Energy Priority Estimation Model for Quantitative Analysis of Potential Bioethanol Feedstock

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Abstract. Conventional energy sources depletion, energy insecurity, fluctuating petroleum prices and global climate change have driven countries worldwide to consider alternative and renewable energy options. The use of biofuel such as bioethanol is as an option over conventional petroleum and important for the development of sustainable and eco-friendly energy resources. However, bioethanol manufactured from various biomass resources is different in terms of its processing stages and the need for extra pre-treatments. This study aims to suggest the most feasible biomass resource for bioethanol generation by using Analytical Hierarchy Process (AHP), one of the multi-criteria decision-making methods based on priority estimation model. Among biomass resources, the issue of selecting the most feasible resource is evaluated, using numerous criteria influencing the biomass selection which are chosen through Focus Group Discussion (FGD) with experts in the biomass research field. Out of the five selected biomass resources, sugarcane is preferable as a bioethanol feedstock with an overall priority of 31.69%, followed by palm oil residues (overall priority= 23.51%), compared to corn (overall priority= 22.59%), rice straws (overall priority= 13.53%) and sugar beet (overall priority= 8.67%). Sugarcane is claimed to be the most feasible bioethanol feedstock due to its high availability over years, high energy ratio, high cellulose and hemicellulose content. Although sugarcane takes a longer time to grow, it is easier to be planted and harvested with the help of developed machineries. However, an ideal bioethanol-producing feedstock should not be food crops. Thus, as a suggestion for future research, more factors to determine the potential and suitability of the crops should be considered.

1.0 Introduction

Energy is everywhere and being one of the ultimate elements required in our daily life. The vast urbanization and industrialization associating with rapid population expansion cause a vast consumption of energy worldwide. Thus, meeting the growing demand for energy has evolved as the dominant challenges for society in the 21st century.

Worldwide, conventional energy sources based on oil, coal and natural gas have greatly contributed in driving the economic progress. Overconsumption of fossil fuels results in economic and environmental impacts. For mitigating the enhancing greenhouse effect, application of renewable energy sources is a potential alternative option in addressing the challenges of energy and environment. They are preferable in terms of sustainability, greenhouse gases (GHGs) emission reduction and supply security.
Renewable energy sources currently supply between 15 and 20 percent of world’s total energy demand. Biomass emerges as the world’s fourth largest energy source worldwide, following coal, oil and natural gas [1]. It drew worldwide attention recently due to several criteria: renewable, highly productive, carbon neutral, and easy to transport and store [2].

Biofuel is a type of liquid or gaseous fuel for the transport sectors that are mainly derived from biomass or bio-waste through thermochemical and biological (such as fermentation) methods. For example, bioethanol, biodiesel, methanol, biobutanol are widely used in the world. Both dedicated energy crops and/or agricultural residues have the potential in contributing to biomass for energy purposes.

Focusing on bioethanol production, the potential feedstock are sugar-containing biomass, starchy materials and lignocellulosic feedstock. For instance, corn in the United States, sugarcane in Brazil, sugar beet in European Union, as well as palm oil residues in Malaysia. Despite the geographical availability, there are many criteria to be considered before selecting a potential bioethanol feedstock which will basically affect their production efficiency and feasibility.

In order to generate bioethanol more economically and environmentally efficient, the selection of the most potential biomass resource as bioethanol feedstock is the key factor that needs to be considered. Thus, a multi-criteria decision-making method based on priority estimation model which is called Analytical Hierarchy Process (AHP) will be used in this study. Among the biomass resources, the issue of selecting the most feasible resource is evaluated, using numerous criteria related to their properties. This study also will highlight an insight into multi-criteria decision-making technique to assess the feasible biomass resources for bioethanol production that could aid decision-making in the industry and policy development.

