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Technological Screening of Algae-Based Biorefinery for Sustainable Biofuels Production using Analytic Hierarchy Process (AHP) with Feature Scaling Normalisation

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Algal biomass has recently attracted attention as a promising source for renewable energy production due to its capability to grow on non-arable land, and assist on carbon sequestration and wastewater remediation. Although algal biomass has the potential to be utilised as a feedstock for biorefinery, there have been no definite technological pathways adopted for algae processing and biofuels production. Thus, a technological screening framework using multi criteria decision making approach based on analytic hierarchy process (AHP) with feature scaling normalisation is proposed to select the optimum processing pathway for sustainable biofuels production of an algae-based biorefinery. The technological alternatives are evaluated by defining the main criteria of the system and assigning sub-criteria under each main criterion to analyse the impacts of each criterion on the biorefinery system. The main criteria considered in this study are economic viability, and environmental and safety impacts. The sub-criteria are evaluated using pairwise comparison matrices, whereby the inputs are the numerical data normalised using the feature scaling method. A case study is presented to illustrate the normalised AHP-based technological screening methodology.

1. Introduction

The increasing environmental awareness of our society has led to the development of sustainable biofuel production to mitigate greenhouse gas emissions and global warming issues. Among the various biomasses available, algae is considered as a promising feedstock for biorefinery to sustainably produce biofuels and other high-value products including nutraceutical and cosmetic products (Sadhukhan et al., 2014). Algae provides the sustainability potentials due to its capability for carbon bio-fixation from flue gas and bio-remediation for wastewater treatment (Chisti, 2007). However, the production technology and research on biofuels generated using algae are still relatively new and immature.

The economic and environmental challenges in the utilisation of algae need to be addressed to realise its potential as a sustainable feedstock for biofuel production. Due to the biological nature of algae, the cultivation and extraction processes requires proper selection of algae strain and technologies to be utilised to optimise variables such as lipid content, growth efficiency, carbon uptake rate, and energy demand (Klinthong et al., 2015). Therefore, to analyse the economic, environmental, and safety benefits and trade-offs of algae processing, the technological pathways of algae-based biorefinery for biofuel production are investigated. Rizwan et al. (2015) formulated stochastic mixed integer nonlinear programming (sMINLP) model to determine the optimal algae-based biorefinery configurations and parameter uncertainties. Tay et al. (2011) adapted fuzzy mathematical modelling to synthesise a sustainable biorefinery, which maximises economic potentials and minimises environmental impacts.

In this paper, a multi-criteria decision-making tool using analytic hierarchy process (AHP) introduced by Saaty (1979) is adopted to evaluate the technological pathway alternatives of algae-based biorefinery for sustainable biofuels production. There are some existing research works that utilised AHP as a decision-making tool.

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Ubando et al. (2016) evaluated technological alternatives for algae cultivation system using AHP method and analysed the uncertainty scenarios using Monte Carlo simulation. Tan et al. (2015) proposed the multi-objective multi-criteria approach, fuzzy AHP, to select the optimum technologies for algae harvesting and drying based on the technology capability, cost, and environmental impact. In this paper, the AHP methodology has been extended to evaluate the economic, environmental, and safety impacts of various technological processing pathways based on its numerical data using feature scaling normalisation technique (Cristóbal et al., 2016) instead of using the 9-point scale to represent the importance of an element over the other as introduced by Saaty (1979). Normalisation is applied on the numerical data to produce the same data range of value for inputs to the AHP model to guarantee stable weightage distribution when developing the pairwise comparison matrices of alternatives with respect to sub-criteria. The major novelties of this work are summarised as follow:

- Technological screening framework for algae-based biorefinery that integrates the technoeconomic, environmental, and safety impacts analysis through a multicriteria decision making framework.
- Integration of AHP methodology introduced by Saaty (1979) with feature scaling normalisation technique (Cristóbal et al., 2016) to consider the qualitative and quantitative aspects in the decision making.

2. Methodology

The AHP method, which was initially introduced by Saaty (1979), is a multi-criteria decision making tool that translates complex decision problems with multiple competing factors into a hierarchical decision structure. The hierarchical decision structure consists of a goal for decision making, the main criteria and sub-criteria, and the list of alternatives available to evaluate the outcome of the goal. In this paper, the AHP method is developed as follows:

1. Construct the AHP decision network (Saaty, 1979). Three technological pathway alternatives are compared in the hierarchy network and economic, environment, and safety impacts are defined as the main criteria to select the optimum technological pathway for algae processing to biofuels production.
2. Evaluate the defined main criteria and sub-criteria using pairwise comparison approach based on a priority scale from one to three, which is in the order from less preferred option to most preferred option.
3. Calculate the normalised weight of the numerical data of the sub-criteria, W', using feature scaling normalisation method (Cristóbal et al., 2016). This step is an extension from the AHP method developed by Saaty (1979), which incorporates quantitative aspects of the sub-criteria for decision making. Apply Eq(1) if higher value is preferred i.e. NPV and Eq(2) if lesser value is preferred i.e. water footprint.
4.

$$W' = \varepsilon + \frac{W - \min(W)}{\max(W) - \min(W)} \tag{1}$$

$$W' = \varepsilon + \frac{\max(W) - W}{\max(W) - \min(W)} \tag{2}$$

Where W is the numerical value of each sub-criterion i.e. NPV, min(W) and max(W) is the minimum and maximum value of the sub-criteria for the three pathways, and ε is a small tolerance value of 0.01 to avoid zero values when constructing the pairwise comparison matrices. The application of Eq(1) and Eq(2) allows the numerical data to produce the same range of value between 0 and 1 + ε to allow for stable weightage distribution, where higher value indicates higher overall weighting.

5. Construct the pairwise comparison matrices to determine the normalised weights of each main criterion, sub-criterion, and alternative with respect to the goal, main criteria, and sub-criteria.
6. Solve the overall weighting of the alternatives using the eigenvector method (Saaty, 1979) and identify the alternative with the highest overall priority score to be the optimum pathway based on the overall performance with respect to the environmental, economic, and safety impacts.

The summary of the methodology is illustrated in Figure 1.

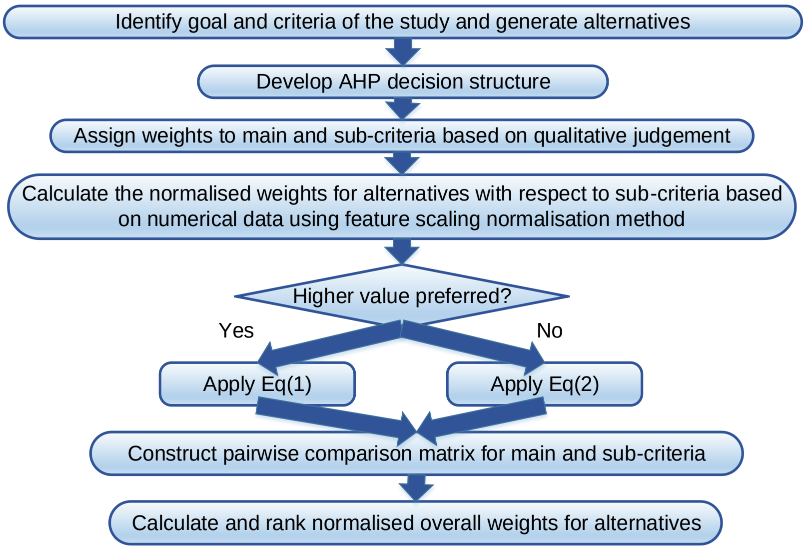

Figure 1: AHP methodology flow diagram

3. Case Study

A case study on Nannochloropsis sp. with base capacity of 100 t/y of algae production is developed to illustrate the methodology. Three pathway alternatives determined from the literature are identified in this paper to select the sustainable technological pathway for algae processing to biofuels production. The process network involves processes for algae cultivation, harvesting, extraction, and algal oil upgrading. The main criteria identified for the decision model are economic, environmental, and safety impacts, with one, four, and two sub-criteria. The process flow diagrams for the three pathway alternatives are shown in Figure 2 and the hierarchical decision network employed with the identified main criteria and sub-criteria is shown in Figure 3.

