Industrial Microalgae Production System Using Process Engineering Approach
-Potential of Wastewater to Bioenergy and Coproducts-

プロセス工学アプローチを用いた工業的微細藻類生産
－ 廃水利用によるエネルギー・副産物生産ポテンシャル －

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Abstract

Industrial scale of microalgae production system potentially boosts large amounts of fertilizer and water consumption in upstream stage and needs excessive energy in the downstream process. To overcome these issues, the integrated energy plantation was introduced as a suitable cultivation system, including the possibility to utilize the wastewater. As a free and rich nutrient source for microalgae growth, wastewater sources from palm oil based agro-industry, municipal wastewater and livestock effluent were carefully evaluated to optimize energy return in the upstream stage. In the downstream stage, the dry and wet bio-oil processes pathways were selected as the possible current technology option. The simulation flowsheet of the integrated process system was synthesized by using Superpro Designer 9.0® to carry out optimization of freshwater, wastewater, flue gases, waste-heat and re-circulated combination stream, including design and sizing of the process equipment to obtain a realistic estimation of energy and material balance. Meanwhile, life cycle assessment (LCA) was analyzed by using Simapro 8.1®.

In the first part, the research evaluated an environmental load of continuous bioenergy production from palm oil (*Elaeis guineensis*) in Indonesia, attached with a proposed 10 ha of microalgae production system. Material and energy balances, greenhouse gas (GHG) emission, nutrient requirement and also water scarcity during bioenergy production cycle were comprehensively evaluated. The integrated system was developed for 60 tons h^{-1} of fresh fruit bunch (FFB) processing capacity of a conventional mill. The aggregate of energy-profit ratio from the proposed system was 3.38, which indicates a positive balance. Microalgae mix culture has the potential to treat organic compounds from palm oil mill effluent (POME) and combined with flue gases from biomass and biogas power plant as the alternative nutrient sources contributed to decreasing GHG emission by 86.21 tons-CO_2 ha^{-1} $year^{-1}$. The integrated system also potentially produced 26,471 tons of biodiesel (which include 223 tons from 10 ha microalgae cultivation) and 45,144 MWh of electricity annually. Additional coproducts of 520.33 tons $year^{-1}$ of animal feed from defatted biomass also possible to be produced.

In the second part, a research addressed the technical design of an integrated system of a

primary municipal wastewater treatment plant and flue gases from a power plant, utilized as the alternative nutrients source for microalgae cultivation. The proposed system was based on field measurement of algae facility located at Fukushima, Japan and scaled up to 1 ha cultivation based. The proposed process plant provides an efficient way to reduce energy consumption in the facilities. The results demonstrated that a polyculture of native microalgae species potentially sequestered CO_2 between 82.77 up to 140.58 tons of CO_2 year^{-1} with approximately 63 up to 107 tons year^{-1} of potential microalgae biomass production.

The third study was conducted in Perth, Western Australia for a livestock waste of anaerobic digestion piggery effluent (ADPE), contains very high inorganic nutrients which need to be treated. An integrated process facility was designed to remove effluent and generated clean water using a consortium of *Chlorella* and *Scenedesmus*. The system was designed for a piggery with 400 (medium piggery) and 2,000 (large piggery) sows producing 71 and 355 m^3 d^{-1} of ADPE with C:N:P ratio adjusted to 41.00:7.20:1.00. Process simulation estimated to produce 48.53 (medium piggery) and 199.90 (in large piggery) tons of biomass year^{-1} which could be used as animal or aquaculture feed. This process can also bio-sequester 374.06 and 2,014.89 tons of CO_2 year^{-1} in medium and large piggeries. The outcome of our preliminary LCA also shows that the proposed system potentially reduced GHG emission by 1.86 kg CO_2eq kg^{-1} of hot standard carcass weight (HSCW).

To understand the techno-economic of industrial scale microalgae production system, a simulation of *Botryococcus braunii* (*B. braunii*) culture was performed for biofuel production. An alternative cultivation technique of algal turf system (ATS) which widely used in the wastewater treatment was found can reduce water need and energy requirements associated with the harvesting and dewatering processes. Two different process systems of a modified algal turf system (ATS) and open raceway pond (ORP) were designed to investigate the detailed process system and the techno-economic associated with overall capital and operational costs required in the cultivation and processing of *B. braunii* for biofuel production. Similar nutrient, water supply, and recycling were used for both systems with harvesting occur every ten days. The associated production costs were estimated for three different ranges; 5.58, 13.81, and 38 g m^{-2}d^{-1} of biomass on the biofilm. Meanwhile, biomass productivity around 7.5 g m^{-2} d^{-1} in ORP system was used as a comparison. The average lipid content for each system was assumed similar for at least 14.21%dw. A sensitivity analysis was conducted to estimate the best operational condition and cost ranges for biofilm to compete with ORP system. For the high biofilm productivity, 38 g m^{-2}d^{-1} achieved in the laboratory scale possible to cultivate on a large commercial scale, resulting in a greater profit potential with Capital Expenditure (CAPEX) 189,385 USD ha^{-1} with annual Operational Expenditure (OPEX) approximately 2,569,910 USD. The biofilm system also significantly reduced freshwater consumption (up to 6 fold) compared with ORP and provided adequate nutrient recycling. Moreover, a concentrated biomass produced by the biofilm system cut the costs associated with harvesting and dewatering around 43%, which could be a significant benefit in the industrial scale of microalgae production. The Economic analysis confirmed that higher biomass productivity and technology improvement were required to achieve feasibility and profitability of current microalgae-based bio-oil production. The integration of microalgae production system with wastewater treatment, waste heat, and flue gases utilization significantly improved the energy balance and economics of biofuel production with potential additional coproducts.