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ORIGINAL PAPER

A fuzzy analytic hierarchy process for the site selection of the Philippine algal industry

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Abstract

The Philippine algae industry is a multi-billion dollar industry that requires restructuring to further gain global market share. Through the development of new algal bioproducts by strategically repositioning and enabling collaboration with existing industries, the Philippine algal industry aims to enhance its economic status. The decentralized locations of regions in the Philippines make it challenging to select a potential site for the industry. A decision support system is proposed to aid the industry for site selection that evaluates the different regions based on environmental impact, costs, social aspects, and industry presence. In addition, the site assessment considers the viewpoints of the various stakeholders to arrive at a sound and just decision. Thus, a fuzzy analytic hierarchy process (FAHP) method is employed to include the uncertainty in the subjectivity in the viewpoints of different stakeholders such as the academe, the government, and the industry. In addition, the FAHP approach is capable of combining both qualitative and quantitative data. The combined results revealed the level of importance of the main criteria with a combined weight of 43% for the environmental impact, 22% for the costs, 21% for the social aspects, and 14% for the industry presence. The disparity of priorities was observed among the stakeholders where the industry chose costs at 29% above other criteria when compared to the government and the academe which chose environmental impact at 44% and 40%, respectively, among other criteria. The highly preferred sites for the Philippine algae industry were Calabarzon, Northern Mindanao, Western Visayas, and Central Luzon due to the good potential labor force, presence of industries, and available resources in the regions. In order to achieve a harmonious prioritization of criteria among the stakeholders, policies on the encouragement of public investment on regions with marginal income must be considered.

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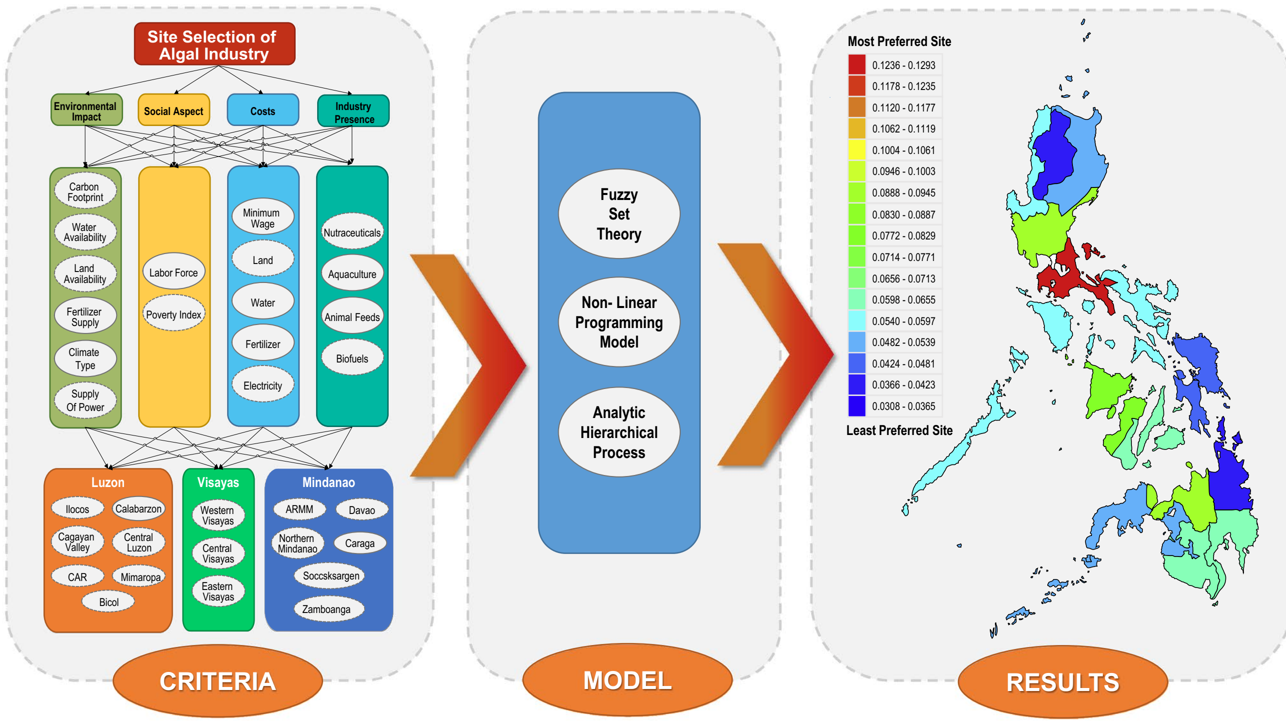
Graphic Abstract



Keywords Algae · Analytic hierarchy process · Fuzzy set theory · Multi-criteria decision analysis · Philippines · Site selection

List of symbols

Parameters

$\hat{a}_{ij}$ Group fuzzy judgment
a_{ij} Crisp fuzzy judgment
$\hat{A}$ Reciprocal pairwise comparison matrix
CI Consistency index
G Set of group
h Members of set of stakeholder value judgment
L Degree of satisfaction
l_{ij} Lower bound of the triangular fuzzy number
m_{ij} Modal value of the triangular fuzzy number
P Maximum number members of set of group
p Members of set of group
Q Set of criteria
Q' Set of sub-criteria
R Set of alternative region
S Maximum number members of set of criteria
s Members of set of criteria
S' Maximum number members of set of sub-criteria
s' Members of set of sub-criteria
T Maximum number members of set of alternative region
t Members of set of alternative region
u_{ij} Upper bound of the triangular fuzzy number
v_h Influence weight
w_i Normalized priority vector
W_i Overall weight vector

Subscripts

AG Alternative with respect to the goal
AS Alternative region with respect to the main criteria
H Set of stakeholder value judgment
i Elements in the row
j Elements in the column
MG Main criteria with respect to the goal
SM Sub-criteria with respect to the main criteria

Introduction

In 2019, the Philippines' Bureau of Fisheries and Aquatic Resources intends to ramp the aquaculture production by 60% to satisfy the global demand (Gomez 2019). In the first quarter of 2019, the aquaculture industry has increased the municipal marine production by 8% compared to the previous year (Philippine Statistics Authority 2019). One of the major sectors in the Philippine aquaculture is the algae industry which comprises of fish and shrimp feeds (Food and Agriculture Organization 2013). In order to maximize the economic potential of the algae industry, the diversification of algal bioproducts aside from aquaculture and the involvement of other industry stakeholders are key steps toward competitiveness. To do this, the synergistic collaboration between various industries must be established which may benefit from the exchange of newly developed bioproducts. However, the Philippines is an archipelago. The challenge is to strategically position the algae industry based on the installed plants and available natural resources situated in various islands. The decentralized location makes it challenging for the industry to synergistically link with other industries to generate various bioproducts from algae. The ranking of preferred sites for the production of algae is necessary to appropriately position and restructure the industry for enhanced competitiveness.