2.0 Methodology

AHP model was applied in this research. This model is generally categorized into two phases: hierarchy design and hierarchy evaluation. The selection of biomass resources and criteria influencing the selection is being done in the first phase of AHP. Meanwhile, the derivation of criteria weightage and local priorities of each alternatives is categorized under the second phase, followed by the evaluation of the most feasible bioethanol-producing feedstock.

2.1 Selection of Bioethanol Producing Feedstock

During the hierarchy design stage, the selection of biomass resources for bioethanol production was assisted by literature review and focus group discussion (FGD). FGD has been conducted among experts from different local universities in Malaysia, which are knowledgeable in biomass research field. The FGD is crucial to ensure the non-biasness in choosing criterion and relatively based on a knowledge-based consensus.

As a result, five types of biomass resources are chosen as the alternatives this research. Cob of Zea Mays (corn cob), Saccharum officinarum L. (sugarcane), straws of Oryza sativa (rice straws), Beta vulgaris (sugar beet), and residues of Elaeis guineensis (palm oil residues) were chosen for this study to evaluate their potentiality as the feedstock for bioethanol production.

2.2 Selection of Criteria Influencing Bioethanol-Producing Biomass Priority

The criteria in determining bioethanol-producing biomass priority were also established through FGD. The five selected criteria are availability over years, chemical composition, easiness to plant and harvest, energy ratio as well as number of harvests per year.

2.3 Bioethanol Producing Feedstock

2.3.1 Saccharum officinarum L. (Sugarcane)

Sugarcane is a type of perennial grass of the family Poaceae. It is generally made up of stem and straw. Its stem is commonly cultivated for its juice for sugar production as well as biofuel production,
especially in Brazil. The harvested canes can be used directly to generate ethanol. The straw (which is composed of fresh leaves, dry leaves and tops available before harvesting) and bagasse (residues from stems after juice extraction) are the by-products from cane sugar processing, which can be used for cellulosic ethanol generation [3].

2.3.2 Zea mays (Corn)
Corn is an annual cereal plant of the grass family (Poaceae), and yet an edible grain and being mostly cultivated in most warm areas of the world. It is well-known in producing first-generation bioethanol. The corn ethanol is typically blended with gasoline to be used as an automotive fuel in the United States. Although corn ethanol is more environmentally friendly compared to petroleum, but their production is controversial as diverting the feedstock from the human food chain.

2.3.3 Beta vulgaris (Sugar Beet)
Sugar beet is similar to sugarcane which is cultivated as one of the major sources of the world’s sugar due to the high sucrose content in the tuber of the beet root plant.

A recent study showed that sugar beets are a superior bioethanol-producing feedstock compared to corn. For the same amount of bioethanol, sugar beets require a smaller acreage of land and lower quantity of sugar beets is needed. The production yield of one acre of sugar beets is 1930kg ethanol, which is much higher compared to 1000kg of ethanol produced from one acre of corn [4].

2.3.4 Elaeis guineensis (Palm Oil Residue)
Oil palm (Elaeis guineensis) is an African tree in the palm family, namely Arecaceae. Basically, it is primarily cultivated as a source of oil, but recently, it has been developed to generate biodiesel as an alternative source of non-renewable fossil fuels. In fact, oil palm has an immense potential to produce cellulosic ethanol, which is also known as the second-generation biofuels. This is because the oil palm plantation is potential in generating a vast quantity of cellulosic biomass.

2.3.5 Oryza sativa (Rice Straws)
Rice plant (Oryza sativa) is an annual warm season grass of the Gramineae family. According to the study of Amamsiri and Wickramasinghe [1], there is about 800,000 hectares of rice is cultivated annually in Sri Lanka. With a ratio of 1:1 for paddy to straw, an estimated 2 million tonnes of rice straws are generated annually in Sri Lanka by assuming an average paddy yield of 2.5 tonnes per hectare of crop land. The potential of rice straws as bioethanol-producing feedstock can be explained through their large availability besides having high cellulose and hemicellulose in content.

