Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

CASE STUDY

Sustainability index analysis of microalgae cultivation from biorefinery palm oil mill effluent

A.D. Santoso, J. Hariyanti, D. Pinardi, K. Kusretuwardani, N. Widyastuti, I.N. Djarot, T. Handayani, A.I. Sitomurni, H. Apriyanto

Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia

ARTICLE INFO

Article History:
Received 30 September 2022
Revised 04 December 2022
Accepted 12 January 2023

Keywords:
Biorefinery
Microalgae
Multidimensional scaling (MDS)
Palm oil mill effluent (POME)
Sustainability

DOI: 10.22035/gjesm.2023.03.13

ABSTRACT

BACKGROUND AND OBJECTIVES: Palm oil mill effluent is a liquid waste product of palm oil milling that contains abundant organic pollutants such as nitrogen and phosphorus that are potentially harmful to the environment. However, palm oil mill effluent can be used as a nutrient for the growth of microalgae with utility in pollutant removal and algae biorefinery production of biofuel and functional foods. The aim of the present study was to analyze the sustainability of microalgae biomass production by calculating a sustainability index.
METHODS: Questionnaires were used to evaluate the scientific judgment of expert researchers in the field of microalgae research. Data were processed and analyzed using multidimensional scaling comprising social, economic, ecological, and technological dimensions with a total of 47 attributes in Rapfish software.
FINDINGS: The sustainability index of microalgae biomass production was calculated as 73.53%, which indicates the process has the potential for sustainable development with consideration of the leverage factors identified in each dimension. Analysis of the four dimensions demonstrated that the environment dimension had the lowest leverage at 67.30%, while the economy, technology, and social dimensions had leverage values of 70.99%, 73.67%, and 82.17%, respectively. These findings indicate that management experience and skills (environment and technological dimensions), involvement of family members (social dimension), and productivity level (economic dimension) warrant further attention in order to improve the sustainability of microalgae biomass production.
CONCLUSION: The prospective analysis in the present study identified production, productivity, land conversion, consumption per capita, and population as key or dominant factors influencing the microalgae supply system. Further research is required to fully utilize microalgae biomass as a value-added product in optimal, technically, economically, environmentally, and socially sustainable systems. The results of the present study provide insights into the feasibility of sustainable microalgae biomass production in Indonesia that may inform governmental policies and programs.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
76	5	5

*Corresponding Author:
Email: *arif.dwi.santoso@brin.go.id*
Phone: +6285 28611 2334
ORCID: 0000-0003-3595-9265

Note: Discussion period for this manuscript open until October 1, 2023 on GJESM website at the “Show Article”.

INTRODUCTION

Production systems using microalgae, including eukaryotic algae and cyanobacteria, represent an alternative method of wastewater treatment that is environmentally friendly and sustainable. This system is also less energy-intensive and currently widely used (Sheehan *et al*., 2017). Microalgae cultivation utilizes the ability of microalgae to absorb carbon dioxide (CO_2) and survive in wastewater using nutrients present in wastewater such as nitrogen and phosphate among others. Untreated palm oil mill effluent (POME) contains large amounts of organic matter in the form of total suspended solids (TSS), volatile suspended solids (VSS), total solids (TS), and oil and grease (O and G), which increase the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of POME (Bala *et al*., 2015). POME also contains other macronutrients such as sulfur, potassium, calcium, and magnesium. Micronutrients that are required for microalgae growth and are typically present in POME include manganese, molybdenum, copper, iron, zinc, boron, chloride, and nickel. Certain algal species require other essential elements for growth such as sodium, silicon, cobalt, iodine, vanadine, and selenium (Larsdotter, 2006). A chelating agent (e.g., EDTA) is often added to commercial algal cultures to prevent growth limitation resulting from high concentrations of micronutrients (Oliver and Ganf, 2000). Given their unique characteristics, microalgae are considered to have potential utility in removing pollutants from POME. However, the high organic content of POME may limit the use of POME for the cultivation of microalgae (Low *et al*., 2021). Furthermore, the suspended solids responsible for the dark appearance of POME prevent photosynthesis by microalgae as light is unable to penetrate through POME. Accordingly, pre-treatment of POME is required to optimize the use of microalgae in treating POME (Sari *et al*., 2022). Components of POME including tannins, lignin, and phenolic have been shown to inhibit microalgae growth. Efficient removal of pollutants from POME has previously been demonstrated, including the removal of high proportions of COD, nitrogen (Kamyab *et al*., 2014), and phosphorous (Kietkwanboot *et al*., 2020). These studies demonstrate the potential utility of microalgae in low-cost wastewater treatments, including the treatment of POME. Besides being a renewable source of biomass, microalgae can be used in wastewater treatment as an effective and feasible CO_2 bio-fixation method (Almomani *et al*., 2019). The primary benefit of using microalgae in wastewater treatment is the formation of oxygen via photosynthesis, which is required for the biodegradation of carbon-containing compounds by heterotrophic bacteria. Previous studies have demonstrated microalgae can promote the elimination of pollutants from wastewater (Chawla *et al*., 2020). The combination of microalgae production and wastewater treatment in industries such as palm oil milling represents an example of a sustainable production system. Previous studies have reported efficient phosphorus elimination using microalgae and the recovery and utilization of phosphorous-rich microalgae biomass from wastewater (Cai *et al*., 2013). Furthermore, microalgae can efficiently capture CO_2 and remove micronutrients from wastewater that may have subsequent utility as potential energy sources (Kamyab *et al*., 2019b). Microalgae can utilize both organic nitrogen (similar to urea) and inorganic nitrogen (as ammonium or ammonia) in addition to nitrites and nitrates (Lage *et al*., 2021). Several microalgae have been cultivated in POME to produce biodiesel such as *Chlorella sp., Dunaliella salina, Chaetoceros calcitrans, Chaetoceros pyrenoidosa, Thalassiosira pseudonana Isocrysis* sp, and *Nannochloropsis oculate* (Kamyab *et al*., 2019a). Analyzing the nutrient content of wastewater provides an opportunity for the recycling of waste products as part of a circular economy. POME has been shown to contain proteins, oil and grease, phenol, nitrogen, phosphate, kalium, iron, sulfate, and ammonia (Mellyanawaty *et al*., 2018). The use of microalgae represents an economic approach to biofuel production as the abundant nutrients present in POME waste can be used as an alternative to expensive chemicals that are otherwise required for the growth of microalgae. The use of microalgae may also reduce energy consumption by utilizing sun light and minimizing the amount of electricity required for stirring (Nur *et al*., 2022). The use of POME has been shown to increase growth of *Chlorella sorokiniana* using a novel photobioreactor design (Cheah *et al*., 2020) and the production of third-generation biofuels (Pal *et al*., 2019). These experiments used microalgae that predominantly contained *Chlorella* sp. in addition to other bacteria, which is representative of natural microalgae found in Indonesia. Microalgae cultivation using both photobioreactors and open ponds is environmentally friendly as microalgae biomass can be used in biorefinery production, including biofuels (Show *et al.,* 2017), pharmaceuticals, nutraceuticals, cosmetics, and food and feed supplements (Begum *et al.*, 2016). These findings indicate that the nutrients contained in POME may have potential utility in reducing carbon emissions and the environmental impacts of wastewater. Furthermore, the use of POME may enhance the biomass yield of *Chlorella* sp. and therefore increase the yield of biodiesel production. Microalgae biomass resulting from phycoremediation during waste treatment can be used in sustainable biorefinery as a food source or a raw energy material, thereby contributing to a circular economy. Biorefinery from microalgae systems has several advantages, particularly compared to biofuel produced from conventional oilseeds. These advantages include the potential to grow microalgae on non-arable land, increased productivity, and the potential use of wastewater and gas flue as sources of nutrients and carbon to accelerate the growth of microalgae (Nurhayati and Basuni, 2013). State-of-the-art methods of producing microalgae biofuel using POME have demonstrated that microalgae typically out-perform other biomass-producing plants in terms of photosynthetic efficiency. Further, microalgae are capable of producing a wide range of renewable bioenergy sources such as biodiesel, bioethanol, biobutanol, bioelectricity, biohydrogen, and biomethane, among others. According to current research, microalgae appear to be the most promising renewable bioenergy source in Indonesia for replacing fossil fuels. Previous studies have shown that microalgae cultivation using POME reduces production costs. Compared to other biodiesel sources, microalgae represent the most promising substitute for fossil fuels (Table 1)

