**Philippine Journal of Science**
147 (4): 693-704, December 2018
ISSN 0031 - 7683
Date Received: 02 May 2018

# Agricultural Residue Feedstock Selection for Polyhydroxyalkanoates Production using AHP-GRA

**Princess J. Requiso**[1,2], **Fidel Rey P. Nayve Jr.**[2], **Catalino G. Alfafara**[3], **Ruby Lynn G. Ventura**[4], **Erwin C. Escobar**[1], and **Jey-R S. Ventura**[1]*

[1]Department of Engineering Science, College of Engineering and Agro-Industrial Technology,
University of the Philippines Los Baños, College, Los Baños, Laguna 4031 Philippines
[2]National Institute of Molecular Biology and Biotechnology (BIOTECH),
University of the Philippines Los Baños, College, Los Baños, Laguna 4031 Philippines
[3]Department of Chemical Engineering, College of Engineering and Agro-Industrial Technology,
University of the Philippines Los Baños, College, Los Baños, Laguna 4031 Philippines
[4]University of the Philippines Rural High School, College of Arts and Sciences,
University of the Philippines Los Baños, Paciano Rizal, Bay, Laguna 4033 Philippines

**The potential of polyhydroxyalkanoates (PHA) as substitute to durable petroleum-based plastics is currently explored because of its biodegradability and satisfactory properties. However, its high production cost – primarily due to the cost of substrate – limits its commercialization. As a solution, lignocellulosic agricultural residues can be used as feedstock to lower the production cost. To systematically determine the best agricultural residue for PHA production, this study employed the Analytic Hierarchy Process (AHP) and Grey Relational Analysis (GRA). Based on the results, it was identified that the feedstock composition criterion was given a higher weight over the economic criterion. Additionally, conversion efficiency was ranked first in terms of the overall weights of all the criteria, followed by cellulose content and processing cost. GRA showed that corn stover was the most preferred lignocellulosic substrate for PHA production, followed by banana pseudostem and sugarcane bagasse. Sensitivity analysis also proved that corn stover is an excellent feedstock candidate, particularly if conversion efficiency and processing cost criteria are given higher weights. Related studies such as economic and life cycle analyses, as well as process improvement, may also be incorporated with the results of this study to provide comprehensive information on selecting a suitable feedstock for sustainable PHA production.**

Key words: agricultural residue, analytic hierarchy process, grey relational analysis, multi-criteria decision analysis, polyhydroxyalkanoates

## INTRODUCTION

Petroleum-based plastics such as polypropylene and polyethylene are extensively used because of their durability, stability, and favorable thermal properties. These qualities made them very suitable for many packaging applications compared with glass and paper. However, the accumulation of recalcitrant plastic wastes – together with the current petroleum problem – has become a serious issue. Every year, about 4% of petroleum resources consumed worldwide is used to produce plastics, and another 4% is used to power plastic manufacturing processes (Gourmelon 2015). Non-biodegradable plastics also progressively accumulate

---

*Corresponding author: jsventura@up.edu.ph in nature over time, causing serious environmental impacts such as marine ecosystem destruction and land pollution. In 2010, the Philippines produced around 1.88 million metric tons (MMT) of mismanaged plastic wastes per year, with about 0.28–0.75 MMT entering the ocean (Jambeck *et al*. 2015). This makes the country one of the highest contributors of plastic pollution in the marine environment (Jambeck *et al*. 2015, Lebreton *et al*. 2017). Thus, it is important to search for alternatives to reduce the environmental impacts of plastics and man's dependence on fossil-based resources. Polymers of biological origin such as polyhydroxyalkanoates (PHA) can be used as substitute for non-biodegradable plastics.

PHA is an ultimately biodegradable bioplastic capable of having the desirable properties of polyethylene and polypropylene. It is typically produced through bacterial fermentation using renewable carbon sources, making it sustainable and ecologically-benign. However, despite its great potential as a plastic alternative, high production cost limits its commercialization. The most significant factor that increases the cost of PHA production is the substrate cost, making it more expensive than petroleum-based plastics (Castilho *et al*. 2009). Since commercial PHA is mostly obtained from food crops, sugar cane, and vegetable oils, PHA processing also competes with food supply production (Jiang *et al*. 2016). Hence, an alternative non-food competing substrate such as agricultural residues should be explored to sustainably produce PHA.

Several strategies such as the use of recombinant strains and cheap carbon sources, and improvement of fermentation strategies have been developed to increase PHA productivity and yield. Researchers also explore the use of industrial wastes and agricultural residues as substrates to further lower the production cost (Yu & Stahl 2008, Haas *et al*. 2008, Castilho *et al*. 2009, Pandian *et al*. 2010, Martinez *et al*. 2015). In the recent investigation of Getachew and Woldesenbet (2016) on different agricultural waste materials for PHA production, it was confirmed that low-cost biomass has high potential as substrate for biopolymer production. Moreover, the use of the cheap biomass serves three important purposes such as lowering the cost of substrate for PHA production, mitigating environmental pollution problem, and providing solution to the proper disposal of agricultural wastes (Getachew & Woldesenbet 2016).