2.4 Criteria Influencing Bioethanol-Producing Biomass Priority

2.4.1 Availability over years
Availability of a bioethanol-producing feedstock can be tracked by determining its global annual production. The crop production is expressed as tonnes and metric tonnes.

2.4.2 Chemical composition
According to the world average composition of the above ground standing biomass, the cellulose, hemicellulose and lignin are by far the most abundant biomass constituents, while the other components are minor in quantity.

A direct correlation was found between glucose yield and cellulose content of a biomass resource [5]. The higher the cellulose content, the higher is the glucose yield, indicating easier for the biomass to be fermented into ethanol. Thus, a biomass resource with high cellulose content is preferable to be chosen as the bioethanol-producing feedstock.
2.4.3 Easiness to plant and harvest
Easiness to plant and harvest of a crop is studied from the technical perspective, focusing on the planting and harvesting stages of selected crops.

2.4.4 Energy ratio
Energy ratio of a bioethanol-producing feedstock can be known as the net energy balance (NEB). Basically, NEB is the difference between output and input energies, and the ratio between them is called as NEB ratio [6]. According to Tilman et al. [7], the NEB ratio is used to indicate energy efficiency of the whole system of biofuel production. Thus, a high NEB ratio indicates an efficient biofuel production system.

2.4.5 Number of harvests per year
Crop duration is different among crops. Short term crops are usually grown for 45 to 60 days, which are aimed to obtain economic benefits in a short period of time. The growing duration for long-term crops are comparatively longer than short-term crops, in which their life span can achieve up to 5 years and above. Thus, as an ideal feedstock for bioethanol production, the crop duration should be shorter to ensure the high availability over years.

2.5 Analytic Hierarchy Process

2.5.1 Developing a model
AHP analysis will be started with building a decision hierarchy, which is also known as decision modelling [8]. AHP initially breaks down the complex MCDM (Multi Criteria Decision Making) problem into a hierarchy of interrelated decision elements, which are goals, criteria and alternatives, and being arranged in a hierarchical structure shown in figure 1.

![Figure 1. AHP Hierarchy.](image-url)
2.5.2 Deriving priorities for selected criteria

After the problem decomposition and hierarchy construction, the priorities for selected criteria were established through pairwise comparison according to the result from FGD (shown in table 3). In AHP multiple pairwise comparisons, a standard comparison scale (shown in table 2) of nine levels is used to express degree of preference of one element over another [9].

The judgements made in priorities derivation were generally subjective. Thus, in order to reduce the biasness in the model, consistency analysis is necessary to be conducted. It is important to ensure that the original preference ratings are consistent. The consistency indices can be calculated by using equation (1) and (2) as shown below.

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1} \quad (1)
\]

\[
CR = \frac{CI}{RI}, \text{ } RI = \text{ random index} \quad (2)
\]

Table 1. Consistency indices for a randomly generated matrix.

| n   | 3   | 4   | 5   | 6   | 7   |
|-----|-----|-----|-----|-----|-----|
| RI  | 0.58| 0.90| 1.12| 1.24| 1.32|

Table 2. Pairwise Comparison Scale.

| Relative Importance | Definition                                      | Explanation                                               |
|---------------------|-------------------------------------------------|-----------------------------------------------------------|
| 1                   | Equal importance                                | Two activities contribute equally to objective            |
| 3                   | Weak importance                                 | Experience and judgement slightly favour one activity     |
|                     |                                                 | over another                                              |
| 5                   | Strong importance                               | Experience and judgement strongly favour one activity     |
|                     |                                                 | over another                                              |
| 7                   | Demonstrated importance                         | One activity is strongly favoured and demonstrated in      |
|                     |                                                 | practice                                                  |
| 9                   | Extreme importance                              | The evidence favours one activity over another is of       |
|                     |                                                 | highest possible order of affirmation                     |
| 2, 4, 6, 8           | Intermediate values                             | When compromise is needed between two adjacent            |
|                     |                                                 | judgements                                                |

According to Saaty [10], the AHP analysis can only be continued if and only if the consistency ratio (CR) calculated is less or equal to 0.10. Any higher value at any level indicates that the judgements warrant re-examination [11].