Previous studies on the site selection of various agencies and institutions have been conducted by considering the least costs and other conflicting factors (Bailey et al. 2003). Various factors can be generally classified as environmental, technological, geographic, political, and socio-economic (Huang et al. 2018). To arrive at a realistic decision on site selection which is capable to consider multiple factors simultaneously, the multi-criteria decision analysis (MCDA) was proposed. MCDA enables the inclusion of numerous criteria in a decision framework facilitating a holistic analysis leading to a sound and well-thought decision. The application of MCDA on the site selection was previously performed on renewable energy technologies such as geothermal energy (Noorollahi et al. 2007), wind energy (Lee et al. 2009), solar energy (Lenin and Kumar 2015), and the combination of wind and solar energy (Janke 2010). One of the known MCDA methods is the analytic hierarchy process (AHP) which is capable to capture both subjective and objective aspects of a complex decision problem. AHP provides a structured and convenient approach to analyze and derive relative priorities between a given set of criteria and alternatives (Anagnostopoulos and Vavatsikos 2012).

AHP has been a method of choice for multi-criteria decision problems due to its simplicity and capability to combine quantitative and qualitative data. AHP was utilized in numerous decision-making applications which consist of multiple criteria and composed of multiple sets of alternatives. Previous AHP studies were implemented on the site selection of various energy-related technologies such as solar (Uyan 2017), photovoltaics (Huang et al. 2018), wind (Multazam et al. 2016), nuclear (Kassim et al. 2016), and energy from waste materials (Rahman et al. 2017). In the aspect of public service, AHP was utilized to guide policy-makers in the establishment of new hospitals (Rahimi et al. 2017), fire stations (Chaudhary et al. 2016), landfill (Rahmat et al. 2017), and tourism sites (Morteza et al. 2016). Based on Scopus, the only AHP work on the site selection of an algae industry was a previous study (Ubando et al. 2015) which did not consider the viewpoint of multiple stakeholders and the uncertainty in the subjectivity in their viewpoints. In order to ensure the success of the restructuring and repositioning of the algae industry in the Philippines, the consensus of multiple stakeholders needs to be considered. To address this, the fuzzy analytical hierarchy process is employed where the uncertainty in the subjectivity of the opinions of multiple stakeholders is represented by the triangular fuzzy numbers (TFNs, van Laarhoven and Pedrycz 1983). The TFNs replace the precise pairwise comparison from the standard AHP approach. The consistency of the solution is then resolved through the employment of the logarithmic least square method in fuzzy linear programming (van Laarhoven and Pedrycz 1983). The fuzzy set theory was initially utilized to address uncertainty (Zadeh 1965) and was later on expanded for conventional decision-making purposes (Bellman and Zadeh 1970). Recent studies were performed which utilized FAHP for various applications such as construction (Darko et al. 2019), sound control (Moradirad et al. 2019), risk in foundry shops (Golbabaei et al. 2019), aircraft selection (Dožić et al. 2018), determination of key performance indicators (Kaganski et al. 2018), and process engineering (Tan et al. 2014). In addition, FAHP was employed as a decision support tool in the selection of algae dewatering processes (Tan et al. 2015) and the selection of low-carbon technologies (Promentilla et al. 2015). Moreover, FAHP was previously employed on the site selection of hospitals (Vahidnia et al. 2009), landfill, forest park (Beskese et al. 2015), parking lots (Salehnasab et al. 2016), bank branch (Çınar 2015), and underground natural gas reservoirs (Arsovski et al. 2017). To date, no FAHP study was found on the site selection of an algae industry based on the Web of Science and Scopus search.

The novelty of the study resides on the application of FAHP to the site selection of the algae industry in the Philippines wherein the TFNs represent the uncertainty in the subjectivity of the pairwise comparison of various stakeholders. The aim of the study is to establish a decision support methodology in positioning the Philippine algae industry through strategic site selection using FAHP. The main objective is to rank the different regions in the Philippines in terms of the most preferred deployment site of the algae industry with respect to a set of defined criteria. The significance of the study is to establish the decision support system that enables a seamless business creation of the algae industry in a country that is composed of decentralized islands such as the Philippines. However, the study excludes the sensitivity analysis on the effect of the varied weights of the identified criteria which may be covered in future studies.

Problem statement

The site selection for the algae industry which considers the perspective of multiple stakeholders was abstracted as a methodological problem which can be expressed as follows:

(1) The hierarchical decision structure of AHP is defined by considering a set of criteria Q ($s = 1, 2, \ldots, S$) supported by a set of sub-criteria Q' ($s' = 1, 2, \ldots, S'$) evaluating a set of alternative regions R ($t = 1, 2, \ldots, T$) to satisfy the defined AHP goal. The elements within each level are assumed to have mutual independence among other elements. These elements may be represented in the form of quantitative data or qualitative data.

(2) The qualitative elements are defined by a survey of the panel of stakeholders which provide the pairwise comparison for the set of criteria Q and sub-criteria Q'. The degree of preference of each element can be represented from the value judgment of the stakeholders for each pairwise comparison. Often times, the elicited value judgment from stakeholders results in an inconsistent reciprocal pairwise comparison matrix when compared to the ideal case matrix (Alonso and Lamata 2006). To ensure consistency of the preference values of each of the elements in the matrix, the consistency index CI should be satisfied at all times as suggested by Saaty (1980).

(3) The panel of stakeholders provides a set of pairwise comparisons for the set of alternative region R based on the set of sub-criteria Q'.

(4) The quantitative elements are determined from available data in the literature as shown in Table 2. Hence, AHP is capable of combining both quantitative and qualitative data in the hierarchical decision structure.

(5) Group decision analysis is implemented by clustering the stakeholder's survey result to group G ($p = 1, 2, \ldots, P$). The considered group G is assumed to be uni-level (not supported by any subgroups).

(6) The fuzzy numbers are defined by the lower limit l_{ij}, middle point m_{ij}, and an upper limit u_{ij} from the group decision analysis. The lower limit l_{ij} represents the geometric mean of all lower limit values in the pairwise comparison matrix. The middle point m_{ij} represents the geometric mean of all value judgment of the panel of stakeholders. The upper limit u_{ij} represents the geometric mean of all upper limit values in the pairwise comparison matrix.

(7) The maximization of the degree of satisfaction λ defines the objective function of the developed nonlinear programming (NLP) model to solve for the normalized weight W_i of the alternative region R. The constraints of the developed NLP model are shown in Eqs. (7)–(11).

(8) The problem is to solve for normalized weight W_i of the alternative region R. Based on the derived normalized weight W_i, the alternative regions R are ranked from highest to the lowest value. The highest weight value represents the most preferred site while the lowest weight value represents the least preferred site. The ranking of weights of the alternative region R shall lead to the recommendation of the most preferred site.

Methodology

The goal of the FAHP is to select the most preferred site for the algae industry in the Philippines based on different criteria. In order to achieve this, the methodology is structured to discuss the FAHP model, the criteria, the Philippine case study on the algae industry, and the data sources.

Fuzzy analytic hierarchy process

The AHP hierarchical decision structure for this study was adopted from Ubando et al. (2015). Feedback and suggestions from stakeholders improved the previous hierarchical decision structure by redefining some of the criteria utilized in the previous study. *Land costs* have been added as a sub-criterion to capture the varying prices of land per region. Some of the sub-criteria under the *Industries* criterion were combined to one sub-criterion as *animal feeds* which was previously composed of various animal feed markets such as poultry and swine. The improved AHP hierarchical decision structure is used in the study and is shown in Fig. 1. The AHP goal is to rank and prioritize suitable sites for the algal industry for the alternative region R based on a set of criteria Q and supporting sets of sub-criteria Q'.