Agricultural residues and lignocellulosic biomass represent a large reservoir of fermentable carbohydrates that can be utilized for sustainable PHA production (Mtui 2009). Selecting the best agricultural residue as feedstock is important in increasing the efficiency of fermentation process. However, it can be quite complicated due to conflicting technical, economic, social, and environmental aspects that must be considered for evaluation. Besides, the criteria to be considered for feedstock selection has not been fully established. Researchers focus mostly on maximizing the yield of production or improving the process economics, but their proposed solutions do not evaluate other factors that can affect feedstock selection. To make the selection process more strategic and comprehensive, a multi-criteria decision analysis (MCDA) can be employed. MCDA methods differ from conventional decision techniques since they incorporate a numerical approach to decision-making that conforms with scientific measurement. They are used to solve actual problems by assessing multiple conflicting criteria and selecting the "best" alternative from a pool of alternatives (Cobuloglu & Büyüktahtakin 2015, Nwokoagbara *et al*. 2015). The techniques commonly include the statement of the goal, identification of the alternatives, formulation of criteria and their respective indicators, weighing, and ranking alternatives (Feiz & Ammenberg 2017).

Currently, several papers had already covered biomass selection for biochemical conversions through the MCDA approach. Tan and Promentilla (2013) ranked sugarcane, corn, cassava, and sweet sorghum bagasse using an augmented Analytical Hierarchy Process (AHP) for bioethanol feedstock selection. The selection criteria were based on agricultural land footprint, supply readiness, life cycle net energy, rural development co-benefits, and water footprint. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) – in addition to Life Cycle Analysis (LCA) – and thermodynamic data for the selection of best biomass for energy production using boiler was also presented by Saelee *et al*. (2014). Efficiency, price, ease of operation, global warming, and acidification potential were the main criteria used in ranking wood chips, palm shells, and wood pellets as biomass for boilers. On the other hand, Cobuloglu and Büyüktahtakin (2015) used the stochastic AHP methodology in ranking switchgrass, miscanthus, sugarcane, corn, and wheat as sustainable biomass crop for biofuel production. Economic, environmental, and social aspects were the main sustainability criteria in which 16 sub-criteria were associated. Khang *et al*. (2016) applied AHP to find the most appropriate feedstock for biodiesel production in Vietnam among three possible options – namely jatropha oil, fish fat, and waste cooking oil. The waste cooking oil was considered the most preferred alternative. All these studies used either combined or hybrid MCDA in choosing the appropriate biomass for biochemical conversion process. In terms of agricultural residues selection, this paper is the only existing study so far that utilizes the MCDA approach in selecting feedstock for biochemical conversion such as PHA production.

### Agricultural Residue Selection using MCDA

The Philippines is known to be an agricultural country because of its tropical climate. Hence, the country is also producing plenty of potential agricultural residues that possess a huge potential for further technological conversion into high-value products. Several of those are sugarcane bagasse, sweet sorghum bagasse, corn stover, banana pseudostem, and pineapple peelings.

In terms of crop production, sugarcane is the fourth largest crop cultivated in 19 provinces of the Philippines (DBP 2015). The bagasse left after juice extraction is often used as fuel for boilers in sugar mills, feedstock for biofuel production, alternative source of pulp for paper processing, ingredient for animal feed, and raw material for particle board production. The local sweet sorghum plantation, which was lately on a field trial, is also considered as a promising source of sugar for the Philippine bioethanol supply (Roc 2012). Thus, a boost in its production may also yield a huge amount of bagasse that might be considered for further use.

On the other hand, corn is second to rice as the most important crop, serving as a substitute staple food during rice shortages (Gerpacio *et al*. 2014). At the same time, it has also been used as a primary animal feed ingredient. As a by-product of corn production, corn stover – the non-grain portion of the crop – is a readily available local resource used as feedstock for biofuel production, component of animal feeds, and substitute to coal as fuel.

Banana is considered as the most important fruit crop in the Philippines, since it is the only locally-grown fruit available all year round (Espino & Espino 2014). Due to the country's highly favorable climate and terrain conditions, it is the second largest international exporter of bananas – bearing a 12% share of the global export volume (Prowse 2013). Since the pseudostem is wasted after harvesting the fruit, banana plantations generate large quantities of agricultural wastes that can be utilized to create value-added products. Moreover, no important local industrial use of banana pseudostem has been reported so far.

Lastly, the Philippines is one of the main pineapple producers in the world – together with Thailand, Brazil, and China. These countries provide about 50% of the total pineapple output. Cayenne, the most common locally grown cultivar of pineapple, is 41% peel by weight (Medina & Garcia 2005). Pineapple peels are used as feeds locally, and their potential as feedstock for bioethanol production is also explored by researchers due to its high sugar content (Antonio *et al*. 2015).

To determine the best PHA substrate from the mentioned agricultural residues, this study utilized an MCDA approach. MCDA is a tool that considers interconnected aspects or criteria related to environmental, technical, socio-cultural, and economic concerns. It involves the organization and analysis of goals, aspects, criteria, alternatives, and weights. The criteria are selected to evaluate the performance of each alternatives. Then, the decision makers – based on their expertise and experience – will categorically weigh the relative importance of each criteria. A numerical score or rating will then be provided in MCDA to classify each alternative with respect to the given criterion. In most cases, some of the criteria may just satisfy an alternative; hence, trade-offs are observed between the goals (Nwokoagbara *et al*. 2015). In this study, the selection of agricultural residues feedstock was based on the combined application of AHP and GRA. The proposed hybrid MCDA approach will provide a better decision-making tool because of the combination of both intangible (AHP) criteria and empirical [Grey Relational Analysis (GRA)] data in selecting and ranking the proposed agricultural feedstocks for PHA production.