Since 0.0794 for the proportion of inconsistency CR (shown in table 4) is less than 0.10, this judgements matrix is reasonably consistent, so the process of decision-making using AHP is continued.

2.5.3 Deriving local priorities for selected alternatives

The criteria assessment of the selected alternatives is shown in table 5. The third step in AHP is the comparison of the alternatives based on the criteria stated, followed by deriving their relative priorities with respect to each criterion [8]. The local priorities for selected alternatives are presented in tables 6 to 10.
Table 3. Pairwise comparison matrix of criteria.

| The Five criteria | Chemical Composition | Availability over years | Number of harvests per year | Energy ratio | Easiness to plant and harvest |
|-------------------|----------------------|-------------------------|----------------------------|--------------|-------------------------------|
| Criteria Weightage | 0.5028               | 0.2602                  | 0.1344                     | 0.0678       | 0.0348                        |

Chemical Composition Availability over Years Number of Harvests per Year Energy Ratio Easiness to Plant and Harvest

Table 4. Results of AHP computations for criteria.

| Criteria                  | Criteria Weightage | \(\lambda_{\text{max}}, \text{CI}, \text{RI}\) | CR   |
|---------------------------|--------------------|-----------------------------------------------|------|
| Chemical Composition     | 0.5028             | \(\lambda_{\text{max}} = 5.3556\)           |      |
| Availability over Years  | 0.2357             | \text{CI} = 0.0889                           | CR = 0.0794 |
| Number of Harvests per Year | 0.1344           | \text{RI} = 1.12                           |      |
| Energy Ratio              | 0.0678             |                                              |      |
| Easiness to Plant and Harvest | 0.0348          |                                              |      |

Table 5. Criteria assessment of the selected alternatives.

| Plants Name | Chemical Composition | Availability over years | Number of harvests per year | Energy ratio | Easiness to plant and harvest |
|-------------|----------------------|-------------------------|------------------------------|--------------|-------------------------------|
| Sugarcane   | Cellulose (48.6%), hemicellulose (31.1%) | 1.84 billion tonnes | 15 months | 9.3            | Moderately high production efficiency, 1 to 5 of operators are needed |
| Corn Cob    | Cellulose (42.0%), hemicellulose (33.0%) | 1.14 billion tonnes | 2.75 months | 0.6-2.0       | High production efficiency, one operator is needed |
| Rice Straws | Cellulose (30-45%), hemicellulose (20-25%) | 1.04 billion tonnes | 4.5 months | 8.3-8.4        | Low production efficiency, more than 1 operator is needed |
Table 5. Criteria assessment of the selected alternatives (Continued…).

| Plants Name | Chemical Composition | Availability over years | Number of harvests per year | Energy ratio | Easiness to plant and harvest |
|-------------|----------------------|-------------------------|-----------------------------|--------------|-------------------------------|
| Sugar Beet  | Cellulose (20-24%), hemicellulose (25-36%) | 301 million tonnes | 5.5 months | 1.2-1.8 | Moderate production efficiency, 1 operator is needed, leaving no residues after harvesting |
| Palm Oil Residues | Cellulose (57.8%), hemicellulose (21.2%) | 69.96 million tonnes | 48 months | 8.3-8.4 | Very low production efficiency, requires large amount of manpower |

Table 6. Pairwise comparison matrix of alternatives for chemical composition criterion.

