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Application of solar photovoltaic for the cultivation of *Arthospira platensis* (Spirulina)

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ABSTRACT

Spirulina farming can be a solution to provide nutritious food for the increasing global population. Mixotrophic cultivation technique using wastewater nutrient to supply the energy for biomass growth beside the light energy is a promising technology to grow more Spirulina biomass. Electricity from solar energy can be utilized as a clean energy to power the aeration and illumination in Spirulina cultivation. A rooftop monocrystalline silicon (m-Si) solar panel with an area of 27 m^2 was used to power Spirulina starter incubation (7 days) and mixotrophic or photoautotrophic cultivation at room temperature, various light intensity (1500–6000 lux), and fix aeration rate at 4 L/min for 5 days. MSI (Maris Sustainable Indonesia™, PT Maris Indonesia) medium supplemented with tempeh industry wastewater (1% v/v to MSI media) was used as organic carbon and growth nutrient source in mixotrophic cultivation. Mixotrophic culture grew faster than photoautotrophic culture (0.2615/day vs. 0.2107/day) due to its capability to harness catabolism activity for growing and multiplying. Growth inhibition by high photon density was implicitly observed in the slower or no increase of specific growth rate with the increasing light intensity in photoautotrophic culture. Application of solar panel lowered about 5.9% of carbon footprint in contrast to the fossil fuel sourced electricity. Net negative carbon footprint could be achieved through carbon fixation into Spirulina biomass.

Keywords: Photovoltaic panel, Microalgae, Spirulina, Mixotrophic, Carbon footprint.

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1. INTRODUCTION

Recent meeting of world leaders on climate change issues has resulted in an agreement to achieve net zero carbon emission by 2040 on all human activities, including farming (Wang et al., 2020; Arora and Mishra, 2021). To achieve that objective, carbon-free renewable energies are employed to replace the current fossil fueled energy supplies. Among all available renewable energies, solar cell is more advantageous due to its space and process versatility as well as its low overall cost (Guangul and Chala, 2019). Moreover, solar cell technology has shown a bright prospect to be more developed by years in Indonesia and around the globe (Handayani and Ariyanti, 2012; Sahu, 2015).

Arthospira platensis (Spirulina) is a nutritious blue-green microalgae known to be rich in vitamin, protein, antioxidant, antibacterial and anti-fungus compounds (Osman et al., 2016; Mala et al., 2017; Nawrocka et al., 2017; Mohammadi et al., 2022). Spirulina not only can harness light energy but also utilize carbon substances for its growth, which is known as mixotrophic growth. Such growth can be performed using organic wastewater, including dairy wastewater (Pereira et al., 2019), tempeh industrial

wastewater (Riadi et al., 2021), and olive oil industrial wastewater (Mostafa et al., 2019). It was found that certain level of wastewater concentration resulted in the optimum biomass growth.

Although the use of wastewater as nutrient source has increased the economic feasibility of Spirulina cultivation, high energy requirement for a sufficient aeration and proper light intensity are still overshadowing the environmental aspect of microalgae cultivation (Soni et al., 2019). Such steady requirement of electricity may be proportional to larger carbon footprint, especially when fossil fuels are used to power the grid. Only by applying clean and renewable energy, Spirulina cultivation can be an environmentally friendly and sustainable food farming. Up to now, study on the utilization of renewable energy to power Spirulina cultivation was nowhere to be found.

In this study, solar photovoltaic (PV) system was applied to power Spirulina cultivation. Effect of cultivation techniques (photoautotrophic and mixotrophic) under various light intensity on the biomass growth was discussed thoroughly. Furthermore, application of solar panel energy supply was evaluated technically and environmentally. The effect of cultivation technique on the carbon footprint was assessed. Finally, the best practice to grow Spirulina biomass was pointed out.

2. MATERIALS AND METHODS

2.1 Media Preparation

The MSI (Maris Sustainable Indonesia™, PT Maris Indonesia) medium was prepared for the photoautotrophic cultivation, which consists of $NaHCO_3$ at 0.5 g/L, NaCl at 0.5 g/L, urea at 0.05 g/L, triple superphosphate (TSP) at 0.02 g/L, and cobalamin (vitamin B12) at 0.01 g/L. The pH was adjusted to 9 with the addition of 1 N NaOH. For mixotrophic cultivation, tempeh wastewater from a local tempeh home industry was added at 1% (v/v) as urea and TSP replacement. Prior to Spirulina inoculation, media were autoclaved at 121°C and 15 psi for 15 min.