## METHODOLOGY

### AHP

AHP, which has been studied extensively and adopted in many general applications related with MCDA, was used to evaluate the proposed criteria in selecting the best feedstock. The process was used in the study due to its simplicity, ease of use, and great flexibility. Likewise, AHP can be integrated with other techniques to consider not only both qualitative and quantitative factors, but also some real-world resource limitations to give a more realistic and promising decision (Ho 2008). Developed by Saaty (1980), it can handle multiple criteria and objectives in a complex decision-making process, which usually involves subjective variables. It simplifies decision-making by organizing a complex problem in a hierarchy involving goals, criteria, constraints, and alternatives – as shown in the proposed selection process (Figure 1). At a given hierarchy level, elements are assessed and compared in pairs for their relative importance. In case of the criterion of each aspect, the assessment of the pairwise comparison is made with respect to the former hierarchy level. The comparisons are made on an increasing importance from a scale of 1–9. The values 1, 3, 5, 7, and 9 indicates equal, moderately more, strongly more, very strongly, and extremely more in importance, respectively. The remaining intermediate judgment values 2, 4, 6, and 8 are intended to compromise value of importance. At the same time, the calculations evaluating pairwise comparisons are relatively convenient to perform since the mathematical thinking behind the process is based on linear algebra (Saaty 1980).

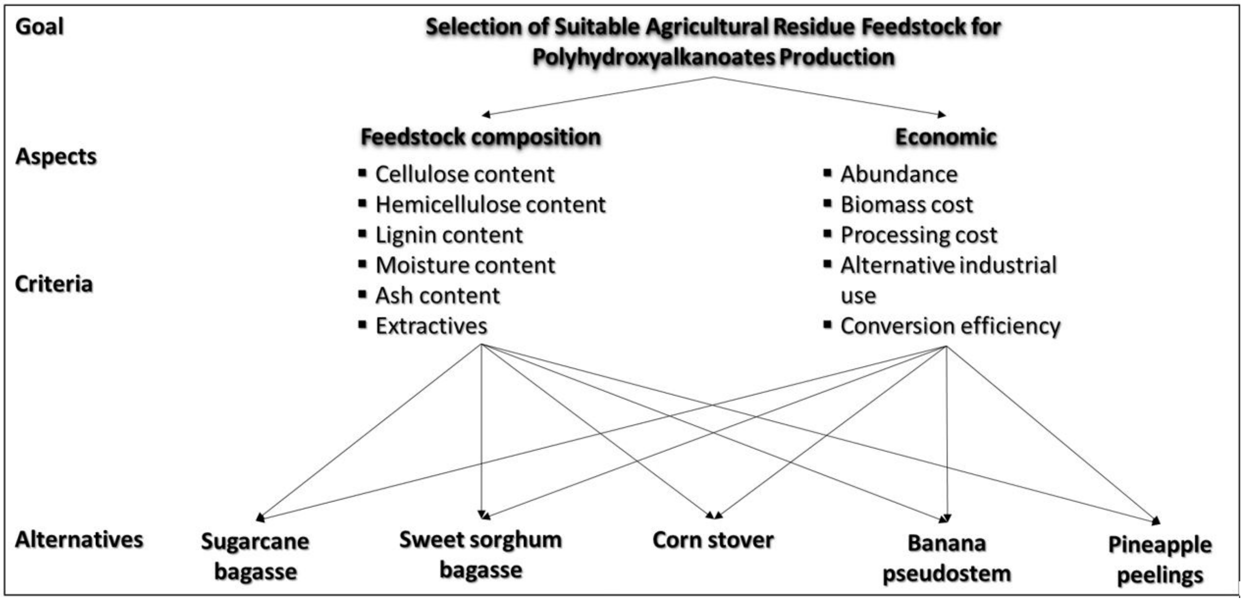

**Figure 1**. Decision hierarchy.

The goal of the study was to select the suitable agricultural residue for PHA production. To achieve the goal, two main aspects – namely feedstock composition and economic aspects – were considered (Figure 1). The next level included the criteria under each aspect. The proposed criteria for feedstock composition included cellulose, hemicellulose, lignin, moisture, ash, and extractive content. For the economic aspect, abundance, biomass cost, processing cost, alternative industrial use, and conversion efficiency were selected. These sets of aspects and criteria were compared pairwise by six domain experts.

