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Fuzzy Analytical Hierarchy Process (AHP) for Multi-Criteria Selection in Drying and Harvesting Process of Microalgae System

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Over the decades, biofuels from agriculture crops have gained interest due to the awareness of environmental benefits with respect to greenhouse gases emissions and global warming. Among many types of crops, microalgae are considered to be the most promising new source of biomass compared with first and second-generation feedstocks. However, high energy requirement for harvesting and drying of the biomass, as well as the lack of cost-effective techniques for harvesting large quantities of microalgae, pose challenges to commercialization. In this work, we propose a systematic and simple methodology in the multi-criteria evaluation of alternatives for the harvesting and drying process. A fuzzy analytical hierarchy process (AHP) approach is used, where the pairwise comparison of the criteria and alternatives is done and expressed with triangular fuzzy numbers. In a case study, four alternatives each for the harvesting and drying process options are compared. Cost, environmental impacts and technology capability are used as the criteria in selecting of optimum option for harvesting and drying processes. From the pairwise comparison, filtration is found to be the best option for harvesting, compared with other options such as centrifugation, flotation and sedimentation with flocculation. On the other hand, sun drying process is found to be better than other drying alternatives, i.e., freeze drying, spray drying and drum drying. Fuzzy AHP allows the degree of confidence of the expert to be quantified. This method also allows the inconsistency of the judgments to be reconciled within the bounds of the fuzzy numbers.

1. Introduction

Microalgae have been the subject of considerable interest as potential feedstocks for producing sustainable biofuels and other high-value products (Guldhe et al., 2014). The demand for biomass for both food and use is expected to increase by more than 50 % in the next two decades as a result of world population growth coupled with increasing living standards (Foley et al, 2011). At the same time, initiatives have been taken to move from a fossil-fuel-based global economy to biomass-based economy, in which biomass replaces fossil fuel as a source of energy and as feedstock for the chemical industry (Haveren et al., 2008). The production of first-generation biofuel from food crops such as sugarcane ethanol, corn, oilseed rape and palm oil is already technologically mature, and is constrained only by economic factors, most notably by the conflict between food and fuel use. The global demand for liquid biofuel is more than tripled between 2004 and 2014, which has been shown to affect food markets (Rosegrant et al., 2008). Second generation biofuels from agricultural and forest residues and from non-food crop feedstock can potentially reduce the "food-versus-fuel" competition associated with first generation feedstocks. However, production technology for second generation biofuel are still relatively immature; in the future, there may be potential for cost reductions and increased efficiency levels as more experience is gained (IEA

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Bioenergy, 2008). On the other handy, microalgae are considered to be the most promising new “third generation” source of biomass due to the fact that microalgae production does not compete with conventional agriculture; also, high biofuel yields per unit of terrestrial area are also possible due to high photosynthetic efficiency (Chisti, 2008). However, despite the potential of algae biofuels as a renewable energy source, with the technology available today, a number of factors continue to hinder their commercialization.

The challenge in the upstream processing of microalgae lies in separating the microalgae from their liquid growth medium. This step takes place in the harvesting and drying processes. In order to have a cost effective harvesting and drying of microalgae is considered to be the most challenge process of microalgae biofuel production (Greenwell et al., 2010). Studies show that 20 – 30 % of the costs of microalgae biomass production contribute from harvesting process (Mata et al., 2010). In addition, estimated of 90 % of the equipment cost for microalgae biomass production in open systems is due to the harvesting and dewatering process. Razon and Tan (2011) showed that removal of moisture is the single most energy-intensive step in the process chain. Microalgae can be harvested by employing different technologies, e.g., filtration, centrifugation, flocculation, sedimentation, flotation etc. (Milledge and Heaven, 2012). Drum drying, spray drying, sun drying and freeze drying are some of the technologies that can be used in drying process (Chen et al., 2009). Each process technology of course has its own advantages and disadvantages.