Indonesia is the largest palm oil producer in the world with a 23.2 million ha plantation area producing 46.22 million tons of crude palm oil (CPO) in 2021 (DGEC, 2021). However, palm oil production has led to the accumulation of huge amounts of POME disposed of as liquid waste. Furthermore, an estimated 5–7.5 tons of water are required to produce 1 ton of CPO (Susanto *et al.*, 2017). Environmental issues associated with POME disposal have led palm oil producers to re-evaluate and develop waste management strategies using a range of techniques. During the past two decades, several biological, physical, and chemical techniques have been reported as methods of treating POME; however, few have been accepted by the palm oil milling industry (Rana, *et al.*, 2017). Calculation of the sustainability index using MDS allows evaluation of the sustainability of biomass and biodiesel production. The impacts of industrialization on the environment have prompted policymakers to consider solutions that increase sustainability (Khan *et al.*, 2018). As the importance of sustainability is increasingly recognized, there is increasing need for instruments that allow the evaluation of sustainability. The sustainability index assesses the status of sustainable developments from the economic (business and industries) perspective while simultaneously evaluating social and environmental impacts. The sustainability index can be used to increase the efficiency and effectiveness of management policies. Technology and the environment are two dimensions that directly and simultaneously affect algae growth. The right environmental conditions can support rapid growth of microalgae (Sofiyah *et*

Tabel 1: Annual production and land required according to biodiesel source (Koyande *et al.*, 2019)

Type of source	Yield of biodiesel (L/ha/year)	Required Land (m^2/kg/biodiesel/y)
Microalgae	58,700–136,900	0.1–0.2
Palm oil	5,366	2
Castor	1,307	9
Sunflower	1,070	11
Repeseed	974	12
Camelina	915	12
Jatropha	741	15
Soybean	636	18
Hemp	363	31
Corn	172	66

al., 2021). Cultivation technologies can also increase algal growth (Harun *et al*., 2010). Accordingly, the creation of suitable environments using cultivation technologies can improve the yield of microalgae cultures. The economic dimension indirectly affects the growth of algae. Given the increasing demand for biomass and biodiesel, an increase in business scale and productivity is expected. Business scaling will likely increase the production POME, thereby potentially increasing algal yield. The social dimension is similar to the economic dimension and does not directly affect algal growth but remains quite important. As an example, levels of education and knowledge regarding environmental conservation (algae utilization) are increasing. However, palm oil producers must choose between the large number of treatment methods available when determining the most suitable waste utilization method according to the company's capabilities and considering the environmental, economic, social and technological impacts of the method chosen. In the present study, practical methods (namely MDS) were used to provide information that may inform CPO industry entrepreneurs when making decisions regarding waste management strategies. MDS is a statistical analysis tool that describes patterns of closeness in the form of similarity or resemblance. MDS can provide quantitative estimates of similarity between groups of items. MDS can transform consumer judgments of similarity or preference (e.g., preference for a store or brand) into distances represented in a multidimensional space. More formally, MDS refers to a set of statistical techniques that are used to reduce the complexity of datasets by providing a visual representation of the underlying relationships between groups (Hout *et al*., 2013). MDS is broad applications in many disciplines including the management of natural resources, marketing (Carroll and Green, 1997), political science, sociology (Russel and Bullock, 1985; Amato, 1990), and ecology (Kenkel and Orloci, 1986) among others. There are two advantages of MDS compared to other multivariate techniques. First, MDS analysis can be performed at the individual level by providing a perceptual map for multiple objects or subjects. However, multivariate MDS does not allow analysis at the individual level. Second, MDS allows the selection of dimensions without having to rigidly describe product attributes (Hout *et al*., 2013). The present study also provides information that may reduce economic costs and the price of microalgae-based biofuels. The objectives of the present study, in general, were to assess the sustainability of microalgae supply systems. Specifically, this study aimed to 1) determine the multidimensional sustainability index and status of microalgae production; 2) assess the sustainability index of each dimension of the sustainability index (socio-cultural, economic, ecological, and technological); 3) identify factors that affect microalgae production systems; and 4) determine the most dominant factor affecting microalgae production systems. A sustainability index for microalgae production systems may have utility as a reference for developing microalgae production systems that meet the needs of biorefinery for both current and future generations by managing factors that affect each dimension of the index, thereby improving methods of algal production. The present study was performed at the Research Center for Sustainable Production System and Life Cycle Assessment of the National Research and Innovation Agency, Indonesia in 2022.

MATERIALS AND METHODS

The present study was conducted at the Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, South Tangerang Regency, Banten Province, Indonesia.

Research materials

The present study evaluated the cultivation of *Chlorella sp*. with a bacterial consortium in POME in a 1 m^3 open raceway pond. Data were used to calculate the sustainability index of microalgae biomass production in Indonesia.

Study procedure

Researchers in the microalgae research community and the scientific judgment of experts were provided questionnaires regarding microalgae production. Data were processed and analyzed using the MDS method. MDS analysis was performed using Rapfish software (Pitcher and Preikshot, 2001). The present study analyzed four dimensions (social, economic, ecological, and technological) consisting of 47 attributes related to the environment, society, economy, and technology. Attributes in the environmental dimension were efficiency of chemicals use, water use, harvesting process, pollution potential, utilization of CO_2 gas and generated waste, level of exploitation of natural resources, and land conservation rate. Attributes in the social dimension were education level, involvement of family members, business motivation, the potential for public unrest, potential job loss, and knowledge of environmental conservation. Attributes in the economy dimension were productivity of biomass, potential for increasing business scale, efficiency or transportation, and level of management production. Attributes in the technology dimension were biomass production system, management experience and skills, production facilities, technological improvement potential, and biodiesel production system.

Data analysis

For MDS, points were mapped such that the distance between objects was proportional to their similarity. The ordination or distance determination techniques used in MDS are based on Euclidian distance in n-space using Eq. 1 (Alder *et al*., 2000; Pitcher and Preikshot, 2001).

$$d = \sqrt{\left(\left|x_1 - x_2\right|^2 + \left|y_1 - y_2\right|^2 + \left|z_1 - x_2\right|^2 + \ldots\right)} \quad (1)$$

Where, configurations of objects or points in MDS are approximated by regressing Euclidian distance (d_{ij}) from point i to point j with point of origin (o_{ij}) using Eq. 2 (Alder *et al*., 2000).

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (2)$$

The ALSCAL algorithm is used for regression in the above equation. The ALSCAL method optimizes squared distance (squared distance = d_{ijk}) against squared data (point of origin = o_{ijk}), which in three dimensions (i, j, k) is termed S-Stress using Eq. 3 (Alder *et al*., 2000).

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (3)$$

Where, the squared distance is Euclidian distance assigned a value using Eq. 4 (Alder *et al*., 2000).

$$d_{ijk} = \sum_{a=1}^{r} w_{ka}\left(x_{ia} - x_{ja}\right)^2 \quad (4)$$

The Rap-biomass ordination analysis of the sustainability of microalgae biomass production in Indonesia comprised a number of stages: 1) determination of microalgae biomass production sustainability attributes in Indonesia covering environmental, economic, social, and technology dimensions; 2) evaluation of each attribute on an ordinal scale (scoring) based on the sustainability criteria of each dimension; and 3) preparation of sustainability indices for microalgae biomass production. An ordinal scale was used to rank the sustainability attributes of each dimension from the least (0) to the greatest (3). Accordingly, the sustainability index was divided into four levels (Kavanagh and Pitcher, 2004); not sustainable (0%–25%), less sustainable (> 25%–50%), moderately sustainable (> 50%–75%), and sustainable (> 75%–100%). The sustainability levels of each dimension were also presented using a radar chart. The random errors for all dimensions were determined using the Monte Carlo approach. Outputs from the Monte Carlo and MDS analyses were compared, with a 95% degree of confidence indicating that the difference in value between the outcomes was 5%. The social, ecological, economic, and technological dimensions used in the present study of microalgae cultivation sustainability (Lam, 2016) are derived from known determinants of sustainability. Finally, a sensitivity analysis was performed to determine the variables with the greatest effect on the microalgae cultivation sustainability index. Several tests were used to determine data validity and the accuracy of the analysis. Stress values were calculated (standardized residual sum of a square), with stress values of 0.20 indicating 50% stress. Monte Carlo ordinated results were declared satisfactory if a narrow range of values was obtained. Previous studies using the MDS method are presented in Table 2.

RESULTS AND DISCUSSION

To determine the sustainability of the biorefinery process and identify related attributes, the sustainability index value was calculated using the MDS method. The dimensions of the MDS used in the present study were social, economic, environmental

Table 2: Previous studies using MDS analysis

No.	Title/topic of research	Dimensions of sustainability index	References
1	Palm oil-based bioenergy in Indonesia	Environmental, social, economic	(Papilo *et al.,* 2018)
2	Bioenergy policy: The biodiesel sustainability dilemma in Indonesia	Ecological, social, economic	(Dharmawan *et al.,* 2020)
3	Evaluating the sustainability of energy plantation forests in East Lombok District, Indonesia	Ecological, social, economic	(Narendra *et al*., 2019)
4	Evaluating the sustainability status of fisheries	Ecological, social, economic, ethical	(Pitcher and Preikshot 2001)
5	Assessing the potato farming index and the sustainability status of in Gowa	Ecological, social, economic, institutional	(Saidaa *et al.,* 2016)
6	Applying metric and nonmetric multidimensional scaling to ecological studies	Ecological	(Kenkel and Orloci, 1986)
7	Sustainable agricultural development	Ecological, social, economic, institutional	(Suardi *et al*., 2022)
8	Palm oil sustainable management	Social	(Dahliani and Maharani, 2018)

and technology. The data used for this calculation were obtained from questionnaire answers. The present also identified the attributes contributing to the sustainability of microalgae culture.

