively, against those obtained using the f/2 media 0.1703 d⁻¹ and 0.52 g/(L.day) respectively [14]. This means with the new nutrient, algae thrived faster and better and thus more CO2 can be fixed.

2.4. *Photobioreactor design and engineering*
In this regard, attention and consideration were made to minimize the photo-inhibition effect to the microalgae, as well as peculiar design on the pilot PBR that promotes modularity, accessibility and durability.

Trending of sunlight illumination level was carried out at designated location of TNBJ power station before the pilot PBR was installed. For a week’s recording, readings gave a minimum illumination of 28.5 klux (~527 μmol.m⁻².s⁻¹) and a maximum of 107.5 klux (~1,990 μmol.m⁻².s⁻¹) corresponds to morning and afternoon time respectively. Depending on geographical location, the Illuminance Saturation Level, Is, is estimated to be 140–210 μmol.m⁻².s⁻¹ [15] and this is the level where photoinhibition can still be coped. It is about two times lower than the minimum illumination recorded at TNBJ.

Thus detrimental photoinhibition effect was kept at its bay by adjusting the light exposure the algae cells received while it is travelling and recycling inside an air-lift bubble column. Through separate
experiment, it was found that when the level of light exposure is limited to about 72% the growth rate is better [16]. This finding was incorporated in the design of the pilot PBR where the transparent outer column and opaque inner column was specified to be in pre-calculated dimensions, in order to acquire the effect obtained in the experiment as closely as possible.

The pilot PBR as installed at TNBJ is shown in Figure 1 below, was mounted on a skid of hot-dipped galvanized steel, equipped with a raised platform for added accessibility during operation and maintenance. The skid can also be used as storage compartment for the columns, underneath it, with peculiar slots, slides and latching mechanism.

2.5. CO2 fixation rate achievement
Figure 2 above summarizes the CO2 fixation rate achievement so far, in g.CO2 per liter culture per day (g/L.day), from 2011 to 2015, with various initiatives – from indoor controlled laboratory conditions to outdoor cultivation, from mono species to consortia. The best fixation rate achieved so far is 0.965 g/L.day that was achieved through use of microalgae consortium species cultured using actual flue gas at TNBJ. Comparison, if it is to be made, with other species or initiatives, shall be done taking into account of the same CO2 fixation calculation method. Biomass analysis method is employed throughout the entire initiatives.
Figure 3 below charts out the comparison of CO2 fixation rates from various species, photobioreactor types, CO2 concentration, and culture condition but with the similar fixation rate method of calculation, i.e. using biomass analysis method. [17], [18] & [13].

![Figure 3. CO2 fixation rates comparison.](image)

The highest so far, by the chart is 1.88 g/L.day as achieved by Chlorella sp. using a mere 15 mL culture receiving 15% CO2 [18], which suggests a laboratory scale effort. An interesting point to note from that work probably is to have a higher concentration of CO2 brought to microalgae culture as a means to improve the fixation rate. This can be a daunting task as the amount of CO2 from a coal-fired power station varies from carbon contents in certain coal types in use, and often it is diluted and mixed with other gases as mentioned. To have it pure and at a uniform elevated concentration can be an expensive assignment, as this requires integration with other carbon capture method e.g. absorption or adsorption, though this is an excellent research challenge to delve into.

The level of CO2 fixation rate we achieved so far, however, is still far from being able to displace the amount of CO2 from a coal-fired power station significantly. If we were to use a baseline carbon footprint of 887 gCO2/kWh (for fuel combustion only) [19], and an annual capacity factor of 85%, a typical sub-critical 1,000-MW coal-fired power plant is capable to produce about 6.6 million tons of CO2 per year, and if biological means is the only effort made to curb this emission, it would require hundreds of hectares of land, millions of volumes of culture facility and millions of investment cost, based on current state of technology. All these are affecting the provision of electricity in accordance to sustainable development principle and components – land use, material and economy. However, as for land requirement, we see similar scenario to the palm oil plantations, rubber trees, rapeseed, and even soy beans where hectares of land are also made use to plant these trees. But why these are not questioned? It is because these plants can be turned into useful products benefitting humankind and bring commercial returns to its developers. Does not microalgae has the same quality?

2.6. Bioactive compound analysis

In answering the above question, we have to look into potential downstream products this consortium of species in use can offer. Bioassays of protein, amino acid, lipids and fatty acid analysis were conducted to the algal biomass as to explore its potential bioproducts. The amino acid compositions was identified using a Waters-Pico Tag Amino Acid Analyzer System. Lipid was extracted using...
soxhlet with hexane, in accordance to Bligh & Dyer method. Fatty acids was analyzed using gas chromatography mass spectrum. Proximate analysis revealed that the consortium content of protein (45%), lipid (21%) and carbohydrate (17%) is comparable and more balanced from other types of mono species. Its protein content of 45% is higher than other common sources of protein for cattle feed. Interestingly, essential amino acids content of 42% are encouragingly good and its composition is comparable if not exceeding some other species and soymeal [20], as displayed in Figure 4.

