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Application of Analytic Hierarchy Process in the Selection of *Botryococcus braunii* Cultivation Technology for Bio-crude Oil Production

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ABSTRACT

Bio-crude oil is obtained through a thermochemical process of biomass and can be used to reduce the Indonesian government's dependence on fossil energy. A potential source of biomass that is generally used for bioenergy production is microalgae, with *Botryococcus braunii* as the promising type. In the conversion of microalgae into bio-crude, the cultivation section is among the units required. Therefore, this study aims to determine the most effective and optimal cultivation technology that can be applied to the bio-crude oil refinery plant. It was carried out at the cultivation simulation system in Cilacap, Central Java, Indonesia, using the Analytic Hierarchy Process (AHP) method. The criteria used were the reactor land area requirement, energy consumption, water usage, cost, contamination risk, ease of scale-up, and adaptation ability to weather changes. Meanwhile, the proposed alternative systems were open raceway pond, flat-panel photo-bioreactor, hybrid, and membrane photo-bioreactor. The AHP results showed that the open raceway pond was selected for application in the bio-crude oil refinery process. The biomass production potential of *B. braunii* from the cultivation unit was 19.8795 ton/year/ha, which can be processed into 11.5301 ton of bio-crude oil with a high heating value (HHV) of 553,448.8 MJ.

I. INTRODUCTION

The derivation of Indonesia's primary energy mix from new and renewable energy (NRE) is still very low. Based on the latest data before the Covid-19 pandemic, only 9.18% of the total national primary energy supply of 1,620.69 million Barrel of Oil Equivalent (BOE) was provided by NRE [1] while others are dominated by oil, natural gas, and coal. Meanwhile, biofuel is a form of using NRE, which supplied approximately 2.95% of primary energy in 2019.

Bio-crude oil is the application of biofuel as alternative energy and is a blackish compound containing various

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hydrocarbons similar to petroleum-based on its straight-chain hydrocarbon content [2]. In its production, processes such as cleaning, hydrotreating, and hydrocracking are required to remove oxygen and heavy compounds to produce a drop in biofuel [3, 4]. Bio-crude oil can be obtained through thermochemical processes on biomass such as fast pyrolysis and hydrothermal liquefaction (HTL) [5]. The main difference between these technologies is the use of dry feedstock in fast pyrolysis, while wet stock is applied in HTL [6]. Furthermore, the oil from HTL has an oxygen content of 10-20 wt.%, which is much lower than 40 wt.% in pyrolysis. This property is due to the calorific value of HTL that is higher than pyrolysis with, 35 MJ/kg and 16-19 MJ/kg, respectively and is comparable to the 40-45 MJ/kg of conventional petroleum fuel [7].

Microalgae is a promising source of biomass that can be processed into bio-crude oil. It is derived from non-food raw materials and can be cultivated on relatively small lands. Furthermore, it has high photosynthetic efficiency, growth rate, biomass productivity, and good capacity to use water, CO_2, and sunlight to synthesize biomass via photosynthesis [8]. In this study, the microalgae species used was *Botryococcus braunii* which is a green colony freshwater microalga that produces hydrocarbons [9] and can be found in all climatic zones except Antarctica [10]. Although *B. braunii* is a type of freshwater microalgae, it has been investigated in cultivation using sea/brackish water media [11; 12]. Meanwhile, the use of seawater is more desirable in industrial-scale culture due to the reduction of the risk of contamination by other freshwater-living organisms in culture ponds [12]. *B. braunii* has a wide temperature tolerance range from -20 to 40^{o}C, which makes the large-scale outdoor cultivation to be carried out because of the minimal effect of extreme temperature shifts on the growth rate [13; 14]. The content of carbon and hydrogen, as well as the high heating value (HHV) which is within 32.9–54.7 MJ/kg in the biomass of this algae has a higher value than other types of microalgae [15]. *B. braunii* has also been considered a slow-growing alga with a generation time of 7 days in nature [16], while the Showa strain shows that it has a fast growth rate of 1.4 days [17]. Recently, it was discovered that there are 9 fast-growing strains with faster growth rates or similar to the Showa strain [18]. A previous report also stated that some of the properties of *B. braunii* crude oil are comparable to diesel oil, except for its higher kinematic viscosity [19]. Therefore, this study aims to select the optimal cultivation system for processing biomass from the *B. braunii* into bio-crude oil.