The domain experts evaluated the pairwise sets of each aspects and criteria based on a scale of importance. Afterwards, a quantitative analysis was carried out to form a comparison matrix (*A*, Equation 1). Numerical ratings based on Saaty's scale were written on the upper triangular matrix, while the inverse of these ratings can be seen on the lower triangular matrix (Saaty 1980). Correspondingly, the geometric mean scores of the pool of experts were inputted for the pairwise comparison.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1q} \\ a_{21} & a_{22} & \cdots & a_{2q} \\ \vdots & \vdots & \vdots & \vdots \\ a_{q1} & a_{q2} & \cdots & a_{qq} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1q} \\ 1/a_{21} & a_{22} & \cdots & a_{2q} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{q1} & 1/a_{q2} & \cdots & a_{qq} \end{bmatrix} \quad (1)$$

After consolidating the pairwise comparisons, the scores in the matrix were summed up to normalize the values. Normalization involves dividing each element by the total score in the particular column and computing the average of each row to get the priority vector or weights. The priority weights within each aspect were multiplied with the weights obtained from the previous hierarchy level (aspects) to get the global weights of each criterion.

Some degree of inconsistency may be observed in the comparisons made by the surveyed experts since the numeric grades were derived from personal or subjective judgments (Khaira & Dwivedi 2017). To ensure that consistent judgments were made, a final procedure termed as consistency verification was incorporated in AHP. The procedure measured the degree of consistency among the pairwise comparisons in matrix (*A*) by calculating the consistency ratio (*CR*, Equation 3) using the value of consistency index (*CI*, Equation 2) and random index (*RI*).

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

The *CI* value was calculated using the maximum eigenvalue ($\lambda_{max}$) and order ($n$) of the comparison matrix. On the other hand, $\lambda_{max}$ was calculated as the summation of the product of the priority vector and the column total of the pairwise comparison matrix of each corresponding criterion. The *CR* value was calculated as the ratio of *CI* and random index (*RI*). Random *RI* values for various *n* has already been proposed by Saaty (1980) (Table 1). A CR ratio of 10% or less implies that the comparisons are

**Table 1.** Proposed random index (Saaty 1980).

| $n$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| $RI$ | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

relatively consistent or acceptable. Conversely, a CR ratio higher than 10% means that an appropriate corrective measure or inconsistency identification must be made.

## GRA

In the study, the results of AHP were integrated with GRA to assess the rank of each feedstock alternative. Introduced by Deng (1982), GRA can generate more reliable solutions efficiently when they are combined with the results of other MCDA methods. GRA has been proven to be useful for dealing with poor, incomplete, and uncertain information, and is suitable for studies with small samples (Sallehuddin *et al*. 2008). By combining the entire range of performance attribute values being considered for every alternative into a single value, the original problem is reduced to a single attribute. Therefore, the proposed alternatives with multiple attributes can be compared easily after the process. GRA scores of each alternative were combined to the previously obtained AHP criterion weights. The GRA scoring system used to evaluate the proposed alternatives for feedstock selection is shown in Table 2. For computational simplification, the scores in the table were arranged by incorporating the positive and negative criteria that will most likely give advantages to the ranking of the agricultural residues. For example, cellulose and hemicellulose content, abundance, and conversion efficiency were considered as positive criterion. Thus, the scores are from 1 to 5 – with 5 as the highest score – while the remaining criteria (negative criteria) were scored reversely.

Initially, a decision matrix was formulated by using the set of alternatives ($\boldsymbol{i}$= 1, 2, . . . , $m$) and criteria ($\boldsymbol{j}$= 1, 2,...,$m$). The $\boldsymbol{i^{th}}$ alternative was expressed as ($Y_i = y_{i1}$, $y_{i2}, y_{i3},..., y_{im}$), where $y_{ij}$ is the performance value of the attribute $j$ of alternative $i$. The $Y_i$ could also be translated into a comparability sequence ($X_i = x_{i1}$, $x_{i2}$, $x_{i3}$,..., $x_{im}$) by using one of the equations below (Equations 4, 5, or 6).

Equations 4, 5, and 6 are used for the larger-the-better, smaller-the-better, and closer-to-the-desired-value-$y_j^*$ -the-better, respectively (Kuo *et al*. 2008). This study used only Equation 4 prior to the pre-arranged scoring system shown in Table 2.

$$x_{ij} = \frac{y_{ij} - Min\{\, y_{ij}, i=1,2,...,m\}}{Max\{\, y_{ij}, i=1,2,...,m\} - Min\{\, y_{ij}, i=1,2,...,m\}} \quad \text{for } i = 1,2,\ldots,m \qquad j = 1,2,\ldots,m \tag{4}$$

$$x_{ij} = \frac{Min\{\, y_{ij}, i=1,2,...,m\} - y_{ij}}{Max\{\, y_{ij}, i=1,2,...,m\} - Min\{\, y_{ij}, i=1,2,...,m\}} \quad \text{for } i = 1,2,\ldots,m \qquad j = 1,2,\ldots,m \tag{5}$$

$$x_{ij} = 1 - \frac{\left| y_{ij} - y_j^* \right|}{Max\left\{Max\{\, y_{ij}, i=1,2,...,m\} - y_{ij}^*, y_{ij}^* - Min\{\, y_{ij}, i=1,2,...,m\}\right\}} \quad \text{for } i = 1,2,\ldots,m \qquad j = 1,2,\ldots,m \tag{6}$$