Index of sustainability

The attributes contributing to sustainability based on the scientific judgment of experts were used to determine the sustainability index for microalgae production. The determination of attributes should be specific and temporal (Pitcher and Preikshot, 2001). The attributes in the environmental, social, economy, and technology dimensions are presented in Table 3.

The attributes in the environmental dimension were efficiency of chemicals use, water use, harvesting process, pollution potential, utilization of CO_2 gas and generated waste, level of exploitation of natural resources, and land conservation rate. The attributes in the social dimension were education level, involvement of family members, business motivation, the potential for public unrest, potential job loss and, knowledge of environmental conservation. Attributes in the economy dimension were productivity of biomass, potential for increasing business scale, efficiency or transportation, and level of management production. Technology attributes consisted of biomass production system, management experience and skills, production facilities, technological improvement potential, and biodiesel production system. To determine the sustainability of the biorefinery process used in biomass microalgae production, the attributes in each dimension were formulated into a sheet questionnaire and provided to relevant experts to obtain their scientific judgment. Furthermore, the results of the experts' assessments were analyzed using the MDS method in Rapfish software. The calculated sustainability indices for each dimension are presented in Table 4.

The conditions for sustainable microalgae cultivation are determined by environmental carrying capacity, production input availability, production processes, product processing, marketing of microalgae, and the role of related institutions. The results of our MDS analysis of sustainable microalgae cultivation are presented in Fig. 1. As measures of the validity and accuracy, we observed a stress value of 0.14 (stress 50%) and almost identical results from the Monte Carlo test between dimensions, i.e.,. the technological attribute (73.67%) and the economic attribute (70.99%).

Environmental dimension

The sustainability index for the environmental dimension was 67.30%, with the ability of microalgae to utilize industrial CO_2 being the most impactful attribute (Table 4). On the other hand, the most

Table 3: List of dimensions and their attributes

Environmental	Social	Economy	Technology
1. Efficiency level in the use of materials (biodegradable) for the manufacture of biomass production reactors 2. Efficiency level in the use of materials (non-biodegradable) for the manufacture of biomass production reactors 3. Efficiency level in the use of chemicals for media/fertilizers with POME 4. Efficiency level of fuel use for harvesting and drying biomass 5. Water use efficiency (biomass) 6. Potential for air pollution (biomass) 7. Potential for water pollution (biomass) 8. Utilization of CO_2 emissions from industry 9. Utilization of generated waste (biomass) 10. Level of exploitation of natural resources for reactor construction 11. Land conservation rate 12. Efficiency level in the use of basic materials (microalgae biomass) for biodiesel production 13. Efficiency level of use of chemicals (biodiesel) 14. Efficiency level of fuel use (biodiesel) 15. Water use efficiency (biodiesel) 16. Potential for air pollution (biodiesel) 17. Potential for water pollution (biodiesel) 18. Utilization of generated waste (biodiesel)	19. Officer education level 20. Involvement of family members in household scale microalgae biomass production 21. Business motivation 22. The potential for public unrest due to the production process 23. Potential job loss 24. Level of knowledge on environmental conservation and restoration 25. Officer education level (biodiesel) 26. Involvement of family members in household-scale microalgae biodiesel production 27. Business motivation (biodiesel) 28. The potential for public unrest due to the boidiesel production process 29. Potential job loss (biodiesel)	30. The productivity level of microalgae biomass with POME 31. Production management level (biomass) 32. Potential for increasing business scale (biomass) 33. Contribution to improving food welfare (biomass) 34. Transport Efficiency Level (biomass) 35. The productivity level of biodiesel 36. Production management level (biodiesel) 37. Potential for increasing business scale (biodiesel) 38. Contribution to increase in fuel/biodiesel substitution 39. Transport Efficiency Level (biodiesel)	40. Biomass production system 41. Management experience and skills (biomass) 42. Availability of production facilities (biomass) 43. Technological improvement potential (biomass) 44. Biodiesel production system 45. Management experience and skills (biodiesel) 46. Availability of production facilities (biodiesel) 47. Technological improvement potential (biodiesel)

impactful environmental attribute was utilization of generated waste. During cultivation of microalgae, it is conceivable to put through wastewater treatment and CO_2 sources (Handayani *et al.,* 2020). Microalgae can grow in any medium that contains the nutrients required for their growth. Nutrients required for

Table 4: Sustainability index results for environmental, social, economy and technology dimensions with data quality indices

Dimension	Index (%)	Stress	R^2(SQR)
Environmental	67.30	0.13	0.95
Social	82.17	0.13	0.95
Economy	70.99	0.14	0.95
Technology	73.67	0.14	0.95
Average	73.53	0.14	0.95

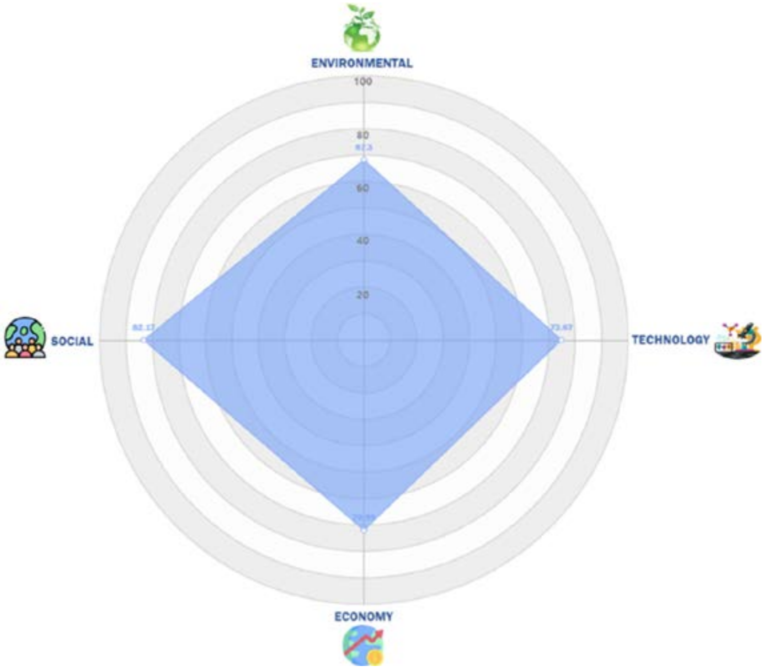

Fig. 1: Sustainability status of microalgae biomass production for biorefinery

microalgae growth include nitrogen, phosphorus, and carbon, which are commonly found in POME ponds (Zullaikah *et al*., 2019). In addition to nutrients found in POME, the growth rate and lipid content of microalgae can be influenced by light intensity, glucose concentration, and carbon dioxide concentration (Chew *et al*., 2018). Many studies have indicated that POME is an ideal medium for microalgae cultivation as it contains all nutrients required for microalgae growth in open ponds with sufficient sunlight. The POME constituents and conditions that are required for microalgae growth are presented in Table 5.

A previous study stated that the potential environmental benefits of using CO_2 from flue gas and wastewater from microalgae cultures for the generation of biofuels (Collotta *et al*., 2018). Before wastewater is released into waterways, it must first be treated to remove phosphate and nitrate. The utilization of CO_2 emissions from power plants to support algae cultivation may contribute to reductions in CO_2 emissions into the environment. Of note, the carbon footprint of algae-based biodiesel is lower than that of conventional diesel (Naeini *et al*., 2020). Microalgae consume CO_2, which is discharged into the atmosphere in power plant exhaust gases (Handayani *et al*., 2018). Accordingly, carbon taxes, carbon trading, and carbon subsidies may have a significant impact on the viability of algal biofuels in the future. The ability of microalgae to absorb and capture CO_2 should be considered when developing policies aimed at increasing CO_2 capture, particularly from power plants. The utilization of industrial CO_2 therefore had the greatest leverage of all environmental attributes included in the present study.

Table 5: POME constituents and conditions (Sasongko *et al*., 2014)

Parameters		Cooling pond (Inlet)	Aerobic pond (Outlet)
Total COD	(g/L)	40–90	0.35–1.3*
Total BOD	(g/L)	15–30	0.1–0.7*
TSS	(g/L)	20–40	0.70
TDS	(g/L)	15–30	
VSS	(g/L)	15–35	
Total Carbohydrate	(g/L)	29–45	
Total Proteins	(g/L)	17–32	
Total Lipids	(g/L)	15–23	
Total N	(g/L)	0.149*	0.456–0.750*
NH_3+N	(g/L)	0.050*	0.0342
Total P (PO_4^+)	(g/L)	0.315*	0.068–0.018*
K	(g/L)	1–2.5	0.110–0.924
Mg	(g/L)	0.25–1	0.017–0.0152
Temperature (°C)		70–80	30–40
pH		4–5	7

*Sample measured at PTPN, Riau.