The value judgment from a panel of stakeholders was obtained through the pairwise comparisons matrices resulting from a survey that employed the fundamental 9-point scale shown in Table 1. The aggregation of the individual value judgment of H stakeholders is modeled as the fuzzy judgment $\hat{a}_{ij} = l_{ij}, m_{ij}, u_{ij}$ using Eqs. (1)–(3).

$$l_{ij} = \min\left[a_{ij1}, a_{ij2} \ldots, a_{ijH}\right] \tag{1}$$

$$m_{ij} = \left[\prod_{h=1}^{H} \left(m_{ijh}\right)^{v_h}\right] \tag{2}$$

$$u_{ij} = \max\left[a_{ij1}, a_{ij2} \ldots, a_{ijH}\right] \tag{3}$$

where the l_{ij} represents the lower bound of the triangular fuzzy number (TFN), the m_{ij} represents the modal value of the TFN, and the u_{ij} represents the upper bound of the TFN,

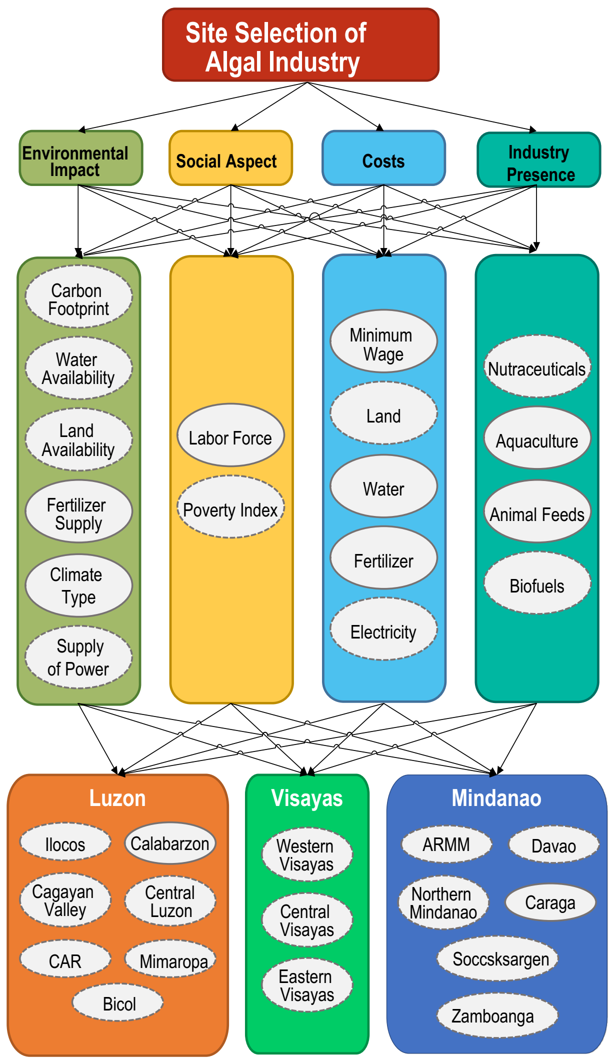


Fig. 1 Hierarchical structure of the decision analysis for the prioritization of site selection of algal biofuels in the Philippines

a is the fractional representation of the score elicited from the survey results of stakeholders, and the v_h is the influence weight of the individual stakeholder. Note that if the stakeholders' influence is equally weighted, then Eq. (2) is equivalent to the geometric mean of the individual judgments. The advantages of using the geometric mean compared to the arithmetic mean are the avoidance of biases in the derivation of weights and the limitation of the influence of the sample distribution (Krejčí and Stoklasa 2018).

The derived $\hat{a}_{ij}$ is then used as an input to the reciprocal pairwise comparison matrix $\hat{A}$ of order such that:

$$\hat{A} = \begin{bmatrix} \langle 1,1,1 \rangle & \hat{a}_{12} & \cdots & \hat{a}_{1n} \\ \hat{a}_{21} & \langle 1,1,1 \rangle & \cdots & \hat{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{a}_{n1} & \hat{a}_{n2} & \cdots & \langle 1,1,1 \rangle \end{bmatrix} \quad (4)$$

$$\hat{a}_{ji} = \frac{1}{\hat{a}_{ij}} = \left\langle \frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}} \right\rangle \quad (5)$$

where $\hat{A}$ is the reciprocal pairwise comparison matrix, $\hat{a}_{ij}$ is the reciprocal of $\hat{a}_{ij}$, n represents the number of elements considered in the criteria or sub-criteria.

The FAHP model used in this study approximates the values of $\hat{a}_{ij}$ which leads to the solution of the crisp priority vector weight W_i from the reciprocal pairwise comparison matrix $\hat{A}$. The FAHP model consisted of the objective function shown in Eq. (6) subject to the constraints described in Eqs. (7)–(11):

$$\text{maximize } \lambda \quad (6)$$

subject to:

$$a_{ij} - l_{ij} \geq \lambda\left(m_{ij} - l_{ij}\right); \quad a_{ji} - l_{ji} \geq \lambda\left(m_{ji} - l_{ji}\right) \quad (7)$$

$$u_{ij} - a_{ij} \geq \lambda\left(u_{ij} - m_{ij}\right); \quad u_{ji} - a_{ji} \geq \lambda\left(u_{ji} - m_{ji}\right) \quad (8)$$

where

$$a_{ij} = \frac{w_i}{w_j}; \quad a_{ji} = \frac{w_j}{w_i} \forall \quad i = 1, \ldots, n-1; \quad j = 2, \ldots, n; \quad j > i \quad (9)$$

$$\sum_{h=1}^{n} w_h = 1; \quad w_h > 0 \quad (10)$$

$$0 \leq \lambda \leq 1 \quad (11)$$

where λ is the degree of satisfaction of the objective function, and w is the normalized priority vector of weight. The

Table 1 Saaty's 9-point scale for pairwise comparisons (Saaty 1980; Ramzan et al. 2008)

Numerical rating or scale	Verbal judgment or importance
1	The two criteria contribute equally
3	Experience and judgment slightly prefer one criterion over another
5	Experience and judgment strongly prefer one criterion over another
7	Experience and judgment very strongly prefer one criterion over another
9	Affirmed evidence of preferring one criterion over another
2, 4, 6, 8	When compromise between values of 1, 3, 5, 7, and 9 is needed