**Table 2.** Scoring system used to evaluate the feedstock alternatives.

| Criteria | Score | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Cellulose content, % dry weight | <20% | 20–30% | 30–40% | 40–50% | >50% |
| Hemicellulose content, % dry weight | <12% | 12–22% | 22–32% | 32–42% | >42% |
| Lignin content, % dry weight | >24% | 18–24% | 12–18% | 6–12% | <6% |
| Moisture content, % wet weight | >100% | 60–80% | 40–60% | 20–40% | <20% |
| Ash content, % dry weight | >8.3% | 6.0–8.3 | 3.7–6.0 | 1.4–3.7 | <1.4% |
| Extractives content, % dry weight | >14% | 10.5–14% | 7–10.5% | 3.5–7% | <3.5% |
| Abundance | very low | low | moderate | high | very high |
| Biomass cost | very high | high | moderate | low | very low |
| Processing cost | very high | high | moderate | low | very low |
| Alternative industrial use | very high | high | moderate | low | very low |
| Conversion efficiency, % conversion | <20% | 20–40% | 40–60% | 60–80% | >100% |

The preference index was then normalized into [0,1] using the grey relational generating procedure (Equations 4, 5, or 6). An alternative with preference index closest to or equal to 1 is deemed the best; however, this does not usually exist (Kuo *et al.* 2008). Thus, reference sequence($X_0 = x_{01}, x_{02}, x_{03},..., x_{0m}) = (1, 1,...,1,...,1)$ was made to find the comparability sequence close to the reference sequence.

Then, the grey relational coefficient was computed to determine the closeness of $x_{ij}$ to $x_{0j}$. The closer the $x_{ij}$ to $x_{0j}$, the larger the grey relational coefficient. Equation 7 – $\gamma(x_{0j}, x_{ij})$ – is the grey relational coefficient between $x_{ij}$ and $x_{0j}$, and $\Delta_{ij} = |x_0 - x_{ij}|$, $\Delta_{min} = Min\left\{\Delta_{ij},\ i = 1, 2,...,n; j = 1, 2,...,m\right\}$, $\Delta_{max} = Max\left\{\Delta_{ij},\ i = 1, 2,...,n; j = 1, 2,...,m\right\}$, and $\zeta$ is the distinguishing coefficient. The $\zeta$ is in the range of 0 to 1 and could be set by the decision maker. In this study, the distinguishing coefficient was set at 0.5 computed.

$$\gamma(x_{0j}, x_{ij}) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{ij} + \zeta\Delta_{max}} \quad \text{for } i = 1, 2, \ldots, m \quad j = 1, 2, \ldots, n \qquad (7)$$

Finally, the grey relational grade was obtained using Equation 8.

$$\Gamma(X_0, X_i) = \sum_{j=1}^{n} w_j\, \gamma(x_{0j}, x_{ij}) \quad \text{for } i = 1, 2, \ldots, m \qquad (8)$$

The integrated grey relational grade between reference sequence ($X_0$) and comparative sequence ($X_i$) was computed from the summation of the product of the priority vector of each criteria ($w_j$, for $j = 1, 2,...,n$) multiplied by the corresponding grey relational coefficients between $x_{0j}$ and $x_{ij}$. It usually denotes the level of correlation between the reference and comparability sequence. Thus, if the comparability sequence for an alternative has the highest grey relational grade with a reference sequence (*i.e.*, comparability sequence is almost similar to the reference sequence), the alternative would be the most preferred (Kuo *et al.* 2008).

## RESULTS AND DISCUSSION

### Agricultural Residue Selection for PHA Production

To develop a method for selecting the feedstock for PHA production, it is important to evaluate the agricultural residues both in terms of composition and economic feasibility. Thus, two main aspects (feedstock composition and economic aspect) were used to group the criteria employed as basis for determining the best feedstock for PHA production. The first main aspect, feedstock composition, describes the percentages of the components of the feedstock that affect the overall efficiency of PHA production. Lignocellulosic biomass contains structural sugars (cellulose and hemicellulose), lignin, and moisture, together with smaller amounts of ash and extractives. The composition of these constituents is highly dependent on the plant species. The composition of the proposed feedstocks for PHA production are found in the supplementary material (Appendix I).

The feedstock should contain high amounts of glucose, which can be derived mainly from plant cellulose. Hemicellulose also contains glucose; however, other monomeric sugars such as mannose, xylose, arabinose, glucuronic, methyl glucuronic, and galacturonic acids (Taherzadeh & Karimi 2007) may also be released during pretreatment and hydrolysis. On the other hand – ideally – lignin, moisture, ash, and extractives composition of the agricultural residues should be at their lowest proportions. Lignin provides structural support to the plant; however, high lignin content may pose costlier and energy-consuming pretreatment methods to expose the cellulosic fiber of the biomass. Thus, an ideal feedstock, from a process-economics viewpoint, should contain a low amount of lignin for better digestibility. Moisture present in raw biomass is dependent on the type, location, time of harvest, and storage conditions after harvest. The list of moisture content of the raw feedstocks is found in the supplementary material (Appendix II). In general, the moisture content of various biomass ranges 30–60% but can also reach as high as 90% (Pandey *et al.* 2014). Moisture affects the processing cost of biomass, especially the drying and transportation costs. Moreover, high moisture-containing biomass has a higher risk of biological deterioration, which can cause storage difficulties. Thus, minimal or reduced moisture content is very essential in improving materials handling, product recovery, and process efficiency. Lastly, ash and extractives should also be at their lowest proportions to maximize the availability of sugars for conversion. Studies have shown that both ash and extractives may interfere during the pre-treatment and hydrolysis of the biomass (Huang *et al.* 2016).