| C1: Chemical Composition | Sugarcane | Corn Cob | Rice Straws | Sugar Beet | Palm Oil Residues | Priority Vector |
|--------------------------|-----------|----------|-------------|------------|------------------|----------------|
| Sugarcane                | 1         | 2        | 4           | 6          | 1/2              | 0.2900         |
| Corn Cob                 | 1/2       | 1        | 2           | 4          | 1/2              | 0.1767         |
| Rice Straws              | 1/4       | 1/2      | 1           | 2          | 1/5              | 0.0841         |
| Sugar Beet               | 1/6       | 1/4      | ½           | 1          | 1/6              | 0.0498         |
| Palm Oil Residues        | 2         | 2        | 5           | 6          | 1                | 0.3994         |

Table 7. Pairwise comparison matrix of alternatives for availability over years criterion.

| C2: Availability over Years | Sugarcane | Corn Cob | Rice Straws | Sugar Beet | Palm Oil Residues | Priority Vector |
|-----------------------------|-----------|----------|-------------|------------|------------------|----------------|
| Sugarcane                   | 1         | 3        | 5           | 7          | 9                | 0.5028         |
| Corn Cob                    | 1/3       | 1        | 3           | 5          | 7                | 0.2602         |
| Rice Straws                 | 1/5       | 1/3      | 1           | 3          | 5                | 0.1344         |
| Sugar Beet                  | 1/7       | 1/5      | 1/3         | 1          | 3                | 0.0678         |
| Palm Oil Residues           | 1/9       | 1/7      | 1/5         | 1/3        | 1                | 0.0348         |
### Table 8. Pairwise comparison matrix of alternatives for number of harvests per year criterion.

| C3: Number of Harvests per Year | Sugarcane | Corn Cob | Rice Straws | Sugar Beet | Palm Oil Residues | Priority Vector |
|---------------------------------|-----------|----------|-------------|------------|-------------------|-----------------|
| Sugarcane                       | 1         | 1/7      | 1/6         | 1/5        | 1/3               | 0.0404          |
| Corn Cob                        | 7         | 1        | 2           | 3          | 9                 | 0.4261          |
| Rice Straws                    | 6         | 1/2      | 1           | 2          | 9                 | 0.2845          |
| Sugar Beet                     | 5         | 1/3      | 1/2         | 1          | 8                 | 0.1940          |
| Palm Oil Residues              | 3         | 1/9      | 1/9         | 1/8        | 1                 | 0.0551          |

### Table 9. Pairwise comparison matrix of alternatives for energy ratio criterion.

| C4: Energy Ratio | Sugarcane | Corn Cob | Rice Straws | Sugar Beet | Palm Oil Residues | Priority Vector |
|------------------|-----------|----------|-------------|------------|-------------------|-----------------|
| Sugarcane        | 1         | 9        | 2           | 8          | 2                 | 0.4187          |
| Corn Cob         | 1/9       | 1        | 1/7         | 1/2        | 1/7               | 0.0355          |
| Rice Straws      | 1/2       | 7        | 1           | 6          | 1                 | 0.2472          |
| Sugar Beet       | 1/8       | 2        | 1/6         | 1          | 1/6               | 0.0513          |
| Palm Oil Residues| 1/2       | 7        | 1           | 6          | 1                 | 0.2472          |

### Table 10. Pairwise comparison matrix of alternatives for easiness to plant and harvest criterion.

| C5: Easy to Plant or Harvest | Sugarcane | Corn Cob | Rice Straws | Sugar Beet | Palm Oil Residues | Priority Vector |
|------------------------------|-----------|----------|-------------|------------|-------------------|-----------------|
| Sugarcane                    | 1         | 1/2      | 4           | 1/3        | 7                 | 0.1864          |
| Corn Cob                     | 2         | 1        | 5           | 1/2        | 8                 | 0.2790          |
| Rice Straws                  | 1/4       | 1/5      | 1           | 1/5        | 6                 | 0.0888          |
| Sugar Beet                   | 3         | 2        | 5           | 1          | 9                 | 0.4157          |
| Palm Oil Residues            | 1/7       | 1/8      | 1/6         | 1/9        | 1                 | 0.0300          |
2.5.4 Deriving overall priorities

After obtaining the local priorities which indicate the preferred alternative with respect to each criterion, the overall priority for each alternative is calculated. This step is called model synthesis and being presented in Table 11.