2.2 Spirulina Starter Cultivation

Spirulina suspension in MSI medium was inoculated into fresh MSI medium with volumetric ratio of 1:1 to make a total volume of 2 L. Then, the mix was incubated under ambient air aeration (30°C) at 4 L/min and at a certain light intensity of fluorescent tube lamp (1500, 3000, 4500 or 6000 lux) for 7 days. Variation of light intensity at 1500–6000 lux was done by regulating the number of lamp tubes. Every 2 days of incubation, a small amount of mixture solution consisting of $NaHCO_3$ (0.5 g/L), NaCl (0.5 g/L) and cobalamin (0.01 g/L) in sterile water was added into microalgae culture to maintain the system volume at 2 L as well as the salinity and growth promoter availability in the culture system (Taufiqurrahmi et al., 2017).

2.3 Photoautotrophic and Mixotrophic Cultivation

Spirulina was cultivated by mixing 1 L of starter liquid with 1 L of fresh media for the photoautotrophic or mixotrophic culture. Each culture was made in duplicate. The culture mix was then put under the same incubation setup and conditions that was used to incubate the starter. Optical Density (OD) of 1 mL liquid sample at 680 nm was measured in triplicate everyday by a spectrophotometer. When OD value was relatively unchanging to that of prior sampling, solid biomass yield was determined by filtering a measured volume of final liquid culture followed by drying at 40°C until a constant dry mass was achieved (approximately 6 h).

Certain amount of dried biomass from each cultivation mode was further re-suspended in distilled water to make a series of concentration and then analyzed spectrophotometrically at 680 nm to calibrate the OD against the biomass concentration. The biomass concentration data of each cultivation mode were consecutively processed by $\ln X = \ln X_0 + \mu t$, where X_0 is biomass concentration at the beginning of incubation (g/L), X is biomass concentration at a certain incubation time (g/L), and μ is specific growth rate (1/day).

2.4 Solar PV Monitoring

In this study, photobioreactors set-up were powered by solar PV system as depicted in Fig. 1. A 3000 WP-monocrystalline silicon (m-Si) solar panel was installed on the 27 m^2 rooftop area of the University of Surabaya, Indonesia. Solar panel was connected to a solar charge controller, batteries, and a grid-interactive inverter. A kWh meter was used to continuously monitor and record the electricity consumed by photobioreactors (aeration and lighting systems) and oven. In order to get the overall electricity consumption data, values of electricity usage related to water pumping and centrifugal separation taken from a previous study (Collet et al., 2011) was added to actual laboratory data, which were 0.05 KWh/m^3 and 0.042 kWh/kg Spirulina, respectively. The remaining stored electric power was used to operate the other electronics in the university buildings.

2.5 Annual GHG Emission Estimation

Greenhouse gas (GHG) emission of Spirulina cultivation system in this study can be calculated based on the life cycle analysis (LCA) approach. The calculation excluded the emission potential from the cultivation process equipment fabrication (photobioreactor, lamps, pumps, oven, etc.) with an exception on the solar panel fabrication since it was inseparably incorporated into the electricity generation system. GHG emission can be broken down into two main parts of the cultivation system: electricity consumption and material usage. Spirulina cultivation plant was assumed to operate for 360 days.

