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Editorial

Microalgae Biomass as Biofuel and the Green Applications

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With the increasing concern on the global energy security and environmental sustainability [1], renewable energy has been getting more interest as an alternative source where the production of biofuel through green technology could be a solution in addressing the issue [2]. With all the advantages on the photosynthetic ability to reduce greenhouse gases emission through carbon sequestration [3,4], high biomass productivity and adaptation to adverse growth condition [5,6], microalgae with their significant contributions are known as the promising feedstock for renewable biofuels such as biodiesel, bio-oil, and bio-hydrogen [7]. Furthermore, microalgae also possess benefits in the green applications to the environment and agricultural use [8,9]. With the utilization of microalgae for bioenergy production and the associated value-added environmental applications [10], this can be an approach towards a carbon neutral bio-economy [2,11]. The editorial paper aims to provide an insight on the renewable microalgae source of the biofuel and green applications. Papers included range from topics on the cultivation and harvesting of microalgae biomass integrated with biorefinery approach, biofuel, and bioenergy production with value-added bio-products, as well as large scale implementation and techno-economic evaluation of the microalgae system. The latest updates and technologies related to the microalgae have also been included. The content of each of the related papers has been summarized in brief as followed.

In terms of the biorefinery approach, the work by Mehariya et al. [12] reviewed the microalgae biorefinery through integration of biofuel production with wastewater treatment. The paper highlighted the wastewater treatment system using microalgae can provide a sustainable and higher pollutants removal compared to conventional systems. Advanced cultivation systems such as algal turf scrubber and hybrid cultivation system are highly recommended for wastewater pollutants removal with cost-effective and efficient biomass harvesting. The exploitation of biomass from microalgae for biofuels production such as biodiesel, biomethane, biogas can be carried out while recycling the effluent for cultivation system. As a summary, the integration of wastewater treatment and bioenergy production with microalgae biorefinery approach provide a sustainable, green, and economic solution to the field.

Furthermore, the work by Makareviciene and Sendzikiene [13] reviewed the application of microalgae biomass for biodiesel production. The overview of the microalgae biomass preparation and oil extraction has been provided where the oil quality indicators and the suitability for biodiesel synthesis are presented. The examples of catalysts, alcohols, and other acyl receptors for transesterification of microalgae have been discussed, other than the influencing operating parameters towards process efficiency and biodiesel yield. The properties of algal biodiesel and its operational performance on engine performance and exhaust gas emissions have also been presented and evaluated. Finally, the paper also evaluated the economic efficiency of the algal biodiesel where co-production of other valuable products and simultaneous production system in the cultivation, wastewater treatment, and biogas production are proposed as future research trends.

With the feasibility of microalgae on wastewater treatment applications, Nguyen et al. [14] investigated the microalgae cultivation in seafood wastewater while determining the bacteria growth and lipid production. The study showed that optimal lipid attained in the moderate *Chlorella vulgaris* microalgae culture in the seafood wastewater effluent. Furthermore, the condition is able to inhibit the bacteria growth and enhances the lipid accumulation. The highest of two times lipid content has been achieved with the incorporation of microalgae cultivation with seafood wastewater. The study presented the future perspectives in approach of microalgae biorefinery through the development of a wastewater treatment plant utilizing the nutrients from seafood wastewater effluent in the production of economic and high value lipids.

The work by Spennati et al. [15] also investigated the application of microalgae on winery wastewater treatment towards production of low-cost biomass for bioenergy production. The co-culture of microalgae *Chlorella vulgaris* and *Arthrospira platensis* using different stage of winery wastewaters in the wine production process has been carried out and the daily growth of the microalgae culture and wastewater pollutant reduction were determined. The highest biomass productivity of 0.66 g dry weight/L/day and lipid productivity of 7.10 g lipid/100 L/day have been achieved from the study using second washing winery wastewater. In addition, the chemical oxygen demand and polyphenol content of the winery wastewater were reduced by up to 92% and 50%, respectively. The study demonstrated the utilization of winery wastewater for the cultivation of microalgae with the reduction in biomass production costs towards biofuel application.