Table 2 Inventory list of regional data for each sub-criterion

Main criteria	Sub-criteria	Regional data type	References
Environmental Impact	Carbon dioxide	CO_2 emissions of coal and diesel plants per region	Philippine Department of Energy (2014a)
	Water availability	Water resources potential per region	Green Peace (2007)
	Land availability	Idle land area available per region	Philippine Statistics Authority (2014a)
	Fertilizer availability	Fertilizer supply per region	Philippine Statistics Authority (2014b)
	Climate	Climate type per region	Cinco et al. (2013)
	Power supply	Fuel supply per region	Philippine Department of Energy (2014b), Philippine Statistics Authority (2014c)
Social aspects	Potential labor force	Labor force capacity per region	Philippine Statistics Authority (2014d)
	Poverty index	Poverty incidence among families per region	Philippine Statistics Authority (2014e)
Costs	Minimum wage	Price per day per region	Philippine Department of Labor and Employment (2014)
	Land	Ratio regional idle land area to the overall regional land area	Philippine Statistics Authority (2014a)
	Water	Water price per region per day	Philippine Statistics Authority (2014f)
	Fertilizer	Price of inorganic fertilizer per bag	Philippine Department of Agriculture (2014)
	Electricity	Cost of electricity per kWh per region	Philippine Department of Energy (2014c)
Industry presence	Aquaculture	Aquaculture production per region	Philippine Bureau of Fisheries and Aquatic Resources (2014)
	Nutraceuticals	Number of nutraceutical companies per region	Health and Dietary Supplement Association of the Philippines (2016)
	Biofuels	Capacities of existing biofuel plants per region	Philippine Department of Energy (2014d, e)
	Animal feeds	Poultry, swine, carabao, and cow heads produced per region	Philippine Statistics Authority (2014g, 2014h, 2014i, 2014j)

objective function maximizes the degree of satisfaction λ as shown in Eq. (6) wherein λ is used in Eqs. (7) and (8) as part of the piecewise linear membership function. Equation (7) used the fuzzy membership function for maximization while Eq. (8) used the fuzzy membership function for minimization to satisfy the objective function shown in Eq. (6). With the utilization of the fuzzy membership functions shown in Eqs. (7) and (8), the model employs the min–max aggregate rule described by Zimmermann (1978) which enables to solve the maximum value of λ from the derived values of the membership functions that progress toward the desired goal. In turn, the λ-value depicts the trade-off between multiple conflicting goals. Due to the fractional solution of weights shown in Eq. (9), the solution of weights resulted in an NLP model. To ensure the sum of the fractional weights in a set of criteria or sub-criteria is equal to 1, Eq. (10) was used as a constraint. A positive value for λ denotes the solution trade-off among the multi-objective goals with a value ranging from 0 to 1 shown in Eq. (11). As λ approaches 1, the solution approaches the desired multi-objective goals. The FAHP model was solved using Lingo 12.0 with a global optimum solver installed in a desktop powered by Intel i7 microprocessor with 8 GB of RAM. The solution time is less than a second per simulation treatment.

Once the normalized priority vector of weight w has been derived, the overall priority vector W for the alternative region R is then computed by combining the qualitative and quantitative (regional data) information in the analysis.

$$W_{AG} = W_{MG} W_{SM} W_{AS} \tag{12}$$

where W_{AG} is the vector matrix containing the weight obtained by an alternative with respect to the goal, W_{MG} is the vector matrix containing the priority weight of the main criteria with respect to the goal (qualitative), W_{SM} is the vector matrix containing the priority weight of the sub-criteria with respect to the main criteria (qualitative) and W_{AS} is the matrix containing the performance weights appropriated to each alternative region relative to all of the sub-criteria (the quantitative type of data for each sub-criteria is shown in Table 2).

The derived weights from the reciprocal pairwise comparison matrix $\hat{A}$ most often have mismatched with the ideal matrix case where inconsistencies with the derived weights were quantified (Alonso and Lamata 2006). The inconsistency in the weights is due to the biases from the elicited value judgment of the respondents. Alonso and Lamata (2006) performed a review study and summarized the various random index (RI) used to evaluate the consistency index

(CI) in nine previous studies. Their results have revealed that for a matrix size of 6×6, the averaged RI for the nine previous studies has garnered a value of 1.21 with a standard deviation of 0.07. In comparison, the *RI* proposed by Saaty (1980) with a value of 1.24 for a matrix size of 6×6 is within the reasonable range of the average RI reported by Alonso and Lamata (2006). Due to this reason, the study employed the *RI* suggested by Saaty (1980) along with the least square method to ensure the consistency of the derived overall priority vector *W*.

Case study

The Philippines is divided into sixteen regions, excluding the National Capital Region (NCR) which is known as Metropolitan Manila; which are grouped collectively into three major island groups shown in Fig. 1. Luzon is located in the north and has the biggest land area consisting of seven provincial regions. The Visayas comprised of three regions of relatively smaller islands situated in the south of Luzon. The southernmost part is Mindanao, composed of the remaining six regions. The archipelagic setting greatly affects the logistics of products and services as well as the synergistic exchange of products between collaborating industries.

The deployment of an algal-based industry in the Philippines due to its vast abundance of algae species and tropical climate could be made successful through careful and comprehensive planning of the site selection process (Ubando et al. 2015). The identification of criteria in the decision-making process entails consideration of multiple factors that are conflicting. Hence, the proposed model in the selection of the optimal algal cultivation and processing sites combines the benefits of natural resource availability, social acceptability, anticipated costs of resources, and potential partner industries that may have an interest in the raw material itself. The proposed model hierarchical structure is presented in Fig. 1. Based on a previous study (Ubando et al. 2015) and the consultation with various stakeholders, the identified criteria to assess and rank the suitable sites for the algal industry for this study are (1) environmental impact, (2) costs, (3) social aspect, and (4) the presence of industries. The inventory list of the regional data for each sub-criteria identified in this study is shown in Table 2. The justification for the four main criteria is shown in "Appendix 1", the model assumptions are further discussed in "Appendix 2", and the data sources are elaborated in "Appendix 3".

Results and discussion

The results and discussion are categorized into the main criteria, the sub-criteria, and the site ranking which are discussed as follows.

Main criteria

The resulting weights of the main criteria for the industry, government, and the academe stakeholders are shown in Fig. 2a. Using the TFNs from the results of the survey, an example of the derivation of the weight importance W_{CG} is shown in Table 3 for the industry stakeholders. Using the objective function in Eq. (6) and the constraints shown in Eqs. (7)–(11), the weight importance for the environmental impact, social aspects, costs, and industry presence for the industry, yielded 27%, 16%, 29%, and 28%, respectively. The same procedure was adopted to solve for the W_{CG} of the main criteria and sub-criteria for the government and the academe. The resulting λ-value for the academe, the government, and the industry are 0.94, 0.76, and 0.74, respectively. It was observed that the industry stakeholders prioritized the costs (29%), closely followed by the industry presence (28%), then followed by the environmental impact (27%), and lastly followed by the social aspects (16%). On the other hand, both the government and the academe stakeholders prioritized the environmental impact compared to other criteria with weights of 44% and 40%, respectively. The difference in the opinions of the three stakeholders was

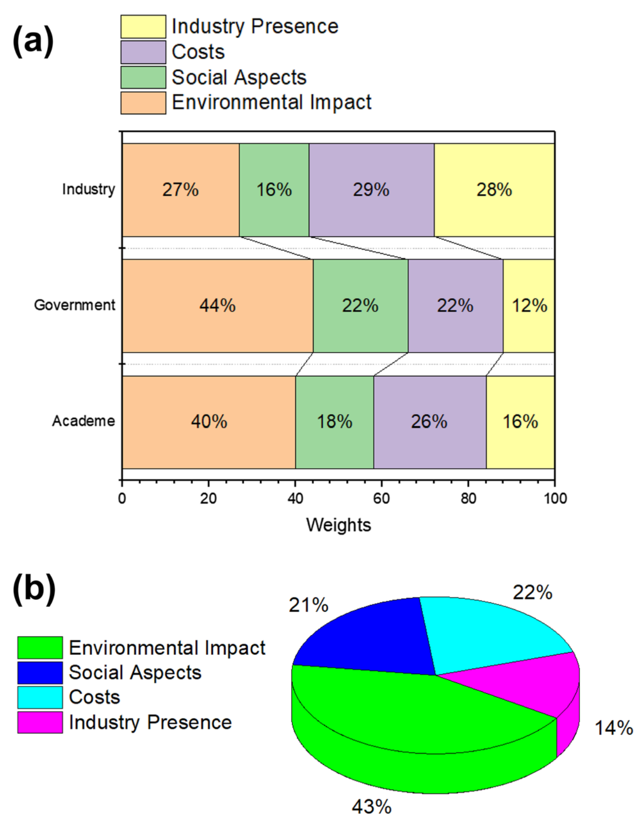


Fig. 2 Resulting weights of the main criteria for **a** the three respondent groups, and **b** the combined