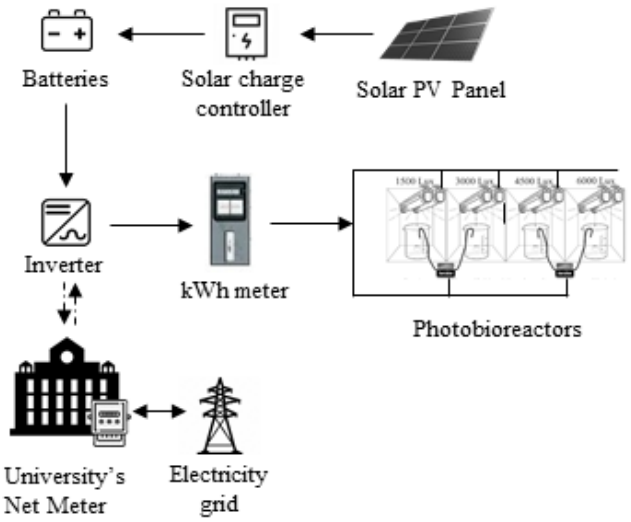

Fig. 1. Illustration of solar cell-powered photobioreactors set-up

GHG emission from the material usage was mainly estimated by EcoInvent database in openLCA software version 1.11.0. In case of tempeh industry wastewater, GHG emission was calculated according to the Chapter 6 of 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Wastewater GHG emission (g CO_2 eq/L wastewater) = $25\frac{\text{g CO}_2}{\text{g CH}_4} \times \text{B}_0 \times \text{MCF} \times \text{COD}_{\text{final}}$, where B_0 is maximum methane formation (0.25 g CH_4/g COD) and MCF is methane correction factor, which is 0.3 for a not well-managed and overloaded aerobic treatment plant that possesses similar practical situation to the wastewater dumped into the open wastewater channel throughout the city. Chemical oxygen demand (COD) values were supplied from the laboratory measurement of wastewater samples using the closed reflux method (LaPara et al., 2000). The average values of triplicate samples without standard deviation were inputted to simplify the calculation. The average initial COD of 1% tempeh wastewater was found to be 220.6 mg/L.

GHG emission from PV electricity production can be estimated by: PV electricity emission factor $\left(\frac{\text{g CO2 eq}}{\text{kWh}}\right) = \frac{\text{Embodied energy } \left(\frac{\text{kWh}}{\text{m}^2}\right) \times \text{Area} \times \text{Fossil fuel Emission factor}}{\text{Generated energy (kWh/day)} \times \text{annual operating day} \times \text{lifetime (years)}}$, where embodied energy for a rooftop m-Si solar panel was known to be 1441 kWh/m^2 (Prabhu et al., 2022). Fossil fuel emission factor can be assumed as the emission of a coal-fired power plant (975.3 g CO_2 eq/kWh), natural gas (607.6 g CO_2 eq/kWh) or oil (742.1 g CO_2 eq/kWh) accordingly (Tawalbeh et al., 2021). This reflects the current situation where fossil fuel is still the main power source to generate electricity for various purposes. The average m-Si solar panel lifetime was assumed to be 25 years as the other studies did (Rajput et al., 2016; Xu et al., 2018). GHG emission from the electricity consumption can be calculated by direct multiplication of total electricity consumption (kWh/g Spirulina) and the GHG emission of corresponding power supply scheme (PV powered or fossil fuel powered).

3. RESULTS AND DISCUSSION

3.1 Growth Rate of Spirulina

Fig. 2 showed that Spirulina growth in mixotrophic culture was better than the photoautotrophic one regardless of the light intensity. This result confirms the advantage of mixotrophic culture that can utilize both light as the source of energy and organic carbon in tempeh wastewater as biomass building block (Vonshak et al., 2000). Further inspection showed that the specific growth rate of mixotrophic culture was kept increasing, while the autotrophic culture was remained steady at 3000 lux illuminations or higher. This indicates the higher resistance of mixotrophic Spirulina to the stress conjured by high photon flux density (photoinhibition) in contrast to the photoautotrophic culture.

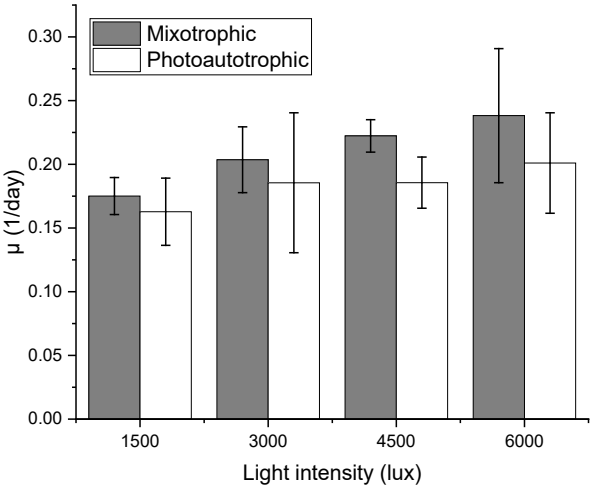

Fig. 2. Specific growth rates of Spirulina in photoautotrophic and mixotrophic culture under different light intensity