In this paper, a systematic multi-criteria decision making (MCDM) using Fuzzy Analytical Hierarchy Process (FAHP) for evaluating the technology alternatives in the microalgae harvesting and drying process is developed. AHP which was introduced by Saaty (1979) has been used widely applied in various industry (Vaidya and Kumar, 2006). It is specifically designed for decision that require integration of quantitative data with less tangible, qualitative consideration such as value and preferences, especially in situations where there are important qualitative aspect that require consideration in conjunction with varies measureable quantitative factors (Noh and Lee, 2003). On the other hand, Fuzzy Set Theory (FST) is introduced to deal with the uncertainty and vagueness, with capability in representing the uncertainty in the data (Zadeh, 1965). Application of fuzzy optimization in identifying the optimum pathways was done by Liew et al. (2013). In their studies, multiple production pathways were assessed based on multiple sustainability criteria to screen the biodiesel production pathway and proven of fuzzy optimization is effective to synthesize most sustainable pathway. Therefore, in this work, FAHP through the pairwise comparison of the multi-criteria and alternatives are done and expressed with triangular fuzzy numbers to priorities the best harvesting and drying method. This paper is organized as follows. Section 2 gives a brief description of the methodology. Example of the results and discussions based on the harvesting process is illustrated and the overall prioritize ranking of the alternatives for harvesting and drying processes are presented in Section 3. Finally, concluding remarks are given in Section 4.

2. Methodology

Rehak and Senavsky (2014) presented a mathematical formula for multi-criteria analysis in assessing the risks in the electric power sector. Tan et al. (2014) conducted study on quantifying the degree of confidence of the experts in AHP. They also allow the inconsistencies in judgement to be reconciled within the bound of fuzzy numbers to generate reasonable values for AHP weighting factors. Promentilla et al. (2014) extended the fuzzy preference programming technique to derive the group priorities or weights from fuzzy pairwise comparative judgment matrices. It uses fuzzy analytic network process in a group decision making environment to address the complexity of the decision structure and the uncertainty inherent in eliciting value judgments from stakeholders or experts. In this paper, the FAHP technique is developed as the following:

i) Construct the AHP network (Saaty, 1979). Four alternatives for each harvesting and drying process options are compared individual hierarchy network. Whereas, cost, environmental impacts and technology capability are defined as the criteria in selecting of optimum option for harvesting and drying process, respectively (Figures 1 and 2).
ii) The pairwise comparison of the criteria based on a nine-point scale is done for the elements of the hierarchy based on the judgments experts’ experiences. The AHP method requires the following pairwise comparison matrix, **A**, which contains the relative weight of the criteria. w_i is the importance weight of the *i*th criteria with respect to goal, or the importance weight of the *i*th sub criteria (i = 1, ….,n) with respect to criteria and so on (Eq 1). Scale 1 represents the equal importance whereas scale 9 indicates as extreme importance of one activity over another. Values 2 and 4 are used to show an intermediate importance between the criteria (Saaty, 1979).

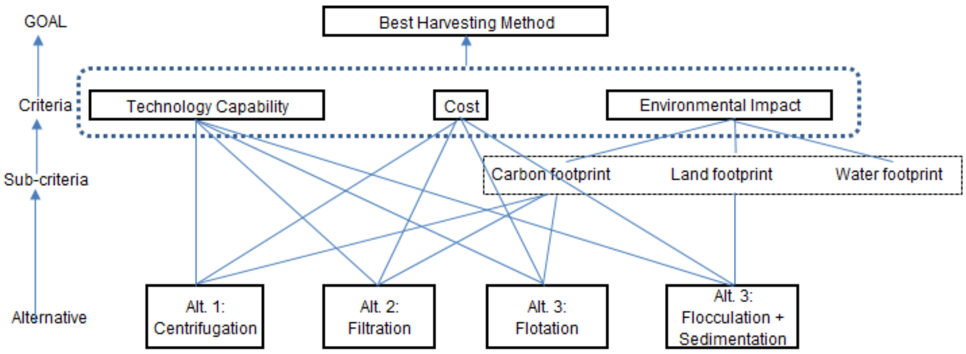

Figure 1: AHP decision structure for harvesting process

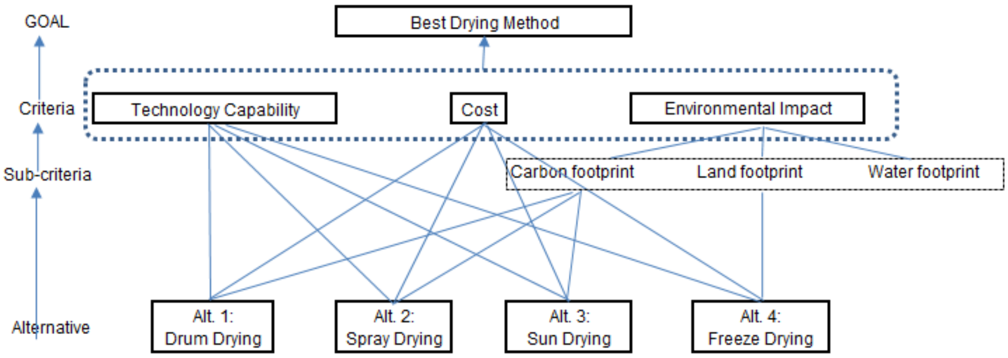

Figure 2: AHP decision structure for drying process

$$\mathbf{A} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_i}{w_1} & \frac{w_i}{w_2} & \cdots & \frac{w_i}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \tag{1}$$