The second main aspect – referred to as the economic aspect – assesses the economic potential of PHA production in terms of local abundance of the feedstock and its cost, as well as the sum of the expenses that can be incurred in processing the material. Additionally, it also considers the alternative industrial uses of the feedstock and its conversion efficiency. Criteria such as the abundance of raw material should also be evaluated to estimate if the local production of the feedstock is sufficient to significantly contribute to PHA production. The abundance of the proposed feedstocks is found in the supplementary material (Appendix III). On the other hand, low biomass and processing cost is ideal to have a feasible biomass feedstock. Biomass cost is defined as the sum of the costs involved in purchasing the main raw material.

It includes expenses usually charged by agricultural plantations on post-harvesting and collection, as well as preliminary storage operations. In this study, biomass cost also includes expenses incurred on transporting the biomass to the processing plant. Processing cost covers all the expenses due to additional drying, size reduction and pre-treatment, detoxification, and hydrolysis of biomass prior to bacterial fermentation. Sugarcane bagasse has an estimated biomass cost of 21.20 US$/ton, while corn stover is at 79.34 US$/ton (Thompson & Tyner 2011). Sweet sorghum bagasse may be assumed to have similar biomass cost as the sugarcane bagasse. The apparent high cost of corn stover and bagasse may have been brought by their industrial importance. Banana pseudostem and pineapple peelings, on the other hand, are considered free because currently, both do not possess high commercial importance.

In addition to the criteria that were mentioned previously, competition between the existing industrial use of the substrates and their possible use for PHA production (alternative industrial use) – as well as the conversion efficiency of the feedstock – is also considered under the economic aspect. Determining the current industrial uses of the lignocellulosic biomass is crucial to determine competition factors for PHA production. Agricultural residues are presently used as fuel in cogeneration plants, feedstocks for biodiesel and bioethanol production, pulp in papermaking, and as main raw materials in particle board production. These residues are also used as animal feeds and natural fertilizer in agricultural farms. Finally, the conversion efficiency or the amount of sugar yielded after hydrolysis of pre-treated biomass should be high enough to obtain high sugar recovery. Sugar yields and conversion efficiencies of the agricultural feedstock may depend on the treatment used as observed by several studies. Corresponding values of the sugar yields and conversion efficiencies are found in supplementary material (Appendix IV).

Using the aspects and criteria above, a survey using pairwise comparisons was conducted from different experts to clearly assess and rank the different aspects and criteria presented. These experts include national scientists, professors, engineers, and researchers who are experts in the utilization of lignocellulosic biomass to produce value-added products. The knowledge and expertise of the respondents were complemented with literature reviews. Finally, the pairwise comparisons were quantified using AHP, while the ranking of alternatives was done using GRA. Using Equation 1, Table 3 shows the pairwise comparison matrices of the two main aspects, while Tables 4 and 5 represents the comparison matrix of the criteria under the feedstock composition and economic aspect. Upon normalization of the comparison matrices, the computed *CR* (using Equation 3) was less than 0.1 (<10%) in both aspects. Thus, the pairwise comparisons were consistent and can be used for the decision-making process. Finally, the criteria and their relative importance to the feedstock selection – as indicated by their overall weights – are shown in Table 6.

**Table 3.** Pairwise comparison matrix of the feedstock composition and economic aspects.

| Aspect | FC | EA |
|---|---|---|
| Feedstock composition (FC) | 1.00 | 0.92 |
| Economic aspect (EA) | 1.09 | 1.00 |
| Total | 2.09 | 1.92 |

Note: $\lambda_{max}$ = not applicable, $CR$ = not applicable.

**Table 4.** Pairwise comparison matrix of the different criterion under the feedstock composition aspect.

| Criteria | CC | HC | LC | MC | AC | EX |
|---|---|---|---|---|---|---|
| Cellulose content (CC) | 1.00 | 4.04 | 4.99 | 2.72 | 2.53 | 4.15 |
| Hemicellulose content (HC) | 0.25 | 1.00 | 2.26 | 1.31 | 2.08 | 3.22 |
| Lignin content (LC) | 0.20 | 0.44 | 1.00 | 1.57 | 1.32 | 2.40 |
| Moisture content (MC) | 0.37 | 0.76 | 0.64 | 1.00 | 1.15 | 1.99 |
| Ash content (AC) | 0.39 | 0.48 | 0.75 | 0.87 | 1.00 | 1.44 |
| Extractives content (EX) | 0.24 | 0.31 | 0.42 | 0.50 | 0.69 | 1.00 |
| **Total** | **2.45** | **7.04** | **10.06** | **7.97** | **8.79** | **14.21** |