Table 11. Model Synthesis.

| Criteria | Chemical Composition | Availability over years | Number of harvests per year | Energy ratio | Easy to plant/harvest | Overall Priority |
|----------|----------------------|-------------------------|-----------------------------|--------------|-----------------------|------------------|
| Weights  | 0.5028               | 0.2602                  | 0.1344                      | 0.0678       | 0.0348                |                  |
| Sugarcane| 0.2900               | 0.5028                  | 0.0404                      | 0.4187       | 0.1864                | 0.3169           |
| Corn Cob | 0.1767               | 0.2602                  | 0.4261                      | 0.0355       | 0.2790                | 0.2259           |
| Rice Straws | 0.0841             | 0.1344                  | 0.2845                      | 0.2472       | 0.0888                | 0.1353           |
| Sugar Beet | 0.0498              | 0.0678                  | 0.1940                      | 0.0513       | 0.4157                | 0.0867           |
| Palm Oil Residues | 0.3994      | 0.0348                  | 0.0551                      | 0.2472       | 0.0300                | 0.2351           |

According to the Overall Priority Vector (OPV) calculated, the most feasible alternative with respect to the selected criteria was determined in this study. The biomass resource with the highest OPV indicates it has the most preference to be chosen as a bioethanol-producing feedstock.

3.0 Result and Discussion

Chemical composition was the criterion with the highest influence in determining bioethanol producing plant priority according to the result of AHP computation on the importance of criteria weightage (shown in Table 4.6). On the other hand, the criterion with the least influence was the easiness to plant or harvest. The results obtained as criteria weightage is listed from the highest to the lowest as follows—chemical composition (0.5028), availability over years (0.2602), number of harvests per year (0.1344), energy ratio (0.0678) and easiness to plant or harvest (0.0348) (shown in figure 2).

The OPV of each alternative reflects the priority to be selected as bioethanol producing feedstock. The obtained result from priority determination shows that sugarcane with the priority of 0.3169 is the most feasible biomass in generating bioethanol. It is followed by palm oil residues with an overall priority of 0.2351, corn cob (overall priority= 0.2259), rice straws (overall priority= 0.1353) and the least preferable biomass is sugar beet (overall priority= 0.0867). Result from AHP analysis of alternatives is shown in figure 4. In short, sugarcane is preferable as the best candidate for alternative in bioethanol production.
Figure 2. Criteria Weightage of Selected Criteria.

Figure 3. Priorities Weightage of Biomass Resources Respective to Selected Criteria.

Figure 4. Overall Priority Vector (OPV) of Each Alternative.
4.0 Conclusion
This study evaluates the potential bioethanol-producing feedstock through a quantitative analysis of various biomass resources by using priori estimation model, which is called Analytic Hierarchy Process (AHP) model. This model is helpful in making a sensible decision based on the critical assessment of relevant criteria.

The results obtained are greatly influenced by the outcome of FGD with experts in biomass research field. Among all the five biomass resources selected through the FGD, they are undoubtedly having the potential to be used in producing bioethanol. However, according to the criteria established, this study highlights the sugarcane with the overall priority of 31.69% is the most feasible bioethanol feedstock. On the other hand, based on the OPV derived, sugar beet (overall priority = 8.67%) poses the least preference.

This research was carried out in global context and sugarcane was selected as the most feasible bioethanol feedstock. Focusing on local context, bioethanol industry in Malaysia is still underdeveloped although a vast quantity of lignocellulosic agricultural residues can be found annually. Thus, this study could support the implementation of the government policy regarding bioethanol development from palm oil residues in Malaysia.

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