In terms of biomass productivity (Fig. 3), mixotrophic culture of Spirulina yielded more biomass than the photoautotrophic culture, which is in agreement with the other study (Kamalanathan et al., 2018). Interestingly, biomass concentration of mixotrophic culture yielded higher biomass concentration than photoautotrophic culture only at > 3000 lux intensity.

Further investigation on the growth kinetic of both cultures at 1500 lux (Fig. 4) validated the lower maximum growth of mixotrophic culture than the autotrophic culture at low light intensity. Similar finding was reported only as the insufficient contribution of lower light intensity towards biomass growth in mixotrophic culture (Vonshak et al., 2000). Based on the altering metabolic pathway theory in this study, lower biomass concentration of mixotrophic

culture at 1500 lux can be appropriately explained as the tipping balance of carbon fixation and carbon digestion in the low light intensity situation, where carbon fixation by photosynthesis is prominent regardless of the sufficient energy provided by the organic carbon breakdown.

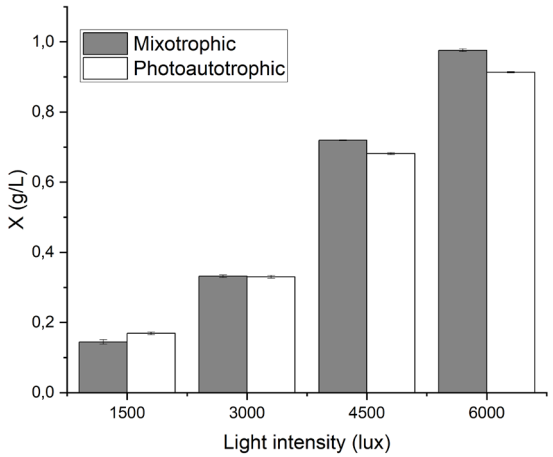

Fig. 3. Maximum Spirulina concentration in photoautotrophic and mixotrophic culture under different light intensity

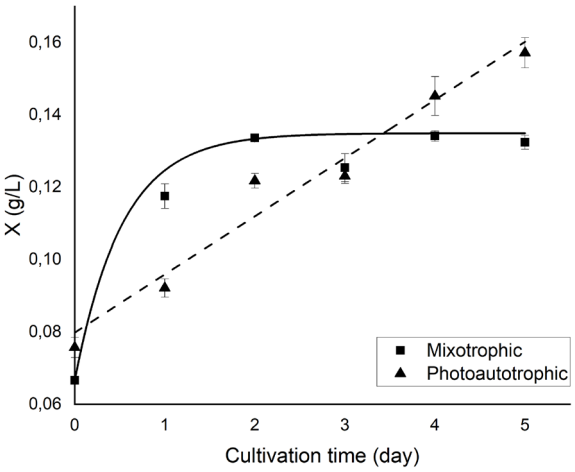

Fig. 4. Time profile of Spirulina concentration in photoautotrophic and mixotrophic culture at 1500 lux lighting

Based on biomass productivity (Fig. 5), mixotrophic culture was slightly able to excel photoautotrophic culture in terms of energy utilization. Increasing the light intensity further could lower increase energy utilization for both culture with more marked efficiency in mixotrophic culture due to higher amount of the obtained biomass concentration. Yet, closer inspection showed the effectivity of energy utilization became gradually insignificant with the increasing light intensity, reflecting photoinhibition effect. Based on the graph, 4500 lux was the most effective light intensity to produce Spirulina biomass by both cultivation modes. Therefore, the analysis of carbon footprint of Spirulina cultivation system will be focused on the mixotrophic culture at 4500 lux.