Note: $\lambda_{max}$ = 6.35, $CI$ = 0.07, $CR$ = 0.06

**Table 5.** Pairwise comparison matrix of the different criterion under the economic aspect.

| Criteria | AB | BC | PC | AI | CE |
|---|---|---|---|---|---|
| Abundance (AB) | 1.00 | 0.66 | 0.35 | 1.00 | 0.34 |
| Biomass cost (BC) | 1.51 | 1.00 | 0.24 | 1.15 | 0.27 |
| Processing cost (PC) | 2.84 | 4.22 | 1.00 | 2.61 | 0.70 |
| Alternative industrial use (AI) | 1.00 | 0.87 | 0.38 | 1.00 | 0.28 |
| Conversion efficiency (CE) | 2.92 | 3.71 | 1.42 | 3.51 | 1.00 |
| **Total** | **9.26** | **10.46** | **3.40** | **9.27** | **2.60** |

Note: $\lambda_{max}$ = 5.10, $CI$ = 0.03, $CR$ = 0.02

**Table 6.** Weights of the aspects and criteria for feedstock selection.

| Aspect | Weight | Criteria | Overall weight |
|---|---|---|---|
| Feedstock composition | 0.4787 | Cellulose content | 0.1915 |
| | | Hemicellulose content | 0.0875 |
| | | Lignin content | 0.0607 |
| | | Moisture content | 0.0573 |
| | | Ash content | 0.0501 |
| | | Extractives content | 0.0316 |
| Economic aspect | 0.5213 | Abundance | 0.0537 |
| | | Biomass cost | 0.0579 |
| | | Processing cost | 0.1622 |
| | | Alternative industrial use | 0.0543 |
| | | Conversion efficiency | 0.1931 |

As depicted in Table 6, feedstock composition and economic aspect are both considered crucial in feedstock selection for PHA production. This is indicated by the closeness of their weights (0.4787 and 0.5213, respectively). Conversion efficiency – with an overall weight of 0.1931 – has the highest overall importance, followed by cellulose content (0.1915) and processing cost (0.1622). A higher conversion efficiency will provide more reducing sugars as carbon source in PHA production. This also relates to the importance of an efficient and low-cost pre-treatment and hydrolysis methods to produce high reducing sugar yields. On the other hand, the extractives content with overall weight of 0.0316 was considered the least important criteria, due to its minimal impact on pretreatment and hydrolysis of lignocellulosic biomass and on fermentation of sugars to PHA. Similarly, ash content (0.0501) was least prioritized by the experts possibly because of the content similarity and its minimal effect on biomass comparison. Furthermore, abundance (0.0537) and alternative industrial use criteria (0.0501) were given low scores, since the proposed feedstocks are known to be locally abundant and adequate for PHA production.

The final ranking of feedstocks was then conducted using grey relational analysis. Initially, a decision matrix was made using the scoring system presented in Table 2 for the different agriculture residues. Based on literature surveys (Appendices I, II, III, and IV), the scores of the different feedstocks in relation to the proposed criteria are presented in Table 7. The scores were normalized and processed to obtain the grey relational coefficients and grey relational grades using Equations 7 and 8.

The grey relational coefficients and grades for the proposed feedstock alternatives under the feedstock composition main criterion are shown in Table 8. In terms of cellulose content, sugarcane bagasse and banana pseudostem – with an average cellulose content of 42% based on literature reviews (Appendix I) – were given the highest and equal scores of 0.1915. Banana pseudostem also received the highest score of 0.0875 for the hemi-cellulose content

**Table 7.** Decision matrix for the selection of agricultural residue for PHA production.

| Agricultural residue | CC | HC | LC | MC | AC | EX | AB | BC | PC | AI | CE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sugarcane bagasse | 3.00 | 3.00 | 2.00 | 3.00 | 4.00 | 3.00 | 5.00 | 2.00 | 3.00 | 1.00 | 3.00 |
| Sweet sorghum bagasse | 4.00 | 3.00 | 2.00 | 3.00 | 4.00 | 3.00 | 1.00 | 2.00 | 3.00 | 1.00 | 1.00 |
| Corn stover | 3.00 | 4.00 | 2.00 | 4.00 | 2.00 | 2.00 | 4.00 | 1.00 | 3.00 | 1.00 | 4.00 |
| Banana pseudostem | 4.00 | 5.00 | 2.00 | 1.00 | 2.00 | 2.00 | 3.00 | 4.00 | 2.00 | 5.00 | 3.00 |
| Pineapple peelings | 2.00 | 2.00 | 4.00 | 1.00 | 3.00 | 4.00 | 2.00 | 3.00 | 2.00 | 2.00 | 3.00 |

Note: CC – cellulose content, HC – hemicellulose content, LC – lignin content, MC – moisture content, AC – ash content, EX – extractives content, AB – abundance, BC – biomass cost, PC – processing cost, AI – alternative industrial use, and CE – conversion efficiency.