![Figure 4. Essential amino content comparison.](image)

Fatty acid analysis reveals that its content is more diverse as compared to other common sources like palm oil and soy bean. Table 1 below summarizes pertinent fatty acid content in the microalgae consortium and its potential bioproducts [21].

| Fatty acid content         | Potential bioproducts                                      |
|---------------------------|-----------------------------------------------------------|
| C18:3 Linolenic acid (ALA) | Omega 3 essential fatty acid - health supplement          |
| 14 %                      |                                                            |
| C20:3 Eicosatrienoic acid | Polymer - raw material for high mechanical strength organic plastics |
| 19%                       |                                                            |
| C16:0 Palmitic Acid       | Oleo-chemicals - Suitable for detergent, glycerol, esters, fatty alcohols, and lubricants |
| 22%                       |                                                            |

From this initial work, this microalgae consortium is thus suitable to be further studied in terms of its viability of simultaneous application of CO2 biofixation and bioactive compound production.

3. Premises of microalgal method
Through our involvement and achievement this last four years, we have acknowledged at least the following two important traits and premises microalgae can offer towards sustainable development. They are as follows:

- Bio-fixation works on re-cycling and re-utilizing of CO2
- Living organisms relies on close integration, co-operation and complementing each other
The first premise is evidenced from familiar observations we can make to the creation and roles of plants on the earth. Photosynthesis as practiced by these plants has been providing sustenance to the earth and its aerobic forms of life for more than 3.5 billion years [18]. It is a truly sophisticated and smart process in balancing the amount of CO2 released by nature and human activities to the amount of O2 they in turn need.

The second premise requires a more careful look. Let us take an example of the photosynthesis process that occurs within microalgae’s thylakoid membrane. We can see that a very close cooperation and co-ordination are orchestrated here. From photon energy received at photosystem II, it is converted into ATP (adenosine triphosphate - a reduced form of adenosine diphosphate (ADP)) and NADPH (a reduced form of nicotineamide adenine dinucleotide phosphate), assisted by electron transport chain. Later, under Calvin cycle, these ATP and NADPH convert CO2 into glucose and other sugars [18], and the process repeats itself.

It is also noticed during carbon fixation experiment using mixed species, that each of the species supports and complements each other as evidenced in Figure 5 below. All the three species survived to the end of culture period with good growth profile.

Overall, they have established and maintained an ecology in the culture.

Capitalizing from these premises and observations, it is thus recommended that biological CO2 fixation – an upstream process, to be developed together with potential valuable downstream bioproducts as the end-in-mind. Similar to what microalgae’s roles and behaves in its ecology, this observation should be emulated in industries towards an Industrial Ecology practise, an approach where one’s waste is a commodity to other industries [22], that is by itself, is a subset of a sustainable development. Thus, within a coal-fired power plant, CO2 as a waste from combustion process, is utilized by microalgae which in turn produces lipids, carbohydrates, proteins, pigments, which can be further processed towards productions of useful bioproducts like animal/aquaculture feed, nutraceuticals, cosmetics, biomaterials, biofuel [23], [24]. Several market values and unit price of these compounds have been reported to be high: Omega-3 – USD 25 billion in 2013 [25], Protein, a main constituent in animal feed industry is worth at USD 40 – 50 billion per year [26] and Astaxanthin Euro 7,150/kg [27], which can be justified towards commercial development thus satisfying the ‘economy’ component of sustainable development. After all, this recommendation is in parallel to the emerging science of ‘biomimicry’ where efforts are made to solve global challenges facing humanity using inspirations derived from nature, due to its efficiency, beauty, structure and functions [28].
4. Conclusion

Microalgae is seen fit as to be one of the picture in the broader framework of Carbon Capture and Utilization (CCU). CCU is becoming a new topics to pursue nowadays, with research emphasis on making CO2 utilization more efficient and economical, while at the same time widening the avenues for it. Several avenues have already been identified e.g. methanation, mineral carbonation, turning into chemical feedstock, as well as deriving downstream products from microalgae [29].

This recommendation towards CCU is and shall not be driven entirely by the allures of lucrative gains in profits, wealth or fame, but rather by a deep awareness that this is how nature solves the CO2 emission – by converting it into other substances and recycling it. We have taken microalgae, as inspired by nature, as a means to reduce CO2 emission through their photosynthesis process in our photobioreactors, in microscale, without realizing that it teaches us also a lesson or two in macroscale, on how its bioactive compounds can be turned into various useful products and be exchanged with other relevant industries. This whole framework – recycling and re-utilizing of wastes - if taken seriously from policy and regulatory level down to practitioners can ensure sustainable development agenda be fulfilled.

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