The selection of proper cultivation technology for *B. braunii* becomes a crucial decision since it will affect the whole aspect of the production of bio-crude oil. Meanwhile, the preferred technology needs to provide the best quality of biomass as indicated by yield and growth rate, the complexity of the process, energy consumption, operating cost, and economical aspects. Previous reports have shown that the Analytical Hierarchy Process (AHP) can be applied to make decide on the selection of several alternatives. In this study, AHP was used to compare and decide the best cultivation technology for *B. braunii*.

II. METHODOLOGY

The Analytical Hierarchy Process (AHP) method was used to analyze several criteria in selecting the preferred cultivation system.

2.1 Structure of Analytical Hierarchy Process (AHP)

AHP is a hierarchical structure-based tool developed by Thomas L. Saaty to manage qualitative and quantitative multi-criteria elements involved in decision-making behavior [19]. The basic concept of AHP is the use of pairwise comparison matrices [20], where the pair comparison scales are called the intensity of importance scale (table 1). Subsequently, the priority vector (weight) was calculated from that the pairwise comparison matrices using the eigenvector method. This method is popularly used to method to estimate a priority vector as proposed by Saaty [21].

Table 1. Intensity of importance scale [18]

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another

7	Very strong importance	Activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	When activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value	

The hierarchical structure was divided into 3 levels (figure 1). Moreover, level 1 was the study goal, which was to select a cultivation system for bio-crude oil production. Level 2 was the qualitative and quantitative criteria used for the selection. The land area of the reactor, energy consumption, water usage, and cost were the quantitative criteria, while contamination risk, ease of scale-up, and adaptation ability to weather changes were the qualitative criteria. Level 3 was the alternative of cultivation systems, which include open raceway pond (ORP), flat panel photo-bioreactor (FP-PBR), hybrid, and membrane photo-bioreactor (MPBR).

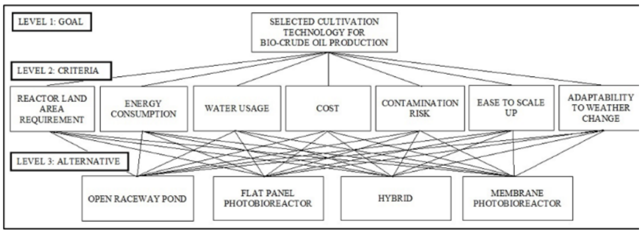

Figure 1. Analytical hierarchy process structure of this case study

2.2 Cultivation System Simulation Site Characteristics

The secondary data used in this study were derived from government reports and the results of previous studies. Subsequently, the location for the cultivation system simulation was in Cilacap Regency. It was selected due to its closeness to abundant water sources from the sea, the existence of oil refineries unit nearby for co-processing between bio-crude oil and crude oil, free carbon source (CO_2), and a dock for the delivery of processing products via sea transportation. The area of land available for the construction of the cultivation system including the utility area is 8 ha. Based on Figure 2, the cultivation simulation had an annual average global horizontal solar radiation of 1,915 kWh/m^2 or 5.25 kWh/m^2/day, while the annual average temperature from 2015 to 2020 of the location was 27.2°C [22].