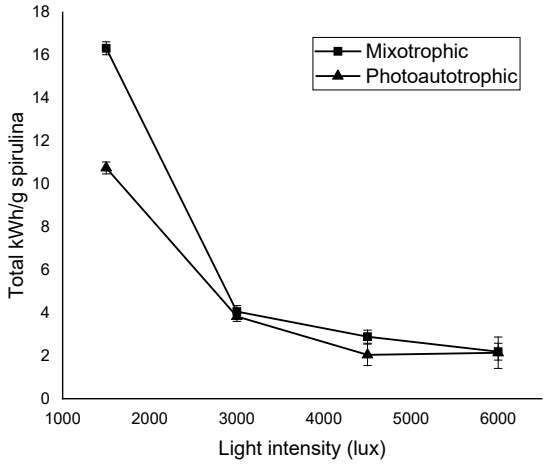

Fig. 5. Energy consumption per gram biomass in mixotrophic and photoautotrophic batch cultivation at different light intensities (a batch consists of 2 L starter and 4 L culture)

3.2 Technical and environmental assessment

As illustrated by Fig. 6, the installed solar PV system could meet the daily energy need of all lab-scale photobioreactor configurations regardless of the weather change from sunny to cloudy. Assuming the batch data can be translated without any deviation into 360 days-continuously operating plant, the solar PV electricity in this study potentially emitted 407.76 g CO_2 eq/kWh each year while producing 10.34 kWh/day. This means PV electricity can cut about 50% of the carbon footprint of electricity production in comparison to fossil fueled system.

To assess the cultivation plant system into a more realistic manner, system should involve all possibly GHG contributing elements and should be scaled up to approach the real-life situation. With actual daily wastewater generation rate at 5 m^3/day, the system has been increased 125000 times from the lab scale. Based on the GHG emission calculation (Fig. 7), annual GHG emission of PV-powered Spirulina cultivation showed about 5.9% less emission than the fossil fuel-powered scheme (118.91 kg CO_2 eq/year reduction from ~2000 kg CO_2 eq/year of fossil fuels powered process). Material (chemical fertilizer) was the major contributor of emission. Re-investigation of carbon footprint calculation involving a fixation of 1.83 kg CO_2 eq/kg Spirulina (Kumar et al., 2011) on the current system resulted in the mitigation of 234228.56 kg CO_2 eq annually, which is far beyond able to subset the potential annual GHG emission released by the cultivation system into the environment. Moreover, the use of tempeh wastewater in mixotrophic culture added a carbon reduction bonus via mitigation of uncontrollable CH_4 release that was equivalent to 1543.5 kg CO_2 annually (corresponded to the average COD removal of 62.2%).

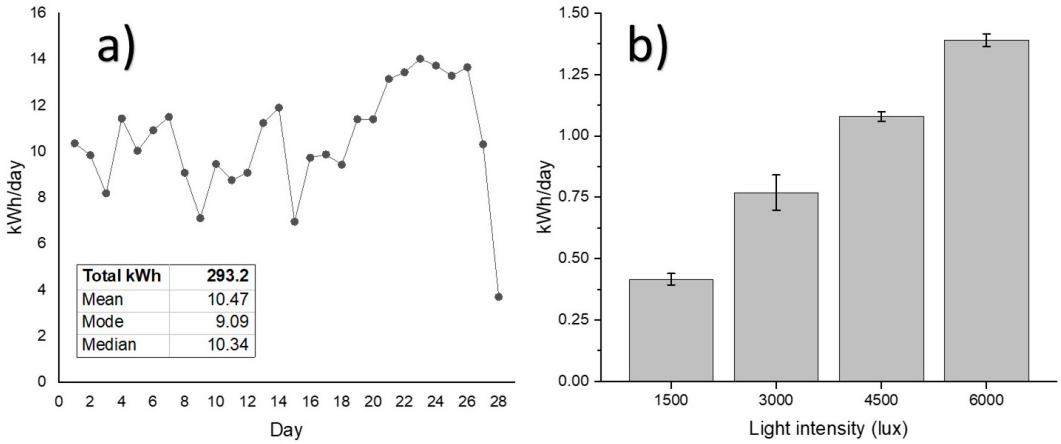

Fig. 6 (a) Daily energy generation by the solar PV system and (b) daily energy consumption of lab-scale cultivation plants (including liquid pumping, aeration, lighting and drying)