iii) For a set element in the matrix **A**, $\hat{\boldsymbol{a}}_{ij}$ is then computed and used as the reciprocal pairwise comparison matrix at Eq(2):

$$\hat{\mathbf{A}} = \begin{bmatrix} (1,1,1) & \hat{a}_{12} & \cdots & \hat{a}_{1n} \\ \hat{a}_{21} & (1,1,1) & \ldots & \hat{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{a}_{n1} & \hat{a}_{n2} & \cdots & (1,1,1) \end{bmatrix} \text{ where } \hat{\boldsymbol{a}}_{ji} = \frac{1}{\hat{a}_{ij}} = \langle \frac{1}{\hat{L}_{ij}}, \frac{1}{\hat{M}_{ij}}, \frac{1}{\hat{U}_{ij}} \rangle \tag{2}$$

iv) Using LINGO 14.0, the objective of the FAHP is to maximize the consistency index; lambda (λ). λ is interpreted as the degree of satisfaction in triangular fuzzy number (TFN) of all computed pairwise comparison ratios satisfy with the initial fuzzy judgments. The consistency index, lambda (λ) shall ranges from 0 to 1. A value of 0 denotes that the fuzzy judgments are satisfied at their boundaries and a value of 1 denotes as the perfect consistency within the fuzzy bounds (Tan et al., 2014). The sum of the weights of all considered criteria, $\mathbf{w}_k$ must be equal to 1. The proposed nonlinear programming (NLP) formulation to determine the optimal **w** is as Eq(3) (Promentilla et al., 2014):

$$\max \lambda; \quad (3a)$$

subject to:

$$\lambda(M_{ij} - L_{ij})(w_j) - w_i + w_j L_{ij} \leq 0\,; \quad (3b)$$

$$\lambda(M_{ji} - L_{ji})(w_i) - w_j + w_i L_{ji} \leq 0\,; \quad (3c)$$

$$\lambda(U_{ij} - M_{ij})(w_j) + w_i - w_j U_{ij} \leq 0\,; \quad (3d)$$

$$\lambda(U_{ji} - M_{ji})(w_i) + w_j - w_i U_{ji} \leq 0\,; \quad (3e)$$

$$\textstyle\sum_{k=1}^{n} w_k = 1\,;\ w_k > 0 \quad (3f)$$

3. Results and Discussion

For this paper, an example of the FAHP is illustrated based for selecting the best method for the microalgae harvesting process (Figure 1). A sample of the numerical calculations is shown to demonstrate the proposed methodology in computing group priority vectors from fuzzy pairwise comparative judgment matrices (PCJM). The four main criteria are technology capability (TECH), cost (COST) and environmental impact (ENV). There are three sub-criteria under the environmental impact, i.e.: carbon footprint (CF), land footprint (LF) and water footprint (WF). The alternatives for selecting the best harvesting process method are namely (1) centrifugation (CG), (2) filtration (FL), (3) flotation (FT) and (4) Flocculation and sedimentation (FS). The expert performed a pairwise comparison to indicate his or her preference for each criterion. The fuzzy evaluation of the sub-criteria relating to each main-criterion and the alternatives regarding each sub-criterion are shown in Figures 3, 4 and 5, respectively. Using LINGO 14.0 to solve for the NLP as described in Eq(3) for the said fuzzy judgement to obtain the preference weight of the alternative for harvesting process with respect to the sub-criteria of ENV and selection criteria - TECH, COST and ENV (Table 1 and 2). With the λ value greater than zero, it indicates that the consistency of the judgement.

Table 3 summarizes the overall priorities ranking of the alternatives computed from the principal eigenvector of the matrixes described in Tables 1 and 2. Results show that the most preferable harvesting alternative technologies are filtration, centrifugation, flotation, flocculation and sedimentation.