Figure 2. Characteristics of the cultivation system simulation site

The biomass productivity of *B. braunii* cultivated in ORP from previous reports with similar characteristics was 0.114 g/L/day [23], which was conducted at an ambient temperature of 29°C, solar radiation of 5 kWh/m^2/day, and air humidity of 71% at a harvesting time of 15 days. During cultivation, a total of 200 L seed culture of *B. braunii* was grown in mini ORP with a biomass concentration of 0.085 g/L. Subsequently, it was transferred to the 2000 L ORP containing 1800 L of modified CHU 13 medium.

The productivity of *B. braunii* cultivated in FP-PBR used reference with a value of 292.5 mg/L/day of biomass [24]. This was carried out using 30 L PBR filled with BG-11 nutrient medium, operating at 0.33 vvm air flow rate & 1% CO_2. The productivity values were calculated on the 4th day of cultivation under the temperature of 27°C, a light intensity of 1,000 μmol/m^2/s, and a maximum biomass concentration of 1.17 g/L. Since 2.02 μmol/m^2/sec photon photosynthetically active radiation (PAR) is equivalent to 1 W/m^2 solar radiation [25], therefore, 1,000 μmol/m^2/s is equal to 5.45 kWh/m^2/day (11 hours of daylight).

In a hybrid cultivation system, productivity was the combination of these two values. Meanwhile, the MPBR productivity has been calculated as 2 times greater than the optimum productivity of PBR, namely for the submerged biomass retention MPBR [26].

The yield of bio-crude oil from the HTL process on the microalgae biomass of *B. braunii* from previous results varied from 4.04 wt% [2] to 58 wt% [27, 28] and 68 wt% [29]. This study used a yield value of 58 wt% to calculate the produced bio-crude oil, however, it was reported that the high heating value in the bio-crude oil was 48 MJ/k [27, 28].

III RESULTS AND DISCUSSION

In this study, the data processing to obtain the value of the intensity of importance scale was completed through 2 methods. In the first approach, the procedure was carried out by calculating the system design based on previous reports. Subsequently, the pairwise comparisons between systems were carried out using the results of these calculations to get the intensity of importance scale to assess the quantitative criteria for alternatives at level 3. In the second method, pairwise comparisons were assessed by respondents (experts) through questionnaires. This was applied to the comparison between criteria at level 2 and the assessment of qualitative criteria against alternatives at level 3.

3.1 Criteria Weight Calculation (Level 2)

The pairwise comparison scale at level 2 was formed from the average assessment made by expert respondents on the contribution of each element (criteria) to achieve the goal. This was carried out to determine the order of importance of the 7 criteria used according to the experts based on the characteristics of the location. From Figure 3, the weighting result showed that the investment cost is the most influential criterion, followed by energy consumption, reactor land area requirement, ease to scale up, water usage, contamination risk, and adaptability to weather change.

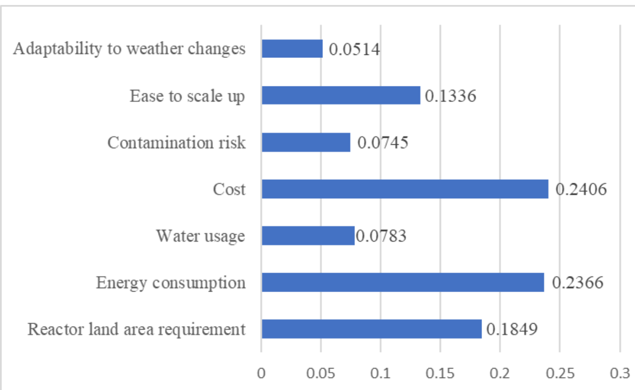

Figure 3. Chart of the weight of each criterion

3.2 Calculation of Alternative Local Weights Against Criteria (Level 3)

The definition of the criteria for the reactor land area requirement was the area required for the cultivation system to produce the same product as the open raceway pond which was built on 8 ha. Meanwhile, the 4 cultivation systems were assumed to have the same utility area and the open raceway pond design is shown in figure 4 [30]. The assumption of effective production time per year was 330 days as used in previous studies [31; 32]. It was discovered that a total of 8 units of open raceway ponds including the utility area can be built in those available land areas with a projected biomass production yield of 79.5179 tons/year.