The metabolism of CO_2 by microalgae represents a potential method of disposing of POME waste produced by palm oil plantations. Compared to terrestrial oil-producing plants, microalgae produce 30 times more oil per unit area of land (Hadiyanto and Nur, 2012a). This difference is attributable to microalgae generally being more efficient in converting solar energy despite the similar photosynthesis mechanisms between microalgae and higher plants. Microalgae have a simplified cellular structure that allows greater access to water, CO_2 and other nutrients (Sheehan *et al*., 1998). Moreover, nitrogen and phosphorus required for cultivation of microalgae can be obtained from wastewater effluent. Wastewater effluents such as POME may provide an appropriate environment for microalgae growth (Cantrell *et. al*., 2008). Biological processing of POME involving microalgae is a considered a better method than anaerobic digestion as microalgae consume organic substances as nutrients to produce biomass as an energy source and reduce the harmful effects of POME on the environment (Nurhayati and Basuni, 2013). The biotreatment of POME using microalgae is particularly beneficial for palm oil manufacturers (Rani *et al*., 2015) as the process is environmentally and economically friendly (Chai *et al*., 2021). Other benefits of using microalgae usage include the absorption of CO_2 from the atmosphere and release of oxygen (Francisco *et al*., 2010). Utilization of wastewater in an integrated manner and renewable bioenergy production are added benefits that may be profitable for palm oil industries (Ahmad *et. al*., 2016). The cost of bioenergy production remains higher than the extraction of conventional fuel sources (Kamyab *et.al*., 2017), particularly for lipid extraction (Lee *et al*., 2021). However, integration of biofuel production into biorefinery pathways may increase the recovery of value-added products (Chia *et. al*., 2018).

Social dimension

Social sustainability can be achieved through the implementation of regulation to reduce negative impacts and promote family-run businesses. Among the attributes in the social dimension, involvement of family members in the household had the highest score and business motivation (biodiesel) had the second highest score. In family-run companies, many employees are family members and are willing to provide the company with their own resources, thereby reducing the financial burden on the company. The organization of family-owned companies can also allow managers to focus on managing the company. The present analysis found a sustainability index value of 82.17% for the social dimension, which this indicates that the social impacts of microalgae production are quite sustainable. The social factors identified as impacting on biomass production systems were land ownership rights, local resource management, and labor rights. Social sustainability of microalgae biomass production is influenced by land ownership rights and promotes reforesting. Family member involvement in family-run microalgae biodiesel production had a significant impact on the sustainability status of microalgae cultivation. This

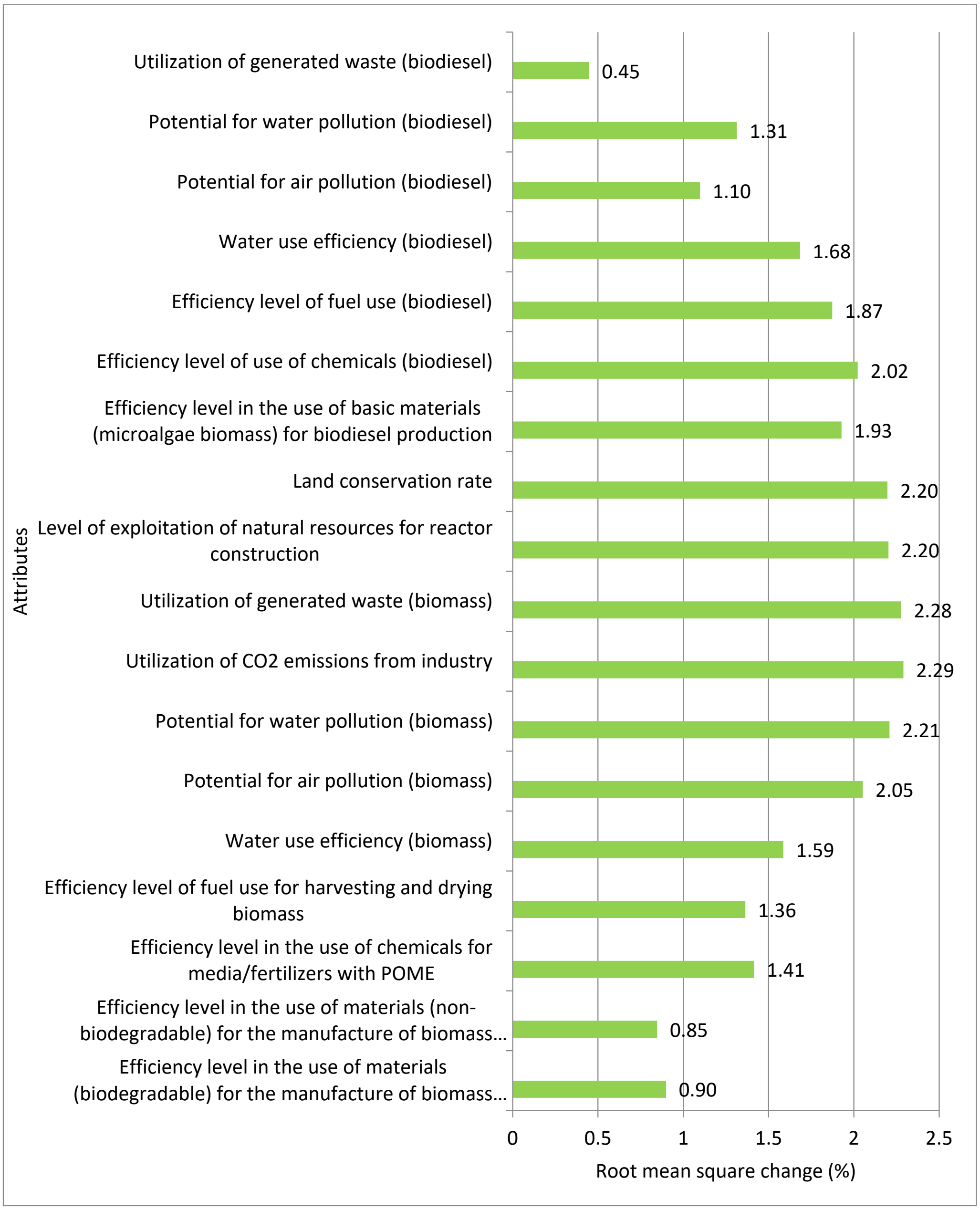

Fig. 2: Leverage of environmental attributes

result corroborates previous research demonstrating that microalgae photobioreactors (PBR) are typically used in low and middle-income countries (Osama *et. al*., 2021).

The management of local common property resources such as shared land, community forest, rivers and riverbeds, and dredging grounds also influences social sustainability. The approval of proposals for micro algae biomass production by management was also particularly important as this allows businesses to be supported by local property management in times of need. Microalgal biomass production contributes to job creation and rural prosperity by increasing the flow of capital, fertilizer, infrastructure, and technology into the agricultural sector, thereby creating jobs, increasing wages, and increasing self-sufficiency in terms of access to electricity and portable pumps. Water pumping without causing adverse impacts is another factor contributing to the social sustainability of microalgal biomass production (Culaba *et al*., 2020). The above factors have been shown to be linked through circular reasoning (Levidow, 2013).

Economic dimension

The sustainability index of the economy dimension was 70.99%, with production management level and the productivity level of biodiesel found to have the greatest leverage on the sustainability of microalgae cultivation (Fig. 4).

The productivity of biodiesel production relies on the availability of capital, people, and technology. In micro-scale production, productivity standards are used to assess the efficiency of machines, factories, companies, systems, or people in converting inputs into desired outputs. In producing biodiesel from microalgae, the level of productivity determines sustainability, particularly in terms of selecting and acquiring raw materials that meet the specification required for biodiesel production. The level of biodiesel production management also affects sustainability. Production management includes planning, organizing, directing, and effectively controlling production. Production management acts to coordinate activities to achieve business goals. Accordingly, production proceeds in accordance with previous planning. The attribute "potential for business scale-up" had the third highest leverage on the sustainability of biodiesel production in the present study. This finding may be attributable to long-term costs, where average production costs are reduced as business size increases (Irawan and Hutabarat, 2016). Planning businesses at large scale may reduce the need for future expansion (Hadiyanto *et al*., 2012b).