Table 3 Fuzzy pairwise comparison judgment matrix for the main criteria of the industry stakeholders ($\lambda = 0.74$)

Main criteria	Environmental impact	Social aspects	Costs	Industries	Weight importance (W_{CG}) (%)
Environmental impact	$\langle 1, 1, 1 \rangle$	$\left\langle \frac{1}{5}, \frac{202}{93}, 7 \right\rangle$	$\left\langle \frac{1}{9}, \frac{5}{7}, 5 \right\rangle$	$\left\langle \frac{1}{9}, \frac{37}{49}, 5 \right\rangle$	27
Social aspects	$\left\langle \frac{1}{7}, \frac{29}{63}, 5 \right\rangle$	$\langle 1, 1, 1 \rangle$	$\left\langle \frac{1}{9}, \frac{69}{97}, 7 \right\rangle$	$\left\langle \frac{1}{9}, \frac{39}{59}, 3 \right\rangle$	16
Costs	$\left\langle \frac{1}{5}, \frac{7}{5}, 9 \right\rangle$	$\left\langle \frac{1}{7}, \frac{97}{69}, 9 \right\rangle$	$\langle 1, 1, 1 \rangle$	$\langle 1, 1, 9 \rangle$	29
Industry presence	$\left\langle \frac{1}{5}, \frac{49}{37}, 9 \right\rangle$	$\left\langle \frac{1}{3}, \frac{112}{76}, 9 \right\rangle$	$\left\langle \frac{1}{9}, 1, 1 \right\rangle$	$\langle 1, 1, 1 \rangle$	28

evident with the varying weights of the main criteria shown in Fig. 2a.

The combined results from the three groups yielded weights of 42% for environmental impact, 22% for costs, 21% for social aspects, and 14% for industry presence as shown in Fig. 2b. The resulting λ-value for the combined result is 0.82. The combined weights shown in Fig. 2b confirmed that the government and the academe prevailed over the industry in terms of the similarity of the ranking of importance of the main criteria. In order for the industry to improve the weights of the social aspects, the draft of policies on the enhancement of the participation of labor force for the unemployed (Messing et al. 2013), women (Cascio et al. 2015), and the aging population (Berkman et al. 2015) are essential. In addition, policies to encourage the public and the industry to invest in regions with high poverty rates (Thorat and Fan 2007) must also be considered to further enhance the social impacts of algal plants. By strengthening the social awareness of the industry through policies, the disparity of opinions between the three stakeholders is minimized. Moreover, the proposed policies generate job opportunities for the marginalized.

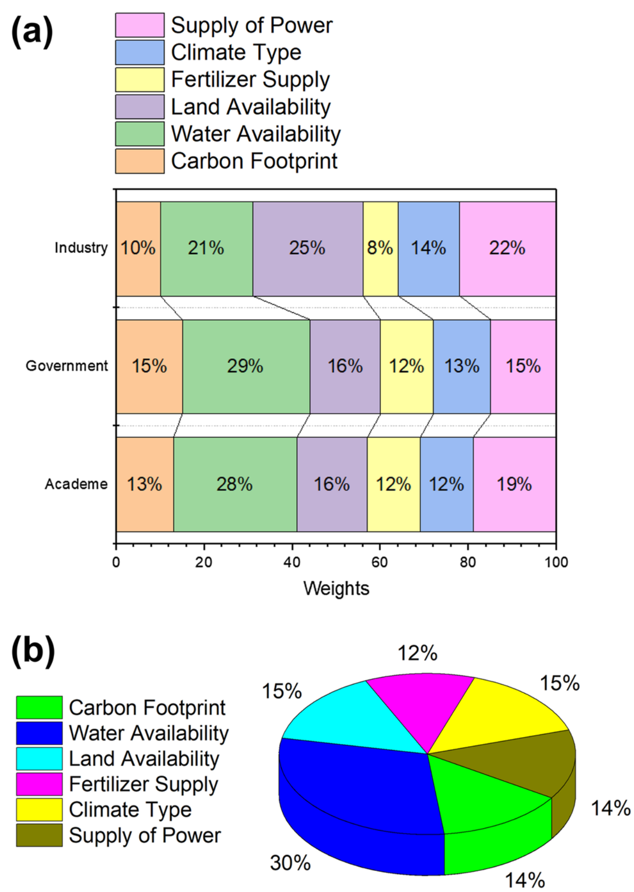


Fig. 3 Resulting weights of the environmental impact sub-criterion for **a** the three respondent groups, and **b** the combined

Sub-criteria

The detailed weight results for the sub-criteria under the main criteria such as the environmental impact, costs, social aspects, and industry presence are discussed as follows.

Environmental impact

The results of the environmental impact sub-criterion are shown in Fig. 3 where the derived weights for the three stakeholders are shown in Fig. 3a. The industry stakeholders prioritized the land availability (25%), the supply of power (22%), and water availability (21%) sub-criteria. It is to be addressed that land availability is the most important criterion for the industry stakeholders since the strategic location of the plant or office significantly enhances the performance of any business. For both the government and the academe, the highest W_{CG} is water availability since the algae industry requires an ample source of water. For the government, land availability follows the water availability with a weight of 16%, closely followed by the carbon footprint and the supply of power both accounted at 15%. For the academe stakeholders, subsequent to water availability is the supply of power with a weight of 19%, followed by the land availability at 16%. The top three sub-criteria for the three groups are recognized to include land availability, water availability, and the supply of power which are considered as the essential operational requirements for the algae industry.

The combined results of the three groups are shown in Fig. 3b. The top-ranked sub-criteria under the environmental impact criterion for the combined results were the water availability (30%), followed both by land availability (15%) and climate type (15%), then followed by the carbon footprint (14%) and supply of power (14%), and lastly the fertilizer supply (12%). To arrive at these results, the λ-value yielded 0.86. With the environmental impact having the highest combined weight shown in Fig. 2b, it is imperative to place policies that would encourage the algae industry to invest in regions with ample supply of resources. However, precautionary policies should also be drafted to avoid the exploitation of natural resources. The energy plan of the country should anticipate the growth of the industry to strategically consider the potential power demand for the regions identified.