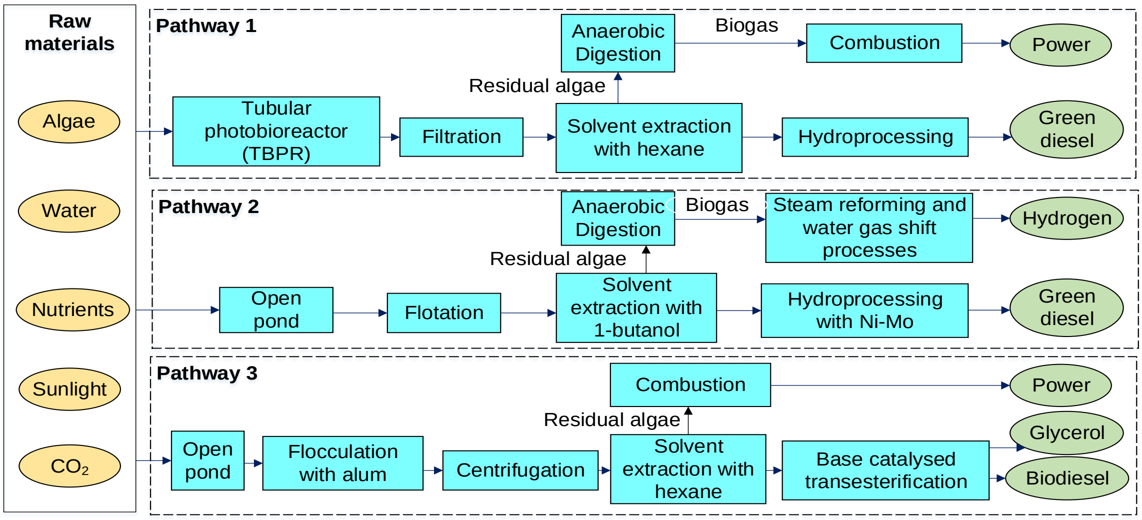

Figure 2: Process flow diagrams for biofuels production for three different algae processing pathways

The priority rankings for each main criterion with respect to the goal and sub-criterion with respect to the main criterion are evaluated based on a priority scale from one to three using the pairwise comparison matrix (Saaty, 1979). The development of algae-based biorefinery for sustainable biofuel production is one of the methods to mitigate the issues caused by fossil fuels including risk of depletion and greenhouse gas emissions. Therefore, biofuels produced from the biorefinery have to be advantageous in terms of economic and environmental aspects in comparison to the fossil fuels. Since the feasibility of algae-based biorefinery to be implemented on a commercial scale remains ambiguous and is highly dependent on the economic and environmental potentials, the economic and environmental impacts are assigned higher priority ranking than safety aspect.

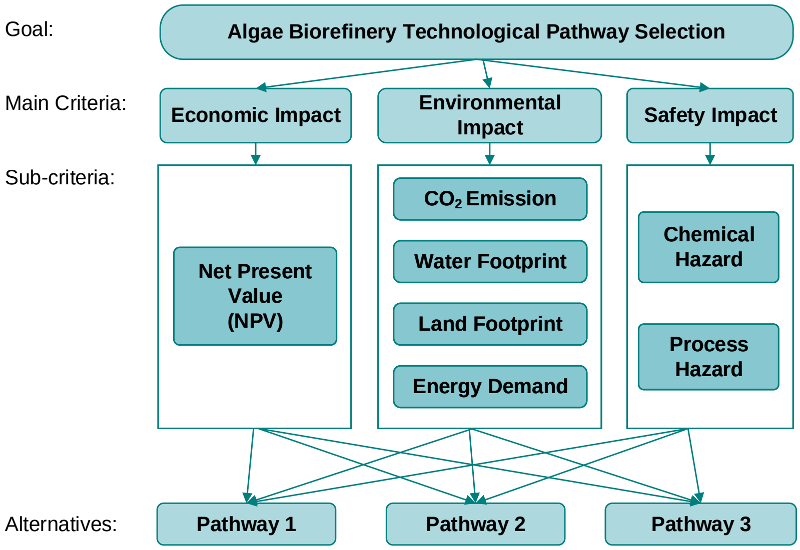

Figure 3: AHP decision structure for algae biorefinery technological pathway

Table 1: Summary of the derivation method for each sub-criterion for technological alternative evaluation

No.	Sub-criteria	Derivation method
1	NPV	Calculated using economies of scale based on algae production base capacity of 100 t/y, capital and operating costs obtained from literature data, and products selling price for every product produced from each pathway as illustrated in Figure 2. The selling price of green diesel and biodiesel of \$3.50/L and \$3/L, is assumed to be higher than the current unit prices to generate positive NPV. The selling price for power, glycerol, and hydrogen is gathered from literature data.
2	CO_2 emission	Determined from literature review based on the carbon dioxide released from the process: Pathway 1 (Gebreslassie et al., 2013), Pathway 2 (Gong and You, 2014), (Gutiérrez-Arriaga et al., 2014). The CO_2 emissions are mainly generated during anaerobic digestion and combustion processes. For every pathway, direct flue gas from a power plant is supplied as carbon source for algae growth, which acts as a form of carbon sequestration in algae.
3	Water footprint	Calculated the water requirement through material balance of the whole system including algae growth and cooling processes (Ercin and Hoekstra, 2012).
4	Land footprint	Calculated the cumulative land use area based on the equipment capacity and quantity for each processing stage (Lundquist et al., 2010).
5	Energy demand	Determined based on the energy requirement for all equipment for each processing stage (Hernández-Calderón et al., 2016). The process flow diagram for each pathway is summarised in Figure 2. The detailed flowsheets can be found as follow: Pathway 1 (Gebreslassie et al., 2013), Pathway 2 (Gong and You, 2014), and Pathway 3 (Gutiérrez-Arriaga et al., 2014).
6	Chemical hazard	Evaluated based on the Chemical Inherent Safety Index (Heikkilä, 1999). The cumulated value accounts for reaction hazards and hazardous substances including flammability, explosiveness, toxicity, and corrosiveness.
7	Process hazard	Evaluated based on the Process Inherent Safety Index (Heikkilä, 1999). The cumulated value includes process operating conditions such as temperature, pressure, and process structure.