Furthermore, Watanabe and Isdepsky [16] reviewed the integration of mixotrophic microalgae polyculture and wastewater treatment towards biocrude oil production. It is known that the integration of wastewater treatment and microalgae biomass production provides advantages in term of economic and environment such as reuse of the wastewater, reduction in the production cost, whilst mitigating the wastewater pollutant in a system. The review highlighted that mixotrophic algae has great potential for utilizing the atmospheric carbon dioxide and organic carbon as the source with feasible deep-water culture for cultivation, whilst playing an important role in the reduction in wastewater chemical and biological oxygen demand. The polyculture also presented good performance on the biocrude oil yield and quality compared to monoculture. Therefore, the production of biocrude oil with integration of deep-water-depth mixotrophic microalgae polyculture and wastewater treatment processes provide simultaneous advantages and sustainability in the production system.

In addition, the study by Park et al. [17] also determined the effects of mixed wastewater consist of pretreated piggery wastewater and acid mine drainage on the microalgae *Uronema* sp. KGE 3 biomass productivity and biochemical content. The study showed significant improvement with the addition of mixed wastewater where the highest 0.51 g/L of dry cell weight was obtained. The highest lipid and β-carotene content obtained were at 52% and 5.9%, respectively. Furthermore, the highest removal efficiencies of 62.3% for total nitrogen and 100% for total phosphate were achieved. The study showed the application of a wastewater treatment plant with microalgae biofuel production could be a cost-effective and environmentally sustainable approach in the field.

Other than biofuel and wastewater treatment, microalgae also possessed other value-added green applications. Dębowski et al. [18] demonstrated the study on the influences of microalgae biomass co-substrate in the biogas production from agricultural feedstock. The study showed that there was increase in the biogas yield and methane concentration with the combination of common agriculture substrates and microalgae biomass of *Arthrospira platensis* and *Platymonas subcordiformis*. The biogas production yield increased with the microalgae biomass concentration of a range of 0–40% volatile solid content in the substrate mixture for anaerobic digestion. Furthermore, the highest of around 65% of methane content was achieved in the biogas with *Arthrospira platensis* microalgae biomass.

The work by Ling et al. [19] presented the bioelectricity output from microbial fuel cell and an approach using a partially submerged carbon cloth electrode to enhance the stability of microalgae biocathode with wastewater as the electrolytic solutions. The findings showed that the stability of electricity output has been improved with the partially submerged electrode and a stable working voltage can be maintained. With the 50% submerged cathode electrodes in the microbial fuel cell, the highest lipid production of 250 mg/L with lipid content of 41% g/g dry weight and biomass production of 616 mg/L were obtained. The highest removal of 75% total nitrogen and 63% ammonia nitrogen were also observed with the microbial fuel cell with the submersion of electrode.

In addition, Viegas et al. [20] evaluated the co-torrefaction of microalgae and lignocellulosic biomass towards the optimization of biochar production with suitable energy properties and material valorization. The effects of independent variables on biochar yield and properties was evaluated using response surface methodology. Characterization such as proximate and ultimate analysis, higher heating value, and methylene blue adsorption capacity were determined. In general, the microalgal biochar has greater stability and density in the final form. The mixing of microalgae with lignocellulosic biomass improved the quality of the biochar where an optimum yield of 76.5% and higher heating value of 17.4 MJ/kg can be obtained. In addition, the utilization of microalgae from the effluent treatment to biochar production presented good adsorption capacities. Even though the biochar possessed properties of high ash content and low calorific value, there is possible application as low-cost adsorbents towards circular economy.

Towards the large scale implementation and commercialization of microalgae, Silkina et al. [21] studied the large scale wastewater bioremediation using microalgae *Nannochloropsis oceanica*. The study was carried out in agriculture, aquaculture, and anaerobic digestion municipal wastewater streams at the scale of 1500 L to investigate the growth of the microalgae. The findings showed that the microalgae possessed high adaptation with high nutrient uptake rate up to above 90% at day 4 of cultivation. The microalgae biomass from municipal wastewater cultivation medium demonstrated the highest protein content of 36.5%, agriculture wastewater medium with the highest carbohydrate content of 27.6%, and aquaculture wastewater medium with highest lipid content of 34.8%. The calorific value also presented a possible application of the microalgae biomass as a bio-fertilizer and aquaculture feed.