Costs

The resulting weights for the sub-criteria of the cost criterion for the three groups are shown in Fig. 4a. The resulting λ-values for the sub-criteria of costs are 0.76 for the academe, 0.79 for the government, and 0.57 for the industry. It was recognized that electricity is the most important sub-criterion for both the industry and academe stakeholders with weights of 33% and 31%, respectively. In contrast, the prioritized sub-criterion for the government stakeholders is the minimum wage at 32%. Although electricity is one of the most important items for the operation of the algae industry, the government is sensitive to the minimum wage criteria of a region. The government stakeholders suggested to set up the algae industry to regions where the minimum wages were low. The establishment of the algae industry to these regions enables job creation leading to the inclusive development of the region. For the industry stakeholders, the land (25%) and water (18%) sub-criteria succeeded the electricity. While for the academe stakeholders, the two sub-criteria which succeeded electricity are water (20%) and land (18%). While for the government stakeholders, the water (23%) and land (19%) sub-criterion succeeded the minimum wage. As a result, both the water and land sub-criteria were found to be part of the top 3 ranked sub-criteria for the three groups.

The derived weights for the combination of the three groups on the cost criterion are shown in Fig. 4b which resulted in a λ-value of 0.83. The prioritized sub-criteria under costs are the minimum wage (25%), the electricity (23%), the water (20%), the land (19%), and the fertilizer (13%). Although the minimum wage tallied the highest score, the challenge is to lower the cost of electricity. The electricity costs in the Philippines are considered as one of the highest compared with other Southeast Asian countries

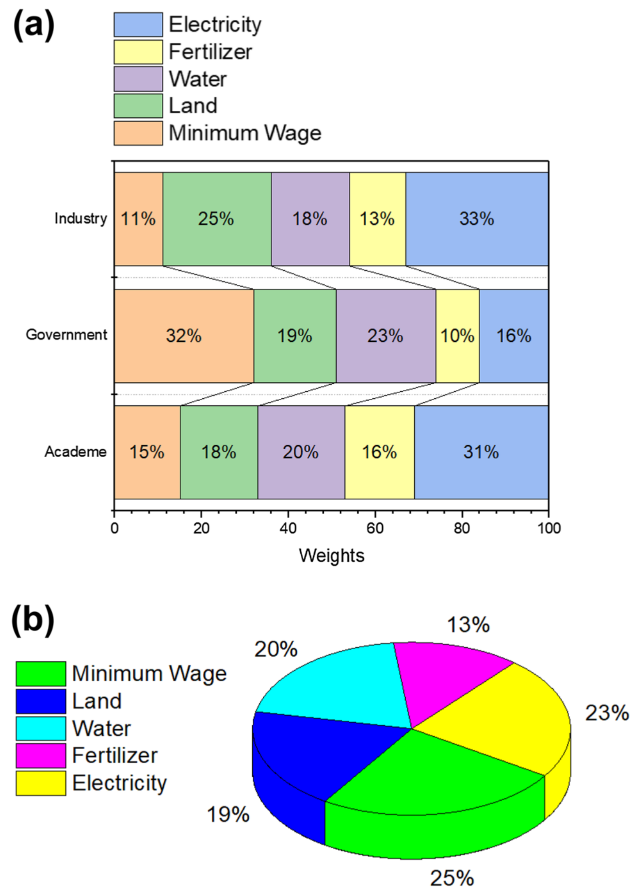


Fig. 4 Resulting weights of the costs sub-criterion for **a** the three respondent groups, and **b** the combined

(USAID 2013). The deployment of renewable energy and clean technologies along with the establishment of a firm structure for the feed-in tariff will enable the reduction in the costs of electricity in the country (USAID 2013).

Social aspects

The results of the sub-criteria under the social aspects criterion for the three groups are shown in Fig. 5a. Since only two sub-criteria were identified under the social aspects, the quantification of the weights is straightforward and has employed the standard pairwise comparison matrix using AHP instead of using the TFNs in the FAHP. It was recognized that the three groups have given greater importance to the potential labor force with weights greater than 50% compared to the poverty index. The combined result of the three groups has shown that the derived weights for the potential labor force were 60% and the poverty index was 40% as shown in Fig. 5b. One of the fundamental aspects of addressing poverty is through education. Policies on free education have been passed and implemented in the country (Congress of the Philippines 2017). In order to further heighten

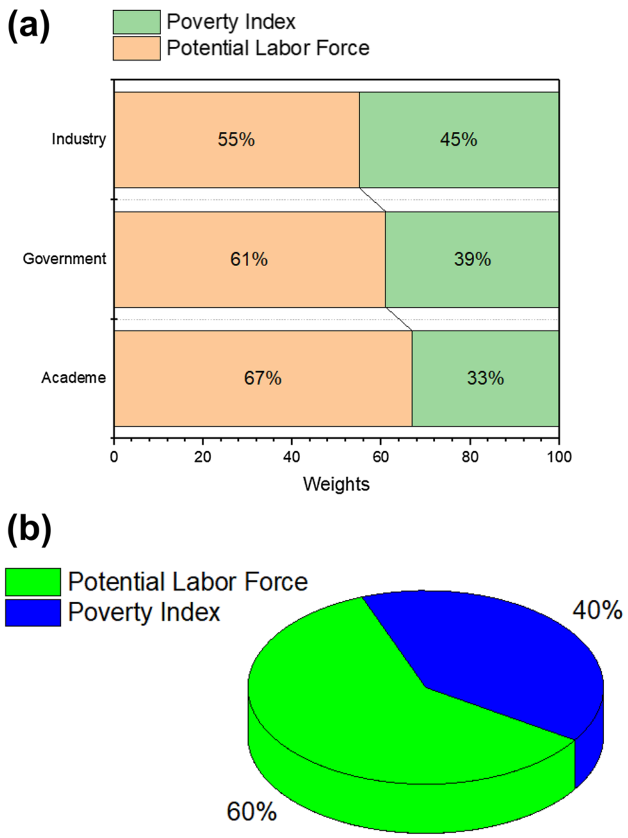


Fig. 5 Resulting weights for the social aspects sub-criterion for **a** the three respondent groups, and **b** the combined

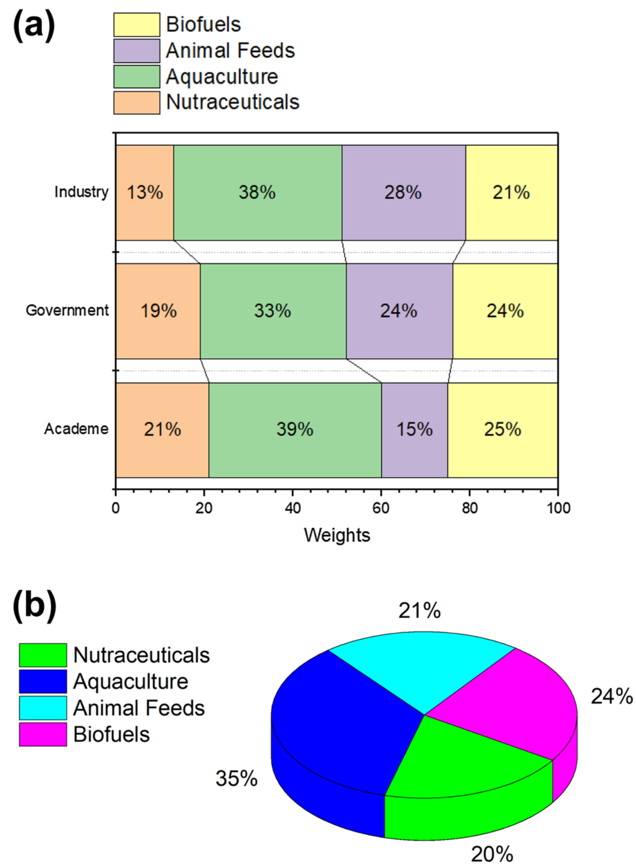


Fig. 6 Resulting weights for the industry presence sub-criterion for **a** the three respondent groups, and **b** the combined

the importance of the poverty index, the dissemination of established policies on free education needs to be addressed.