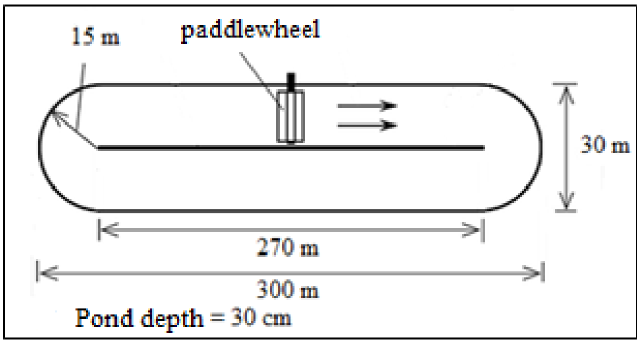

Figure 4. The open raceway pond design

The FPBR design is shown in figure 5 [30; 33], while the land area to build flat panel PBR which was needed for the same production projection as the open raceway pond was 2.4033 ha.

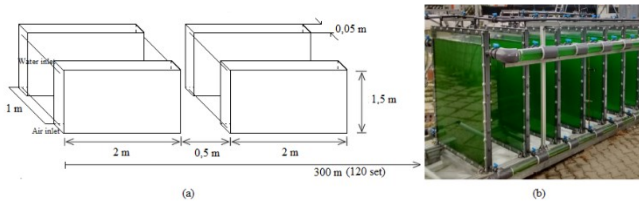

Figure 5. The flat panel PBR design

The hybrid cultivation system was designed by combining 1 unit of ORP and FP-PBR. This system required an area of 3.0950 ha to produce the same amount of biomass, while the MPBR used the design basis of the FP-PBR. The use of reactors with a short light path like the flat panel to construct MPBR is generally recommended [34] and the land area required to build that MPBR was 1.6788 ha.

The energy consumption was the one required for the cultivation system to operate by volume within 330 days per year. The water usage criterion was the flow rate per day needed by the system to maintain the dilution rate. Meanwhile, the cost criterion was the production cost for total biomass of 79.5179 tons within 1 year. The results of the three quantitative criteria are shown in Tables 2-4.

Table 2. Energy consumption of each alternative

No	Alternative	Power or Energy Consumption per Reactor Volume	Volume (m^3)	Energy per 1 Year of Production (MW)
1.	ORP	4 W/m^3 [35]	2113.712	66.9624
2.	FP-PBR	53 W/m^3 [36]	828	347.5613
3.	Hybrid	Combination of ORP & PBR	984.214	310.5975
4.	MPBR	0.64 kWh/m^3 [37]	414	2098.4832

Table 3. Flow rate of each alternative

No	Alternative	Reactor Volume (m^3)	Flow rate (F=D×V; m^3/day)
1.	ORP	2113.7120	528.4280
2.	FP-PBR	828	207
3.	Hybrid	245.5535	245.5535
4.	MPBR	414	103.5

Table 4. Cost of biomass production of each alternative

No	Alternative	Production cost per Kg	Total Production Cost per Year
1.	ORP	€ 4.95 [38]	€ 393,613.61
2.	FP-PBR	€ 5.96 [38]	€ 473,926.68
3.	Hybrid	Combination of ORP & PBR	€ 463,887.73
4.	MPBR	US$11.30 [39]	€ 790,726.00

Note: US $1 = € 0.88

The contamination risk criteria were the risk level of a cultivation system that can be disturbed by an external predator. The ease to scale up criterion was assessed for each system based on its technology maturity and commercial company availability for its development from the laboratory to large scale. Meanwhile, the adaptability to weather change criterion was the ability of a cultivation system to continue production without being affected by weather changes. The pairwise comparison from the assessment result of the three qualitative criteria is shown in Table 5.