Technological dimension

The present analysis found that the technology dimension had a relatively high sustainability index value of 73.67%. This indicates that the technological impacts of microalgae production are quite sustainable (Table 4). Management experience and skills in biodiesel production had the greatest impact on sustainability. The availability of biomass and biodiesel production facilities was also identified as an important factor

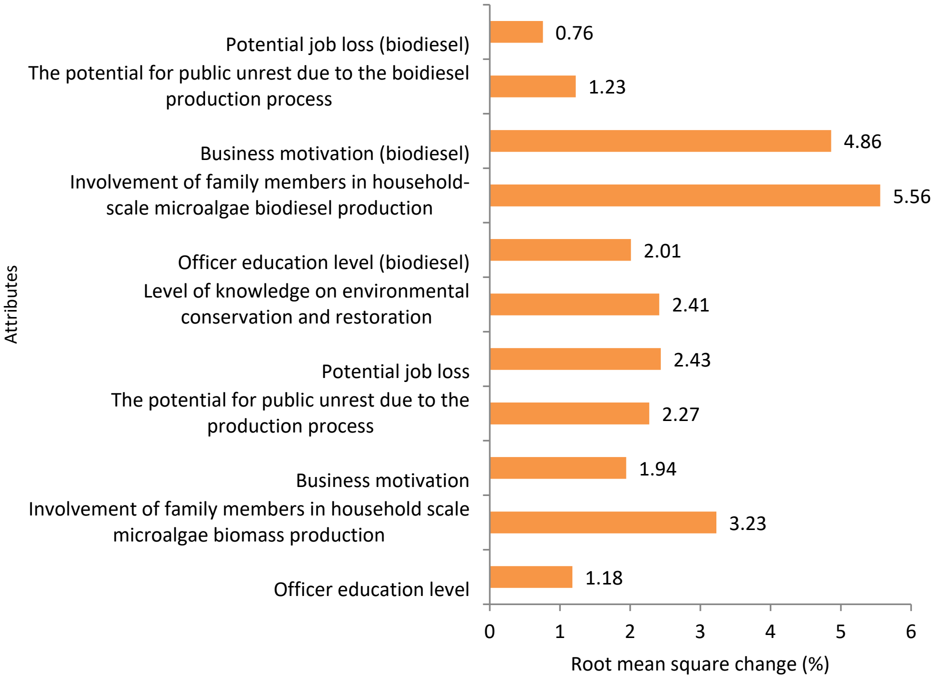

Fig. 3: Leverage of social attributes

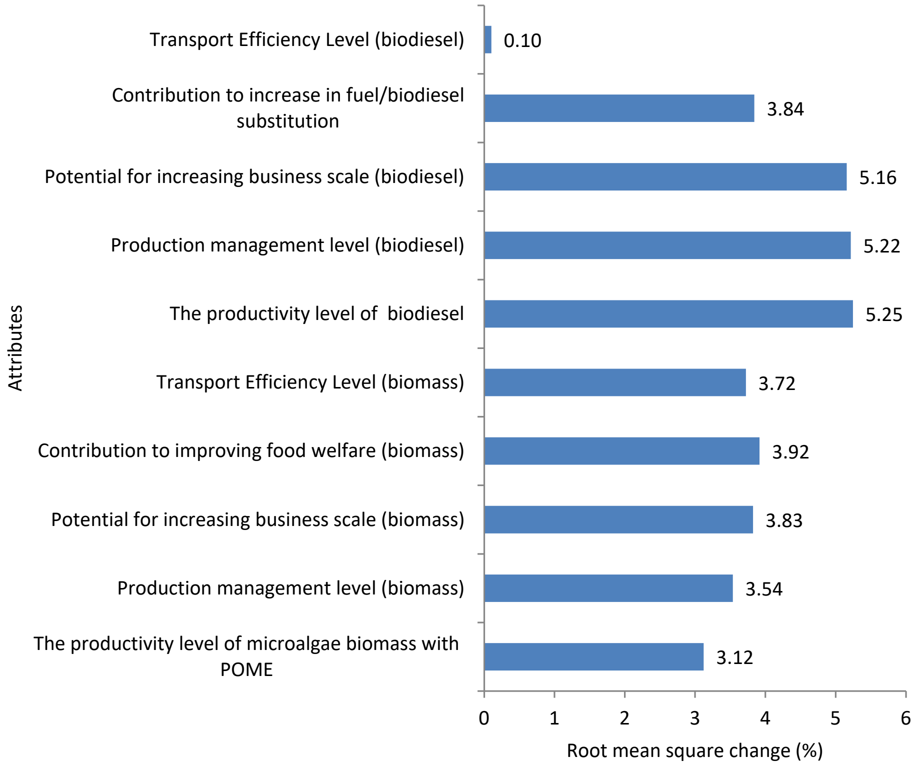

Fig. 4: Leverage of economic attributes

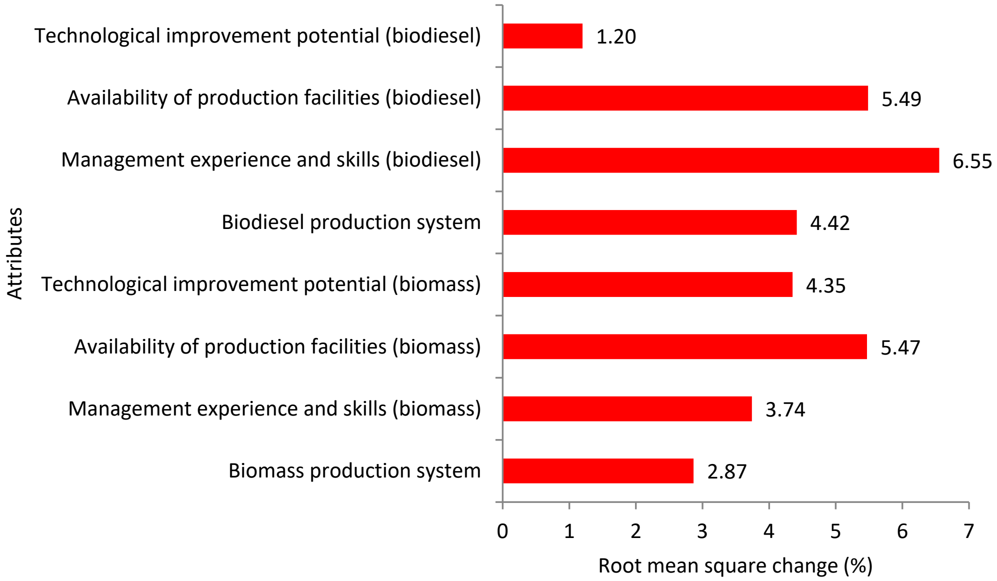

Fig. 5: Leverage of technology attributes

which may have a positive effect on employment opportunities for the surrounding community involved in production. The attribute of management experience and skill had the greatest leverage on the sustainability of microalgae cultivation (Fig. 5). These findings are in line with a report by Responsible Seafood in 2022 suggesting operators of an aquaculture hatchery should consider versatile microalgae production.

The analysis of the eight attributes in the technology dimension demonstrated that management experience and skills in biodiesel production had the greatest leverage on the sustainability index value. The sustainability index value provides information of the sustainability of biofuel production from microalgae biomass and the feasibility of increasing biodiesel production from microalgae in the future. However, the slow speed of technological innovation for scaling-up biodiesel production from microalgae makes it uneconomical for commercial-scale investment compared to the production of biodiesel from other feed stocks. Companies may cease to be viable without sufficient technological innovation. Increasing cooperation between companies and research institutions is important for increasing the development of technologies. Innovation roadmaps utilizing public funds for research development may also lead to the creation of new businesses. Management experience and skills in biodiesel production provide novel ideas that require implementation for commercial-scale production. The short-term outlook for microalgae biodiesel appears bleak; however, aviation technology may contribute to future development programs for biodiesel production (Patnaik and Mallick, 2021). The most critical issues to be addressed by innovations in microalgae technology are increasing growth rate and productivity while minimizing land conversion and consumption (Khan *et. al*., 2018). As microalgae biorefinery becomes increasingly important, there is a greater need for the development of more advanced technologies in the field of biorefinery and wastewater management (Chowdury *et. al.*, 2020). Biological processing of palm oil liquid waste using microalgae helps preserve the environment in addition to being very profitable for producers (Bala *et. al*., 2014). Utilization of microalgae reduces the pollutant content of POME, removes CO_2 from the atmosphere, and produces O_2, which have beneficial effects on the environment (Nur and Buma, 2019).