Industry presence

The derived weights for the sub-criteria of the industry presence criterion for the three groups are shown in Fig. 6a. The resulting λ-value for the academe, government officials, and industry professionals were 0.94, 0.76, and 0.74, respectively. The highest W_{CG} for the three groups was the presence of the aquaculture industry with scores of 38% for the industry, 33% for the government, and 39% for the academe. It is to be addressed that the presence of the aquaculture industry significantly boosted the confidence of different stakeholders to set up algae-related businesses in a region. For the industry stakeholders, the presence of the aquaculture industry was followed by the animal feed (28%), the biofuel (21%), and the nutraceutical (13%) industries. While for the government officials, the animal feeds (24%), biofuels (24%), and nutraceuticals (19%) succeeded the presence of the aquaculture industry. On the other hand, the academe has prioritized biofuels (25%), nutraceuticals (21%), and animal feeds (15%) after aquaculture.

The combined results of the three groups are shown in Fig. 6b which revealed that aquaculture has the highest score of 35%, followed by biofuels at 24%, then followed by animal feeds at 21%, and finally the nutraceuticals at 20%. The λ-value for the combined results was 0.96. In order to have a synergistic collaboration between different industries, the appropriate pricing and exchange of material and energy streams between industries should be agreed upon. Thus, contract agreements need to be negotiated among various stakeholders. Future research directions may involve various model scenarios to aid the synergistic agreement of different industries and stakeholders.

Site selection recommendations

The result of the regional site selection of the algal industry in the Philippines with respect to the combined responses of the three groups is shown in Fig. 7. The most preferred region for the algae industry is the Calabarzon (in red-colored) wherein it has the highest score on (1) the presence of biofuel companies, (2) the potential labor force, (3) the power supply, and (4) the source of carbon dioxide. This was followed by the Northern Mindanao (in

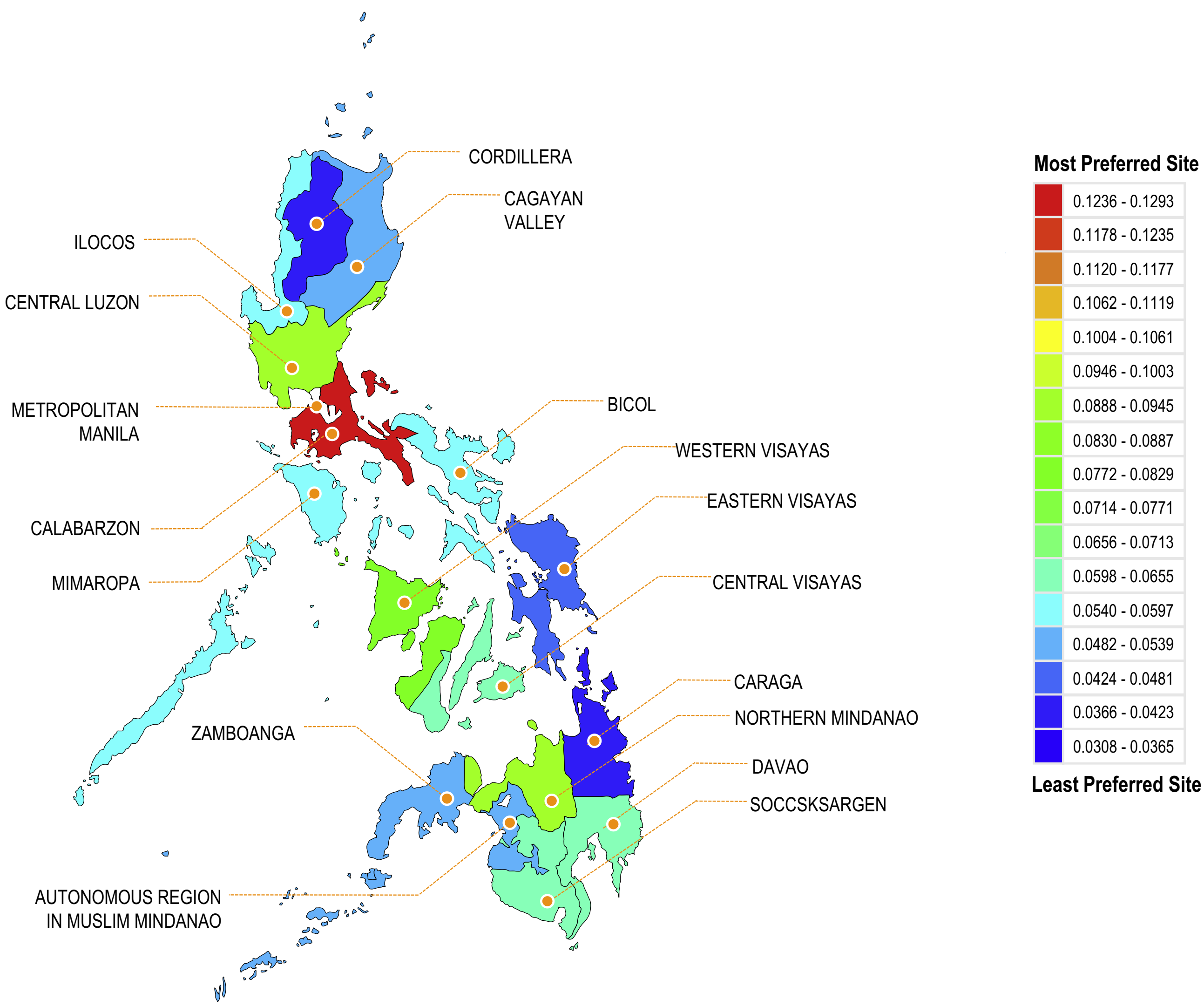


Fig. 7 Resulting ranks of regions for the combined group responses

green-colored) region because of its high water availability which, in turn, makes it suitable for the algae industry. The Central Luzon (in green-colored) region closely succeeded Northern Mindanao due to its high (1) potential labor force, (2) source of carbon dioxide, and (3) power supply. This was then followed by the Western Visayas (in green-colored) region due to the high (1) potential labor force, and the presence of the (2) biofuel, and (3) nutraceutical companies in the region. With the results of the most preferred sites for the Philippine algae industry, the three main islands of the Philippines were represented. Two regions from Luzon were identified which were Calabarzon and Central Luzon. Western Visayas and Northern Mindanao were selected and were located in the Visayas and Mindanao islands, respectively. The common criteria on the most preferred regions in the Philippines were the presence of potential labor force, the presence of other industries that can benefit from the algae industry, and the available sources of material and energy streams for the algae industry.

The least preferred sites for the algae industry were the regions with blue color such as the Caraga, Cordillera, and the Eastern Visayas regions. The Caraga region has a low presence of various industries and is located in the lower eastern region of the country where most of the typhoons pass. For the same reason with Caraga, the Eastern Visayas region is one of the least preferred sites for the algae industry. The Cordillera region is not a preferred site for algae industry since the region is located in the mountainous potion of Luzon where very limited presence of industries was found. In addition, the source of water and carbon dioxide was limited in the region.