There are four sub-criteria considered for environmental impact analysis, namely, CO_2 emission, water footprint, land footprint, and energy demand. Energy demand and CO_2 emission are assigned higher priority ranking followed by water footprint and land footprint. This is because the change in energy demand directly impacts the profitability of the biorefinery and CO_2 emission can cause drastic climate changes. Water and land footprints have been assigned lower weightage compared to energy demand and CO_2 emission due to algae capability to grow on wastewater and non-arable land (Chisti, 2007), resulting in reduced water consumption and land use for the biorefinery. For safety impact sub-criteria, chemical and process hazards have equal weightage since both aspects need to be simultaneously considered for biorefinery design to minimise the risk associated with all hazards.

To construct the pairwise matrices for the pathway alternatives with respect to the sub-criteria, the numerical data are determined using the derivation method as summarised in Table 1. The feature scaling normalisation technique Eq(1) and Eq(2)) is applied on the sub-criteria data collected. The actual and normalised data for each of the sub-criterion is given in Table 2.

Table 2: Numerical and normalised data for economic, environmental, and safety impacts of each processing pathway

Main criteria	Sub-criteria	Pathway	Actual value	Feature Scaling Normalised Value
Economic impacts	NPV ($ M)	1	423.48	0.17
		2	410.5	0.01
		3	489.65	1.01
Environmental impacts	CO_2 emission (kg CO_2eq/y)	1	5,121.93 (Gebreslassie et al., 2013)	0.01
		2	4,385.44 (Gong and You, 2014)	0.230
		3	1,780 (Gutiérrez-Arriaga et al., 2014)	1.01
	Water footprint (kg H_2O/kg algae)	1	4.89	1.01
		2	78.28	0.01
		3	78.28	0.01
	Land footprint (m^2)	1	7,557.72	1.01
		2	13,554.43	0.01
		3	12,141.01	0.246
	Energy demand (MJ/y)	1	3.26×10^8	0.96
		2	2.90×10^7	1.01
		3	5.99×10^9	0.01
Safety impacts	Chemical hazard	1	14	1.01
		2	17	0.260
		3	18	0.01
	Process hazard	1	8	1.01
		2	9	0.01
		3	9	0.01

The overall weighting of the main criteria and sub-criteria for each technological pathway is summarised in Table 3. Based on the results indicated in Table 3, Pathway 1, which consists of algae cultivation using TPBR, algae harvesting through filtration, lipid extraction using hexane as solvent, and hydroprocessing for oil refining, is the most preferred algae processing pathway for biofuels production when evaluated based on its economic, environmental, and safety impacts. This is mainly because it has lower water and land footprints and safety impact scores. However, this also involves trade-offs with the economic and environmental aspects.

Table 3: Overall weighting of each alternative

Main criteria	Economic (0.375)	Environmental (0.375)				Safety (0.25)		Overall priority
Sub-criteria	NPV (1.00)	CO_2 emission (0.33)	Water footprint (0.22)	Land footprint (0.11)	Energy demand (0.33)	Chemical hazard (0.50)	Process hazard (0.50)	
Pathway 1	0.34	0.01	0.98	0.86	0.485	0.79	0.98	0.53
Pathway 2	0.02	0.13	0.01	0.01	0.510	0.20	0.01	0.11
Pathway 3	0.64	0.87	0.01	0.13	0.005	0.01	0.01	0.36

4. Conclusion

A multi-criteria decision-making methodology using AHP approach is developed to evaluate three technological pathways of algae-based biorefinery for sustainable biofuels production. The technological pathways are evaluated based on multiple economic, environmental, and safety metrics. Based on the results, the optimum algae processing pathway to produce sustainable biofuels consists of algae cultivation using TPBR, algae harvesting through filtration, lipid extraction using hexane as solvent, and hydroprocessing for oil refining into biofuel products including biodiesel, biogas, and bioethanol. Future work includes extension of the method to address uncertainties in numerical data and limitations in the predefined technological processing pathways to allow for possibility of integration of the various process steps into new processing pathways.

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