	TECH	COST	ENV
TECH	<1,1,1>	<1/2,1, 2>	<2,3,4>
COST	<1/2,1,2>	<1,1,1>	<2,3,4>
ENV	<1/4,1/3,1/2>	<1/4,1/3,1/2>	<1,1,1>

Figure 3: Fuzzy pairwise comparison matrix of selecting criteria for harvesting method

	CF	LF	WF
CF	<1,1,1>	<1/2,1,2>	<6,7,8>
LF	<1/2,1,2>	<1,1,1>	<6,7,8>
WF	<1/8,1/7,1/6>	<1/8,1/7,1/6>	<1,1,1>

Figure 4: Fuzzy pairwise comparison matrix of environmental impact's sub-criteria

TECH	Alt 1: CF	Alt 2: FL	Alt 3: FT	Alt 4: FS
Alt 1: CF	<1,1,1>	<2,3,4>	<4,5,6>	<6,7,8>
Alt 2: FL	<1/4,1/3,1/2>	<1,1,1>	<4,5,6>	<2,3,4>
Alt 3: FT	<1/6,1/5,1/4>	<1/6,1/5,1/4>	<1,1,1>	<2,3,4>
Alt 4: FS	<1/8,1/7,1/6>	<1/4,1/3,1/2>	<1/4,1/3,1/2>	<1,1,1>

COST	Alt 1: CF	Alt 2: FL	Alt 3: FT	Alt 4: FS
Alt 1: CF	<1,1,1>	<1/4,1/3, 1/2>	<1/8,1/7, 1/6>	<1/8,1/7, 1/6>
Alt 2: FL	<2,3,4>	<1,1,1>	<1/4,1/3, 1/2>	<1/4,1/3, 1/2>
Alt 3: FT	<6,7,8>	<2,3,4>	<1,1,1>	<1/2,1, 2>
Alt 4: FS	<6,7,8>	<2,3,4>	<1/2,1, 2>	<1,1,1>

Figure 5: Fuzzy pairwise comparison matrix of criteria (technology and cost) with alternatives

Table 1: Normalized alternatives and environment's sub-criteria[a] for harvesting process

Alternative	Carbon footprint (w_1=0.467)	Land footprint (w_1=0.467)	Water footprint (w_1=0.067)	Overall score
Alt 1: CF	0.061	0.125	0.086	0.093
Alt 2: FL	0.582	0.625	0.332	0.586
Alt 3: FT	0.179	0.125	0.291	0.161
Alt 4: FS	0.179	0.125	0.291	0.161

[a] weighting from FAHP method (λ = 1.0)

Table 2: Normalized alternatives and criteria[b] for harvesting process

Alternative	TECH[c] (w_1=0.429)	COST[d] (w_1=0.429)	ENV (w_1=0.143)	Overall score
Alt 1: CF	0.550	0.054	0.093	0.272
Alt 2: FL	0.303	0.148	0.586	0.277
Alt 3: FT	0.091	0.399	0.161	0.233
Alt 4: FS	0.061	0.399	0.161	0.220

[b] weighting from FAHP method (λ = 1.0)
[c] weighting from FAHP method (λ = 0.702)
[d] weighting from FAHP method (λ = 0.999)

Table 3: Weighting and ranking of harvesting alternatives

Alternatives	Overall Score	Ranking
Centrifugation (CF)	0.272	2
Filtration (FL)	0.277	1
Flotation (FT)	0.233	3
Flocculation & Sedimentation (FS)	0.220	4

Similarly, the steps are applied for selection of the drying process alternatives. Table 4 indicates the results of the drying process alternatives. It shows both the aggregate scores and the resulting ranks of the available options. The most preferable technology for microalgae drying is sun drying, followed in descending order by freeze drying, spray drying and drum drying.

Table 4: Weighting and ranking of drying alternatives

Alternative	Overall Score	Ranking
Drum drying (DD)	0.178	4
Freeze drying (FD)	0.307	2
Spray drying (SPD)	0.185	3
Sun drying (SUD)	0.324	1

4. Conclusion

In this paper, multi-criteria decision making model based on FAHP approach is developed to analyse the best harvesting and drying process in the microalgae industry. The FAHP model enable the issue of inconsistency during the judgement from the expert to be addressed through an optimization procedure. Future studies will focus on more complex decision structures, with uncertainty analysis to determine the robustness of the proposed decision model.

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