Conclusions

A fuzzy analytic hierarchy process (FAHP) model was developed for the ranking of the potential site of the Philippine algal industry which utilized the stakeholder's opinion from three institutional groups. The model utilized triangular fuzzy numbers (TFNs) to represent the uncertainty in the subjectivity of the perception of various stakeholders of the algae industry. The model was solved using a nonlinear programming method to ensure a maximum degree of satisfaction was derived from the TFNs. A logarithmic least square method was employed to resolve the consistency of the pairwise comparison matrix. The results have shown that the environmental impact criterion yielded the highest importance at 43% compared with the other main criteria. Out of the six sub-criterion of the environmental impact, the water availability sub-criterion scored the highest at 30%. The most preferred sites for the Philippine algae industry were Calabarzon and Central Luzon regions in the Luzon island, the Western Visayas region in the Visayas group of islands, and the Northern Mindanao in the Mindanao island. The study presents a decision support system for the site selection of the Philippine algae industry which captures the weight prioritization of the criteria of various stakeholders. The results suggest the selection of site for the algae industry was mainly influenced by the good potential labor force, presence of collaborating industries, and available sources of material and energy streams in a region. In addition, the study recommends the draft of policies focused on the encouragement of public investment on regions with marginal income. The future direction of research may focus on a higher resolution of the preferred sites using geographic information system coupled with other multi-criteria decision analysis approach together with sensitivity analysis.

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Appendix 1: The four main criteria

Appendix 1.1: Environmental impact

The environmental impact criterion was chosen as a combination of various criteria which may affect the environment with respect to the consumption of natural resources including material and energy streams (United Nations Environment Programme 2010). The sub-criteria considered under the environmental impact were the availability of the natural resources (water and land availability), availability of utilities (fertilizer and electricity supply), and carbon footprint.

The growth, harvesting, and processing of any biomass results to environmental impact such as natural resource consumption and greenhouse gas emissions. Various environmental impacts are exemplified by the environmental footprints described by the review paper of Čuček et al. (2012). The significance of considering the environmental impact of any sustainable industrial process is highlighted by Čuček et al. (2015) where some environmental footprints have exceeded the safe threshold limit of the planet. In the sustainable production of any biomass, the nutrient supply is a major factor as suggested by Razon (2015). The natural resources include most of the resources necessary for biomass cultivation. Generally, photoautotrophic growth of microalgae requires some of the basic natural resources such as sunlight, water, carbon dioxide, and inorganic nutrients for the cultivation medium (Brennan and Owende 2010). Hence, the source of nutrients for the cultivation of microalgae can be sourced from the fertilizers available in a region. For establishing the appropriate facility for the algae industry, the consideration of the availability land per region is an important factor to consider especially that the available land in the Philippines is scarce. The supply of power for operating the biomass production facility is an important aspect of the production of algal bioproducts. This sub-criterion falls under the environmental impact category as the generation of electricity in the Philippines is mostly based on fossil fuel. Hence, the following sub-criteria are selected for environmental impact criterion to assess the alternative region *R*: carbon footprint, water availability, land availability, fertilizer supply, climate type, and supply of power.

Appendix 1.2: Costs of resources

The use of resources entails costs. Thus, the important operational costs of an algae-based establishment were examined such as the natural and human resource costs. The natural resource consumption considered the costs of land, water, inorganic fertilizers, and electricity. On the other hand, the minimum wage which varied per region was accounted for the cost of acquiring human resources.

Appendix 1.3: Social aspects

Social acceptance is recognized to be a contributing factor in the implementation of any renewable energy technology (Moula et al. 2013). The response of the general public may either support or constrain the implementation and use of such technologies. To capture this aspect, some of the socio-economic indicators were investigated. Since job creation is recognized as one of the benefits of the establishment of a new industry in a region, the potential labor force of an area must be considered as one of the criteria. Moreover, the eradication of poverty in conjunction with the Millennium Development Goals set by the United Nations is considered as a criterion in the study. Thus, the respective poverty indices of the regions were taken into account for this purpose.

Appendix 1.4: Industry presence

Microalgal biomass, consisting of high-value contents in the form of protein, carbohydrates, lipids, and pigments, can be further processed into various industrial products (Koller et al. 2014). These primary products from microalgae can further be refined to secondary products which can benefit a wide array of industries such as agriculture, energy production, and health. An effective approach to ensure the success of the establishment of new industries is the consideration of the proximity of collaborating industries. An ideal case of synergistic collaboration among different industries is the co-location of companies in an algae-based eco-industrial park (Ubando et al. 2016). The collaborating industries considered are nutraceuticals for high-valued products, aquaculture for fish feeds, animal feeds, and biofuels for bioenergy. In this regard, the respective regional performance or capacities for the aforementioned industries were considered in the model, wherein the nearer to the top-performing industries, the better.

Appendix 2: Model assumptions

The following assumptions were used in the case study:

(1) The cultivation of microalgae was performed in an open system because of its practicality and maintainability. With the microalgal cultivation exposed to the atmospheric condition, the climate type per region would be a significant criterion in the site evaluation (Schade and Meier 2019).
(2) The climate data type was already normalized for all regions (Cinco et al. 2013) according to the authors' judgment of the climate experienced in all of the regions in the Philippines.
(3) The source of carbon dioxide that could be utilized for microalgal cultivation would come from emissions of coal and diesel power plants (Philippine Department of Energy 2014a), owing to the carbon sequestration capability of microalgae as a phototrophic organism.
(4) Representative values for the land costing per region is loosely approximated to be the ratio of the idle land area available per region with respect to the total land area per region (Philippine Department of Energy 2014a). For a conventional pairwise comparison matrix, the assignment of values followed the notion where a higher performance value is more desired. However, the scenario was made otherwise for the costs sub-criteria such that the lower the costs that is incurred, the better. For the latter analysis, the pairwise comparison matrices were transposed to obtain normalized values which can be combined with the former data.
(5) The National Capital Region of the country was excluded from the set of alternatives assuming that there would be no available land area (Philippine Department of Energy 2014a) in the particular region to serve as cultivation and processing site for the algae industry.
(6) The regional data for the remaining sub-criteria not mentioned in this section were obtained from various literature and Philippine government databases which belonged to a single time period only as shown in Table 2.

Appendix 3: The data sources

One of the advantages of the AHP approach is the ability to combine qualitative and quantitative data to arrive at a sound decision. The results of the survey questionnaires provided the weights for the qualitative aspect through the pairwise comparison of the criteria which followed the hierarchical structure shown in Fig. 1. The weights of the qualitative data were solved through the FAHP approach and the developed NLP model. The quantitative data comprised of the inventory lists of regional data for the identified criteria and sub-criteria shown in Table 2. Most of the quantitative data were sourced from various government agencies of the Philippines as depicted in Table 2.

The survey was conducted for 72 respondents across the Philippines. The respondents were composed of industry professionals (6), government officials (30), and researchers and faculty from the academic community (36). The survey questionnaire followed Saaty's 9-point scale to elicit the importance of the criteria and the sub-criteria shown in Table 1. The questionnaire was structured to follow the pairwise comparison where the importance of two criteria (a pair of criteria) were evaluated at a time (Saaty 1980).

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