Future prospects for microalgae production using POME

South East Asia is the region with the highest palm oil production worldwide. South East Asia's coconut palm oil (CPO) production accounts for 88.6% of global production at 54.38 million tons, rising from 40.33 to 48.12 million tons between 2010 and 2013 (FAOSTAT, 2016). Within this region, Indonesia is currently the leading producer of CPO, followed by Malaysia and Thailand. CPO production in Indonesia increased by 30.14% between 2010 and 2014. Indonesia's palm oil industry continues to grow and now has the highest CPO production worldwide at 32 million tons, accounting for approximately 46.6% of total CPO production worldwide. Global demand for CPO continue to increase and was estimated to be 95.7 million tons in 2020 (Low *et al*., 2021). The Central Bureau of Statistics noted that Indonesia's oil palm production has substantially increased in the past five years. In 2019, production reached 48.42 million tons, an increase of 12.92% from the previous year. Palm oil production continued to increase from 31.07 million tons in 2015 to 31.49 million tons a year later (BPS, 2020). The greatest increase was between 2017 and 2018 where production increased from 34.94 million tons to 42.88 million tons, an increase of approximately 22.72% (Annur, 2020). According to recent information on oil palm production, the South East Asian region faces serious environmental issues. Large amounts of POME wastewater are generated by the wet processing system, which may be harmful to the environment. Different cultivation modes, careful species selection, and different conditions can improve the growth, biomass yield, and productivity of several value-added products from microalgae grown in wastewater. The ability of microalgae to remove unwanted products determines their performance in treating POME. Many undesirable products are present in POME wastewater that are also pollutants that can harm the environment and require treatment to prevent pollution by POME. Microalgae can remove pollutants, thereby providing a cost-effective and long-term solution for POME treatment (Kamarudin *et al*., 2015). There are numerous advantages to using microalgae to treat POME, including reduced pollutant content in wastewater. This technology may also have applications in other sectors. Microalgae grown in POME can be used as a feedstock for the production of biofuels as microalgae have a high biomass yield and can be cultured on smaller land areas that are not suitable for food production (Benedetti *et al*., 2018).

CONCLUSIONS

The data validity and accuracy in the present study had a stress value of approximately 0.14 (stress 50%). In addition, the results of Monte Carlo ordination demonstrated that technological and economical attributes had similar values of 73.67% and 70.99%, respectively. The ability of microalgae to absorb and capture CO_2 can inform future policies for CO_2 capture, particularly from power plants. The present study found that increasing usage of industrial CO_2 had the highest leverage on the environmental impacts of microalgae production. The social sustainability of microalgae biomass production was influenced by land ownership rights allowing successful reforestation. Involvement of family members in household microalgae biodiesel production had a significant influence on the sustainability of microalgae cultivation, with management of local common property resources such as shared land, community forest, rivers and riverbeds, and threshing grounds also contributing. Approval of proposals for micro algae biomass production was also particularly important by allowing businesses to run at the cost of local property management in times of need. Business management allows coordination of activities to achieve business goals. The use of innovation roadmaps for utilizing public funds for research development may lead to the establishment of new businesses. Management experience and skills on biodiesel production may provide novel ideas for commercial-scale production. The average sustainability index value in the present study was 73.53%, indicating microalgae production is sustainable. This finding indicates the treatment of POME with a combination of microalgae and bacterial consortia represents a potentially sustainable method of POME processing. There is a need for continued research on microalgae biomass to improve yields of value-added products using optimal, sustainable, and economical cultivation systems. The concept of sustainable POME processing using microalgae proposed in the present study appears to have high feasibility for implementation in Indonesia.

RECOMMENDATIONS

Research on POME processing using microalgae remains in its infancy. As a result, combining a microalgal system with traditional POME treatment appears promising and feasible. Given its potential as a source of bioenergy, the integration of microalgal culture into currently used POME treatment systems has become much more feasible. To maximize the socio-economic benefit of algae-derived biodiesel development, areas with a high socio-economic impact multiplier should be chosen while taking into account regional climate, marginal land, and socio-economic factors. As a promising and sustainable source of biofuel that can help reduce atmospheric greenhouse gas emissions, microalgal biomass has been demonstrated to be one of the most efficient and environmentally friendly alternative energy sources. The implementation of a biorefinery approach with the recovery of many products from a single operational process provides an opportunity for the development of microalgal biomass-based technologies. A biorefinery platform based on the transformation of microalgal biomass into fuels, food, dietary and feed supplements, fertilizers, and pharmaceuticals represents one of the most promising methods for achieving this goal according to the biorefinery complexity index.

AUTHOR CONTRIBUTIONS

T. Handayani performed the literature review, designed the study, supervised the experimental work, and drafted the manuscript. A.D. Santoso performed the literature review, performed experimental work, and drafted and prepared the manuscript. J. Hariyanti supported experimental and administrative work and provided technical and material assistance. Kusrestuwardani supported experimental work and data acquisition. D. Pinardi performed data analysis and interpretation. H. Apriyanto performed statistical analysis. A.I. Sitomurni performed manuscript preparation and critical revisions. I.N. Djarot performed critical revisions and supervised manuscript preparation. N. Widyastuti supervised all experiments and manuscript preparation.

ACKNOWLEDGMENTS

The authors are grateful to the Head of Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia. The authors would like to thank the editors and anonymous reviewers for their constructive comments.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

OPEN ACCESS

PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
ASCAL	Alternating least-squares algorithm
BOD	Biological oxygen demand
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CPO	Coconut palm oil
d	Euclidian distance
d_{ij}	Euclidian distance from point i to point j
d_{ijk}	Squared distance
Fe	Iron
K	Kalium
MDS	Multidimensional scaling
Mg	Magnesium
mg/L	Miligram per liter
N	Nitrogen
NH_3	Amonia
O_{ij}	Point of origin
O_2	Oxygen
pH	Potencial of hydrogen
PBR	Photobioreactor
PO_4^+	Ortofosfat
P-rich	Phosphate-rich
POME	Palm oil mill effluent
PTPN	Perseroan terbatas perkebunan nusantara, an Indonesian state-owned company engaged in the plantation sector
Rapfish	Rapid appraisal for fisheries
RMS	Root mean square
SQR	Structured query reporter
TDS	Total dissolved solid
TSS	Total suspended solid
VSS	Volatile suspended solid

REFERENCES

Ahmad, A.; Buang, A.; Bhat, A.H., (2016). Renewable and sustainable bioenergy production from microalgal co-cultivation with palm oil mill effluent (POME): A review. Renew. Sustain. Energy Rev., 65(C): 214–234 **(21 pages).**

Alder, J.; Pitcher, T.J.; Preikshot, D.; Kristin, K.; Ferriss, B., (2000). How good is good?: A rapid appraisal technique for evaluation of the sustainability status of fisheries of the North Atlantic. Fisheries Centre, University of British Columbia, Canada **(47 pages)**.

Almomani, F.A.; örmeci, B.; Kiely, P., (2019). Improving the performance of attached-growth wastewater treatment processes by altering the support media surface. J. Environ. Eng., 145(8): 04019045.

Amato, P.R., (1990). Dimensions of the family environment as perceived by children: A multidimensional scaling analysis. J. Marriage Fam., 52(3):613–620 **(7 pages)**.

Annur, C.M., (2020). Produksi Perkebunan Kelapa Sawit Indonesia Terus Naik dalam Lima Tahun Terakhir.

Bala, J.D.; Lalung, J.; Ismail, N., (2014). Palm oil mill effluent (POME) treatment microbial communities in an anaerobic digester: A review. Int. J. Sci. Res. Publ., 4(6): 1–24 (**24 pages**).

Bala, J.D.; Lalung, J.; Ismail, N., (2015). Studies on the reduction of organic load from palm oil mill effluent (POME) by bacterial strains. Int. J. Rectal. Org. Waste Agric. 4(1): 1–10 (**10 pages**).

Begum, H.; Yusoff, F.M.D.; Banerjee, S.; Khatoon, H.; Shariff, M., (2016). Availability and utilization of pigments from microalgae. Crit. Rev. Food Sci. Nutr., 56(13): 2209–2222 **(14 pages)**.

Benedetti, M.; Vecchi, V.; Barera, S.; Dall'Osto, L., (2018). Biomass from microalgae: The potential of domestication towards sustainable biofactories. Microb. Cell Factories., 17(173): 1–18 **(18 pages).**

BPS, (2020). Indonesian oil palm statistics, 1. BPS Statistics Indonesia, Jakarta, 1: 7–8 **(2 pages).**

Cai, T.; Park, S.Y.; Li, Y., (2013). Nutrient recovery from wastewater streams by microalgae: Status and prospects. Renew Sustain Energy Rev., 19: 360–369 **(10 pages).**

Cantrell, K.B.; Ducey, T.; Ro, K.S.; Hunt, P.G., (2008). Livestock waste-to-bioenergy generation opportunities. Bioresour. Technol., 99(17): 7941–7953 **(13 pages)**.

Carroll, J.D.; Green, P.E., (1997). Psychometric methods in marketing research: Part II, multidimensional scaling. J. Mark. Res., 34(2): 193–204 **(12 pages)**.

Chai, W.S.; Tan, W.G.; Halimatul, H.S.; Gupta, V.K.; Ho, S.H.; Show, P.L., (2021). Multifaceted roles of microalgae in the application of wastewater biotreatment: A review. Environ. Pollut., 269: 116–236 **(21 pages).**

Chawla, P.; Malik, A.; Sreekrishnan, T.R.; Dalvi, V.; Gola, D., (2020). Selection of optimum combination via comprehensive comparison of multiple algal cultures for treatment of diverse wastewaters. Environ. Technol. Innovation. 18: 100758.