The weighting results of alternatives against criteria are summarized in Table 6 and are in line with previous studies for most of the criteria that compared ORP, PBR, and hybrid [40] and discussed membrane application in PBR, namely MPBR [41]. The higher the weight value of a cultivation system, the more preferred the system in terms of related criteria. This is indicated by the reactor land area requirement, which was wider on ORP than the others, making its weight value the lowest. Since MPBR energy consumption was the highest, it had the lowest weight value.

On the contamination risk criterion, FP-PBR had a higher weight than MPBR, although both systems had the same design basis. This result showed that based on previous reports and existing applications, respondents preferred FP-PBR to MPBR to face the risk of contamination. Meanwhile on the cost criteria, the difference between the ORP and FP-PBR was not significant, hence it has the same weight in the AHP calculation.

Table 5. Pairwise comparison for qualitative criteria

Pairwise comparison	ORP	FP-PBR	Hybrid	MPBR
Contamination risk				
ORP	1	1/5	1/4	1/5
FP-PBR	5	1	3	3
Hybrid	4	1/3	1	1
MPBR	5	1/3	1	1
Ease to scale up				
ORP	1	5	4	5
FP-PBR	1/5	1	1	4
Hybrid	1/4	1	1	3
MPBR	1/5	1/4	1/3	1
Adaptability to weather change				
ORP	1	1/4	1/3	1/4
FP-PBR	4	1	3	2
Hybrid	3	1/3	1	1/4
MPBR	4	1/2	4	1

Table 6. Weighting results of Level 3

Criteria	ORP	FP-PBR	Hybrid	MPBR
Reactor land area requirement	0.0819	0.2346	0.2107	0.4394
Energy consumption	0.6271	0.1631	0.1720	0.0378
Water usage	0.0922	0.2384	0.2155	0.4539
Cost	0.2857	0.2857	0.2857	0.0632
Contamination risk	0.0632	0.5101	0.2057	0.2210
Ease to scale up	0.5908	0.1751	0.1658	0.0683
Adaptability to weather changes	0.0757	0.4403	0.1430	0.3410

I. Global Weight Calculation

The global weight was calculated to determine the final goal, which was the selection of a cultivation system for bio-crude oil production. This was carried out for the four alternatives by multiplying each local weight against the related criteria and the results were summed as shown in Figure 6.

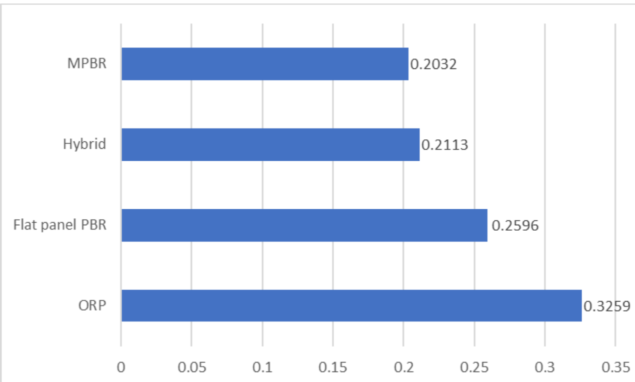

Figure 6. Global weight of each alternative

Based on the global weight calculation, the ORP had the highest weight value, followed by flat-panel PBR, hybrid, and MPBR.

IV. CONCLUSION

Several technologies are available for the cultivation of *B. braunii* for bio-crude oil production. Based on the AHP method, the best alternative cultivation system was the open raceway pond, followed by PBR flat panel, hybrid, and MPBR with the yields of 0.3259, 0.2596, 0.2113 and 0.2032, consecutively.

The biomass production potential was 79.5179 ton/year for an open raceway pond with a land area of 8 ha or 19.8795 tons/year/ha. According to the HTL yield value of 58 wt%, the bio-crude oil that can be produced from the cultivation system was 11.5301 tons/year with an HHV of 553,448.8 MJ/year.

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