Furthermore, the study by Park et al. [22] investigated the cultivation of microalgae biomass in pilot scale using the exhaust gas from thermal power plants. The study demonstrated the cultivation of microalgae namely *Acutodesmus obliquus*, *Acutodesmus obliquus* KGE 17, and *Nephroselmis* sp. KGE8 in a batch scale photobiological incubator, and the possible continuous culture on pilot scale towards biofuel production. The study evaluated the culture productivity and concluded that the direct injection of exhaust gas in microalgae cultivation is a very applicable approach with energy utilization for a large scale cultivation system.

The work by Zieliński et al. [23] also presented the concept of the outflow from biogas plant as the medium for microalgae cultivation and biomass production. Based on the findings, an approximate of 720 kg volatile solid/day of microalgae biomass can be obtained. The technology is part of the hybrid production of biofuels namely ethanol, biogas, bio-oil, and organic fertilizers from lignocellulosic and microalgal biomass towards the agricultural biorefinery approach.

With the development of microalgae field and the related technologies, Rawat et al. [24] reviewed the latest expansions in the microalgae lipid enhancement for biodiesel production. The review provided an update on third-generation biofuels derived from the sustainable algal biomass where recent investigation is more focused on the technology to achieve higher biomass and triglycerides in the microalgae. The lipid enhancement approach through genetic manipulation such as metabolic and genetic alteration, and the applications of nanotechnology are the latest methods to improve the biomass and lipid production in microalgae. Other than genetic engineering and nanoparticles applications, pretreatment methods in term of chemical, biological, and physical have also been explored to maximize the lipid recovery rate from microalgae biomass. The combination of several technologies in improving the biomass and lipid production will be a viable strategy towards efficient microalgal biodiesel production.

Mishra et al. [25] also introduced an easily accessible microfluidic chip device for high-throughput microalgae screening through the growth rate and lipid content determination for biofuel production application. A cheap computer numerical control (CNC) micro-milling system has been employed in the fabrication of hanging-drop microfluidic chips. The easily accessible hanging drop provides an advantage for microalgae culture in a separate bioreactor where the parameters such as density and illumination can be customized easily through design modulation of the chip. The study also demonstrated ultraviolet (UV) mutagenesis approach to enhance the algae growth rate and lipid production. An easy operation using laboratory pipettes for the hanging-drop microfluidic system has been developed for long-term culture of microalgae. Thus, the system is expected to ease the procedure for microalgae mutation breeding and for the application on algae cultivation optimization.

Furthermore, the study by Zhang et al. [26] presented the cell wall disruption method based on electro-Fenton reaction. The method aids in the enhancement of cell harvest and extraction of lipid from wet microalgae biomass. After the electro-Fenton treatment, the yield of neutral microalgae lipid extraction increased from 40% to 87.5%. The results showed that more than 60% of total iron was found on the surface of electrode and microalgae precipitation after electrolysis, and this may contribute to the iron recovery and cell harvest. The study possessed a method for microalgal lipid extraction towards biofuel production with economic efficiency.

Finally, Valdovinos-García et al. [27] evaluated the techno-economic aspects of carbon dioxide capture of a thermoelectric plant using *Chlorella vulgaris* towards bioenergy production. The study suggested that the best choice of scenario depends on the final application of biomass. The biomass production system with the lowest energy consumption process routes should be taken into account to reduce the emissions from the process. The study provided a basis for future development of microalgae biomass production where the integration of carbon capture technology can be implemented in the system.

To summarize, microalgae biomass could be a potential future alternative source in the production of energy towards environmental sustainability. Further research and development will be needed to enhance the overall microalgae system operation and cost efficiency. The integration of several systems such as wastewater treatment [28], simultaneous biomass valorization [29], and the advancement using energy informatics and information technology could be the future approaches and perspectives towards the development of microalgae technology [30,31].

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