Cheah, W.Y.; Show, P.L.; Yap, Y.J.; Mohd Zaid, H.F.; Lam, M.K.; Lim, J.W.; Ho, Y.C.; Tao, Y., (2020). Enhancing microalga Chlorella sorokiniana CY-1 biomass and lipid production in palm oil mill effluent (POME) using novel-designed photobioreactor. Bioengineered. 11(1): 61–69 **(9 pages).**

Chew, K.W.; Chia, S.R; Show, P.L.; Yap, Y.J.; Ling, T.C., (2018). Effects of water culture medium, cultivation systems and growth modes for microalgae cultivation: A review. J. Taiwan Inst. Chem. Eng., 91: 332–344 **(14 pages)**.

Chia, S.R.; Chew, K.W.; Show, P.L.; Yap, Y.J.; Ong, H.C.; Ling, T.C.; Chang, J.S., (2018). Analysis of economic and environmental aspects of microalgae biorefinery for biofuels production: A review. Biotechnol. J., 13(6): e1700618.

Chowdury, K.H.; Nahar, N.; Deb, U.K., (2020). The growth factors involved in microalgae cultivation for biofuel production: A review. Comput. Water Energy Environ. Eng., 09(4): 185–215 **(30 pages)**.

Collotta, M.; Champagne, P.; Mabee, W.; Tomasoni, G., (2018). Wastewater and waste CO2 for sustainable biofuels from microalgae. Algal Res., 29: 12–21 **(10 pages)**.

Culaba, A.B.; Ubando, A.T.; Ching, P.M.L.; Chen, W.H.; Chang, J.S., (2020). Biofuel from microalgae: Sustainable pathways. Sustainability. 12(19): 8009 **(7 pages)**.

Dahliani, L.; Maharani, M.D.D., (2018). Palm oil sustainable management using MDS model from social dimension. 5th International Conference on Community Development. AMCA. Adv. Soc. Sci. Educ. Hum. Resour., 231.

Dharmawan, A.H. Fauzi, A.; Putri, E.I.K., (2020). Bioenergy Policy: The biodiesel sustainability dilemma in Indonesia. Int. J. Sustain Dev. Plan., 15(4): 537–546 **(10 pages).**

DGEC, (2021). The Crop Estate Statistics of Indonesia: 2019-2021 Palm Oil, Secretariat of Directorate General of Estate Crops, Jakarta **(105 pages).**

FAOSTAT, (2016). Crops processed database [Internet]. Food and Agriculture Organization of the United Nations.

Francisco, É.C.; Neves, D.B.; Jacob-Lopes, E.; Franco, T.T., (2010). Microalgae as feedstock for biodiesel production: Carbon dioxide sequestration, lipid production and biofuel quality. J. Chem. Technol. Biotechnol., 85(3): 395–403 **(9 pages).**

Hadiyanto, W.; Kumoro, A.C., (2012a). Potency of microalgae as biodiesel source in Indonesia. Int. J. Renew Energy Dev., 1(1): 23–27 (**5 pages).**

Hadiyanto, H.; Nur, M.M.A.; Hartanto, G.D., (2012b). Cultivation of Chlorella sp. as biofuel sources in palm oil mill effluent (POME). Renew Energy Dev., 2(1): 45–49 **(5 pages).**

Handayani, T.; Mulyanto, A.; Priyanto, F.E., (2018). Growth performance of fresh water microalgae Chlorella sp. exposed to carbon dioxide. Int. J. Environ. Sci. Dev., 8(11): 767–771 (**5 pages**).

Handayani, T.; Mulyanto, A.; Priyanto, F.E.; Nugroho, R., (2020). Utilization of dairy industry wastewater for nutrition of microalgae Chlorella vulgaris. J. Phys: Conf. S., 1655(1): 1–7 **(7 pages).**

Harun, R.; Singh, M.; Forde, G.M.; Danquah, M.K., (2010). Bioprocess engineering of microalgae to produce a variety of consumer products. Renew Sustain. Energy Rev., 14(3): 1037–1047 **(10 pages).**

Hout, M.C.; Papesh, M.H.; Goldinger, S.D., (2013). Multidimensional scaling, WIREs Cogn. Sci., 4(1): 93–103 **(11 pages).**

Irawan, B.; Hutabarat, B., (2016). Analisis efisiensi penggunaan masukan dan ekonomi skala usaha pada usahatani tebu di Jawa Timur. Agro Ekon., 10(1-2): 73–90 **(18 pages).**

Kamarudin, K.F.; Ding, G.T.; Yaakob, Z.; Takriff, M.S., (2015). A review on wastewater treatment and microalgal by-product production with a prospect of palm oil mill effluent (POME) utilization for algae. Pharm. Chem., 7(7): 73–89 (**17 pages).**

Kamyab, H.; Chelliapan, S.; Kumar, A.; Rezania, S.; Talaiekhozani, A.; Khademi, T.; Fatemeh, P.; Rupani, S.; (2019a). Microalgal biotechnology application towards environmental sustainability. S. K. Gupta and F. Bux, Editors, Application of microalgae in wastewater treatment. Springer Nature Switzerland AG **(19 pages)**.

Kamyab, H.; Chelliapan, S.; Lee, C.T.; Khademi, T.; Kumar, A.; Yadav, K.K.; Ibrahimi, S.S., (2019b). Improved production of lipid contents by cultivating Chlorella pyrenoidosa in heterogeneous organic substrates. Clean Technol. Environ. Policy. 21(10): 1969–1978 **(10 pages)**.

Kamyab, H.; Chelliapan, S.; Shahbazian-Yassar, R.; Din, M.F.M.; Khademi, T.; Kumar, A.; Rezania, S., (2017). Evaluation of lipid content in microalgae biomass using palm oil mill effluent (POME). JOM. 69(8): 1361–1367 **(7 pages)**.

Kamyab, H.; Tin Lee, C.; (2014). Effects of nitrogen source on enhancing growth conditions of green algae to produce higher lipid. Desalin. Water Treat., 52(19-21): 3579–3584 **(6 pages).**

Kavanagh, P.; Pitcher, T.J., (2004). Implementing Microsoft Excel software for Rapfish: A technique for the rapid appraisal of fisheries status. Fish. Centre Res., 12(2): 1–75 **(75 pages).**

Kenkel, N.C.; Orloci. L., (1986). Applying metric and nonmetric multidimensional scaling to ecological studies: some new results. Ecology. 67(4): 919–928 **(10 pages).**

Khan, M.I.; Shin, J.H.; Kim, J.D., (2018). The promising future of microalgae: Current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Microb. Cell Factories, 17(1): 36 **(20 pages).**

Kietkwanboot, A.; Chaiprapat, S.; Rudolf Müller, R.; Suttinun, O., (2020). Biodegradation of phenolic compounds present in palm oil mill effluent as single and mixed substrates by Trametes hirsuta AK04. J. Environ. Sci. Health A Tox. Hazard Subst. Environ Eng., 55(8): 989–1002 **(14 pages).**

Koyande, A.K.; Chew, K.W.; Rambabu, K.; Tao, Y.; Chu, D.T.; Show, P.L., (2019). Microalgae: A potential alternative to health supplementation for humans. Food Sci. Hum. Wellness. 8(1): 16–24 (9 **pages)**.

Lage, S.; Toffolo, A.; Gentili, F.G., (2021). Microalgal growth, nitrogen uptake and storage, and dissolved oxygen production in a polyculture based-open pond fed with municipal wastewater in northern Sweden. Chemosphere. 276: 130122.

Lam, M.E., (2016). The ethics and sustainability of capture fisheries and aquaculture. J. Agric. Environ. Ethics. 29(1): 35–65 **(30 pages).**

Larsdotter, K., (2006). Wastewater treatment with microalgae-a literature review. Vatten, 62(1): 32–38 **(7 pages).**

Lee, S.Y.; Khoiroh, I.; Vo, D.N.; Senthil Kumar, P.; Show, P.L., (2021). Techniques of lipid extraction from microalgae for biofuel production: A review. Environ. Chem. Lett., 19(1): 231–251 (**21 pages**).

Levidow, L., (2013). EU criteria for sustainable biofuels: Accounting for carbon, depoliticizing plunder. Geoforum. 44: 211–223 **(13 pages).**

Low, S.S.; Bong, K.X.; Mubashir, M.; Cheng, C.K.; Lam, M.K.; Lim, J.W.; Ho, Y.C.; Lee, K.T.; Munawaroh, H.S.H.; Show, P.L.; (2021). Microalgae cultivation in palm oil mill effluent (POME) treatment and biofuel production. Sustainability. 13(6): 3247.

Mellyanawaty, M.; Chusna, F.M.A.; Sudibyo, H.; Nurjanah,, N.; Budhijanto, W., (2018). Influence of nutrient impregnated into zeolite addition on anaerobic digestion of palm oil mill effluent (POME). IOP Conf. S.: Mater. Sci. Eng., 316: 1–7 **(7 pages).**

Naeini, M.A.; Zandieh, M.; Najafi, S.E.; Sajadi, S.M., (2020). Analyzing the development of the third-generation biodiesel production from microalgae by a novel hybrid decision-making method: The case of Iran. Energy. 195: 11689.