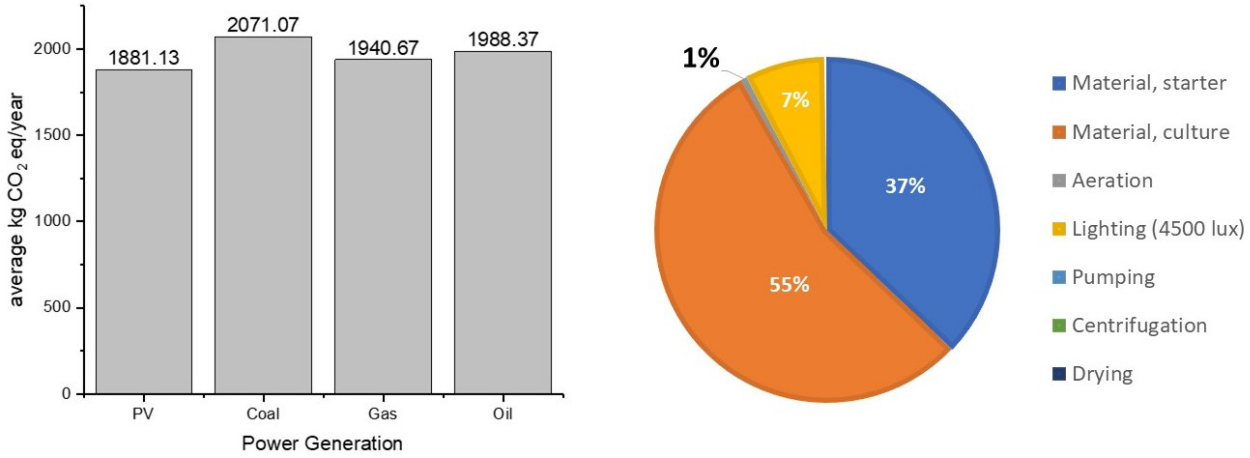

Fig. 7 Total annual GHG emission of Spirulina cultivation and its composition

4. CONCLUSION

Application of solar cell to power Spirulina cultivation was thoroughly studied. Mixotrophic cultivation technique yields more biomass than photoautotrophic cultivation due to more effective light and metabolic carbon utilization. The use of solar cell could lower down the carbon footprint of whole process at certain degree by substituting the use of electricity generated from the combustion of petroleum-based fuels. Mixotrophic cultivation techniques reduces more carbon footprint by cancelling the potential formation and release of CH_4 out from the digestion of not-utilized wastewater. Combination of solar cell and mixotrophic Spirulina cultivation is a green modern farming technology that has negative carbon net emission.

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Table S1. Life cycle inventory and energy consumption data

Starter Incubation					
Material	amount (g)		g CO_2/g		Ref.
$NaHCO_3$	4		1.17		Ecoinvent
NaCl	4		0.2		Ecoinvent
Urea	0.1		0.91		Ecoinvent
TSP	0.04		0.26		Ecoinvent
Cobalamin	0.08		not available		
Energy (kWh)	1500 lux	3000 lux	4500 lux	6000 lux	Ref.
Lighting	2.207	4.444	6.576	8.653	lab meas.
Aeration		0.56			lab meas.
Pumping		0.0001			Collet, 2011

Cultivation and Harvesting				
Material	amount (g)		g CO_2/g	Ref.
	Phototrophic	Mixotrophic		
$NaHCO_3$	3	3	1.17	Ecoinvent
NaCl	3	3	0.2	Ecoinvent
Urea	0.1	0	0.91	Ecoinvent
TSP	0.04	0	0.26	Ecoinvent
Tempeh Wastewater COD final	0	0.0834	1.875	IPCC guideline
Cobalamin	0.06	0.06	not available	

Energy (kWh)	1500 lux	3000 lux	4500 lux	6000 lux	Ref.
Aeration		0.399			lab meas.
Lighting	1.779	3.581	4.784	6.295	lab meas.
Pumping		0.0001			Collet, 2011
Centrifuging	5.68E-03	4.36E-02	8.16E-02	1.43E-01	Collet, 2011
Drying	0.024	0.186	0.348	0.608	lab meas.