Narendra, B.H.; Widiatmaka; Kusmana, C.; Karlinasari, L.; Machfud, M., (2019). Multi-dimensional rapid appraisal technique for evaluating the sustainability of energy plantation forests in East Lombok District Indonesia. Biodiversitas. 20(4): 1027–1033 **(4 pages)**.

Nur, M.M.A.; Buma, A.G.J., (2019). Opportunities and challenges of microalgal cultivation on wastewater, with special focus on palm oil mill effluent and the production of high value compounds. Waste Biomass Valorization. 10(8): 2079–2097 (**19 pages**).

Nur, M.M.A.; Djarot, I.R.; Boelen, P.; Hadiyanto; Heeres, H.J., (2022). Co-cultivation of microalgae growing on palm oil mill effluent under outdoor condition for lipid production. Environ. Pollut. Bioavailability. 34(1): 537–548 (**12 pages**).

Nurhayati, C.; Basuni, H.; Pambayun, R., (2013). Optimasi pengolahan limbah cair karet remah menggunakan mikroalga indigen dalam menurunkan kadar BOD, COD, TSS. J. Din. Penelitian Ind. 24(1): 16–26 **(11 pages**).

Oliver, R.L.; Ganf, G.G., (2000). Freshwater blooms, in the ecology of cyanobacteria: Their diversity in time and space, B.A. Whitton and M. Potts, Editors. Kluwer: Dordrecht: 149–194 (**45 pages**).

Osama, A.; Hosney, H.; Moussa, M.S., (2021). Potential of household photobioreactor for algae cultivation. J. Water Clim. Change. 12(6): 2147–2180 (**34 pages**).

Pal, P.; Chew, K.W.; Yen, H.W.; Lim, J.W.; Lam, M.K.; Show, P.L., (2019). Cultivation of oily microalgae for the production of third-generation biofuels. Sustainability. 11(19): 1–16 (**16 pages**).

Papilo, P.; Marimin, M.; Hambali, E.; Sitanggang, I.S., (2018). Sustainability index assessment of palm oil-based bioenergy in Indonesia. J. Clean. Product., 196: 808–820 (**13 pages**).

Patnaik, R.; Mallick, N., (2021). Microalgal biodiesel production: Realizing the sustainability index. Front. Bioeng. Biotechnol., 9: 1–15 (**15 pages**).

Pitcher, T.J.; Preikshot, D., (2001). RAPFISH: A rapid appraisal technique to evaluate the sustainability status of fisheries. Fish. Res., 49(3): 255–270 (**16 pages**).

Rana, S.; Singh, L.; Wahid, Z.; Liu, H., (2017). A recent overview of palm oil mill effluent management via bioreactor configurations. Curr. Pollut. Rep., 3(4): 254–267 (**14 pages**).

Rani, A.; Rao, H.; Kumar, A.; Shruthi, M., (2015). Eco-friendly approach for treating dairy effluent and lipid estimation using microalgae. Br Biotechnol. J., 7(1): 33–39 (**7 pages**).

Responsible seafood, (2022). Aquaculture hatchery operators should think inside the box for versatile microalgae production. Ocean L. Technol., 1–6 (**6 pages**).

Russell, J.A.; Bullock, M., (1985). Multidimensional scaling of emotional facial expressions: Similarity from preschoolers to adults. J. Pers. Soc. Psychol., 48(5): 1290–1298 (**9 pages**).

Saidaa; Abdullah; Novitab E; Ilsan, M., (2016). Sustainability analysis of potato farming system at sloping land in Gowa regency, South Sulawesi, Agric. Sci. Procedia. 9: 4–12 (**9 pages**).

Sari, F.Y.A.; Suryajaya, I.M.A.; Christwardana, M.; Hadiyanto, H., (2022). Cultivation of microalgae Spirulina platensis in palm oil mill effluent (POME) media with variations of POME concentration and nutrient composition. J. Bioresour. Environ. Sci., 1(2): 57–62 (**6 pages**).

Sasongko, N.A.; Noguchi, R.; Ahamed, T.; Takaigawa, T. (2015). Introduction of integrated energy plantation model for microalgae-using palm oil mill effluent (POME). J. Jpn Inst. Energy 94(6): 561–570 (10 pages).

Sheehan, J.; Dunahai, T.; Benemann, J.; Roessler, P., (1998). A look back at the U.S. Department of Energy's aquatic species program: Biodiesel from algae. NREL/TP-580-24190, National Renewable Energy Laboratory, USA; 1998. NREL/TP-580-24190, National Renewable Energy Laboratory, USA. (**328 pages**).

Sheehan, J.D.; Jiang, J.; Savage, P.E., (2017). Algae and environmental sustainability. Johnson Matthey Technol. Rev., 61(2): 133–137 **(5 pages)**.

Show, P.L.; Tang, M.S.Y.; Nagarajan, D.; Ling, T.C.; Ooi, C.W., (2017). A holistic approach to managing microalgae for biofuel applications. Int. J. Mol. Sci, 18(1): 215–225 **(11 pages).**

Sofiyah, E.S.; Sarwono, A.; Septiariva, I.Y.; Wayan, I.D; Suryawan, K., (2021). The opportunity of developing microalgae cultivation techniques in Indonesia. Ber. Biol., 20(2): 221–233 **(13 pages).**

Suardi, T.F.; Sulistyowati, L.; Noor, T.I.; Setiawan, I., (2022). Analysis of the sustainability level of smallholder oil palm agribusiness in Labuhanbatu Regency, north Sumatra. Agriculture. 12(9): 1469 **(16 pages)**.

Susanto, J.P.; Santoso, A.D.; Suwedi, N., (2017.). Palm solid wastes potential calculation for renewable energy with LCA method. J. Teknol. Lingkungan, 18(2): 165–172 **(8 pages).**

Zullaikah, S.; Utomo, A.T.; Yasmin, M.; Ong, L.K.; Ju, Y.H., (2019). Ecofuel conversion technology of inedible lipid feedstocks to renewable fuel. Advances in eco-fuels for a sustainable environment; A. Azad, Editor; Woodhead Publishing Series in Energy; Woodhead Publish., Cambridge, UK, 237–276 **(40 pages).**

AUTHOR (S) BIOSKETCHES

Santoso, A.D., Ph.D., Senior Researcher at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.

- Email: *arif.dwi.santoso@brin.go.id*
- ORCID: 0000-0003-3595-9265
- Web of Science Researcher ID: NA
- Scopus Author ID: 56516534000
- Homepage: https://brin.go.id/

Hariyanti, J., B.Eng., Principal Engineer at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.

- Email: *jeni001@brin.go.id*
- ORCID: 0000-0003-3693-0050
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

Pinardi, D., Ph.D., Researcher at Research Centre for Horticulture and Plantation, National Research and Innovation Agency, Indonesia.

- Email: *djat002@brin.go.id*
- ORCID: 0000-0002-1742-434
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

Kusretuwardani, K., Ph.D., Principal Engineer at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.

- Email: *kusr001@brin.go.id*
- ORCID: 0000-0003-3271-1299
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

Widyastuti, N., Ph.D., Professor, Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.

- Email: *nett001@brin.go.id*
- ORCID: 0000-0002-9113-2022
- Web of Science Researcher ID: 9723-2022
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

Djarot, I.N., Ph.D., Senior Researcher at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.

- Email: *iran001@brin.go.id*
- ORCID: 0000-0002-5986-8934
- Web of Science Researcher ID: NA
- Scopus Author ID: 57215343961
- Homepage: https://brin.go.id/

Handayani, T., Ph.D., Professor Research at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.

- Email: *titi001@brin.go.id*
- ORCID: 0000-0002-4403-594
- Web of Science Researcher ID: 8677-2022
- Scopus Author ID: 57220029107
- Homepage: https://brin.go.id/

Sitomurni, A.I., M.Sc., Principal Engineer at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.

- Email: *amit001@brin.go.id*
- ORCID: 0000-0002-6180-3187
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://brin.go.id/

Apriyanto, H., Ph.D., Senior Researcher at Research Centre for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency, Indonesia.

- Email: *heri014@brin.go.id*
- ORCID: 0000-0002-5526-7218
- Web of Science Researcher ID: HJH-1680-2023
- Scopus Author ID: 57990823100
- Homepage: https://brin.go.id/

HOW TO CITE THIS ARTICLE

Santoso, A.D.; Hariyanti, J.; Pinardi, D.; Kusretuwardani; Widyastuti, N.; Djarot, I.N.; Handayani, T.; Sitomurni, A.I.; Apriyanto, H., (2023). Sustainability index analysis of microalgae cultivated in palm oil mill effluent for biorefinery. Global J. Environ. Sci. Manage, 9(3): 559-576.

DOI: 10.22035/gjesm.2023.03.13

URL: https://www.gjesm.net/article_701137.html