**Table 8.** Weights of the proposed feedstocks for the feedstock composition aspect.

| Feedstock composition | Sugarcane bagasse | Sweet sorghum bagasse | Corn stover | Banana pseudostem | Pineapple peelings |
|---|---|---|---|---|---|
| Cellulose content | 0.1179 | 0.1915 | 0.1179 | 0.1915 | 0.0851 |
| Hemicellulose content | 0.0437 | 0.0437 | 0.0583 | 0.0875 | 0.0350 |
| Lignin content | 0.0270 | 0.0270 | 0.0270 | 0.0270 | 0.0607 |
| Moisture content | 0.0372 | 0.0353 | 0.0573 | 0.0199 | 0.0199 |
| Ash content | 0.0501 | 0.0501 | 0.0223 | 0.0223 | 0.0309 |
| Extractives content | 0.0194 | 0.0194 | 0.0140 | 0.0140 | 0.0316 |
| **Grade (Total)** | **0.2954** | **0.3671** | **0.2968** | **0.3622** | **0.2632** |

criterion due to its low hemicellulose content. Meanwhile, pineapple peelings has the highest score of 0.0607 for the lignin content criterion due to its low lignin content. Since the lignin content of the four remaining feedstocks were similar, they received equal weights for the lignin content criterion. Corn stover scored the highest value of 0.0573 due to its low moisture content. Correspondingly, banana pseudostem and pineapple peelings received equally low scores of 0.0199 because of their high moisture content, which usually ranges 80–100%. Sugarcane bagasse and sweet sorghum bagasse received the highest scores for the ash content criterion (0.0501), while pineapple peelings obtained the highest score for the extractives content criterion (0.0316). After combining the scores, sweet sorghum bagasse and banana pseudostem scored 0.3671 and 0.3622, respectively – and dominated the pool of alternative feedstocks in terms of composition.

Table 9 shows the grey relational coefficients and grades of the proposed feedstock alternatives evaluated by the criteria under economic aspect. Although banana pseudostem has the highest apparent availability and local production based on agricultural statistics (Appendix III), most of its weight is due to its high moisture content (Appendix II). Therefore, higher scores were assigned to sugarcane bagasse, sweet sorghum bagasse, and corn stover in terms of abundance. Sugarcane bagasse received the highest score (0.0537) for the abundance criterion, while sweet sorghum bagasse scored the lowest for the abundance criterion – with a value of 0.0179. It should be noted that sweet sorghum is still under experimental cultivation in the Philippines, hence the scarce planting and propagation. Banana pseudostem scored 0.0579 and 0.0543 for biomass cost and alternative industrial use criteria, respectively, since it still has no known important application in industrial processes. On the other hand, sugarcane bagasse, sweet sorghum bagasse, and corn stover scored low for both biomass cost and alternative industrial use criteria. These residues are often used as raw materials for biofuel production, as fuel source, and as ingredients for animal feeds. Banana pseudostem and pineapple peelings received the lowest scores for the processing cost criterion. This may be attributed to undesirable high moisture contents that may entail additional costs for further drying. Lastly, the highest score for conversion efficiency criteria (0.1931) was given to corn stover, which exhibited high sugar yields and conversion rates based on literature reviews. After evaluation and combining the scores for the economic aspect, corn stover scored 0.4294 and dominated the pool of alternative feedstocks.

Considering both main criteria, the agricultural residues selected as feedstocks for PHA production are corn stover, banana pseudostem, and sugarcane bagasse – with overall grey relational grades of 0.7262, 0.7087, and 0.6740, respectively. Sweet sorghum bagasse, with a score (0.6582) close to sugarcane bagasse, ranked fourth. Pineapple peelings, on the other hand, was considered the least favorable feedstock – with the lowest overall score of 0.5494.

## Sensitivity Analysis

A sensitivity analysis was made to estimate probable adjustments and shifts on the scores of the feedstock alternatives for PHA production. It was done by adjusting the selected top three criteria (cellulose content, conversion efficiency, and processing cost) weights from 0 to 1 with an interval of 0.1. Based on the results of the analysis, the rank of the alternatives was sensitive to changes in the weights of the top three criteria. As seen on Figure 2a, the top three alternatives retained their ranks if more weight is given on conversion efficiency. However, as the weight of cellulose content criteria is increased, the top three feedstock alternatives were changed to banana pseudostem, sweet sorghum bagasse, and corn stover, while sugarcane bagasse went down to fourth rank (Figure 2b). Likewise, banana pseudostem went down to fourth rank as the weight of the processing cost criterion is increased (Figure 2c).

In general, sensitivity analysis showed that corn stover is an excellent feedstock candidate for sustainable PHA production, especially if conversion efficiency and processing cost are regarded as important parameters for

**Table 9.** Weights of the proposed feedstocks for the economic aspect.

| Economic aspect | Sugarcane bagasse | Sweet sorghum bagasse | Corn stover | Banana pseudostem | Pineapple peelings |
|---|---|---|---|---|---|
| Abundance | 0.0537 | 0.0179 | 0.0358 | 0.0268 | 0.0215 |
| Biomass cost | 0.0258 | 0.0258 | 0.0202 | 0.0579 | 0.0357 |
| Processing cost | 0.1622 | 0.1622 | 0.1622 | 0.0885 | 0.0885 |
| Alternative industrial use | 0.0181 | 0.0181 | 0.0181 | 0.0543 | 0.0217 |
| Conversion efficiency | 0.1189 | 0.0672 | 0.1931 | 0.1189 | 0.1189 |
| **Grade (Total)** | **0.3786** | **0.2911** | **0.4294** | **0.3464** | **0.2862** |

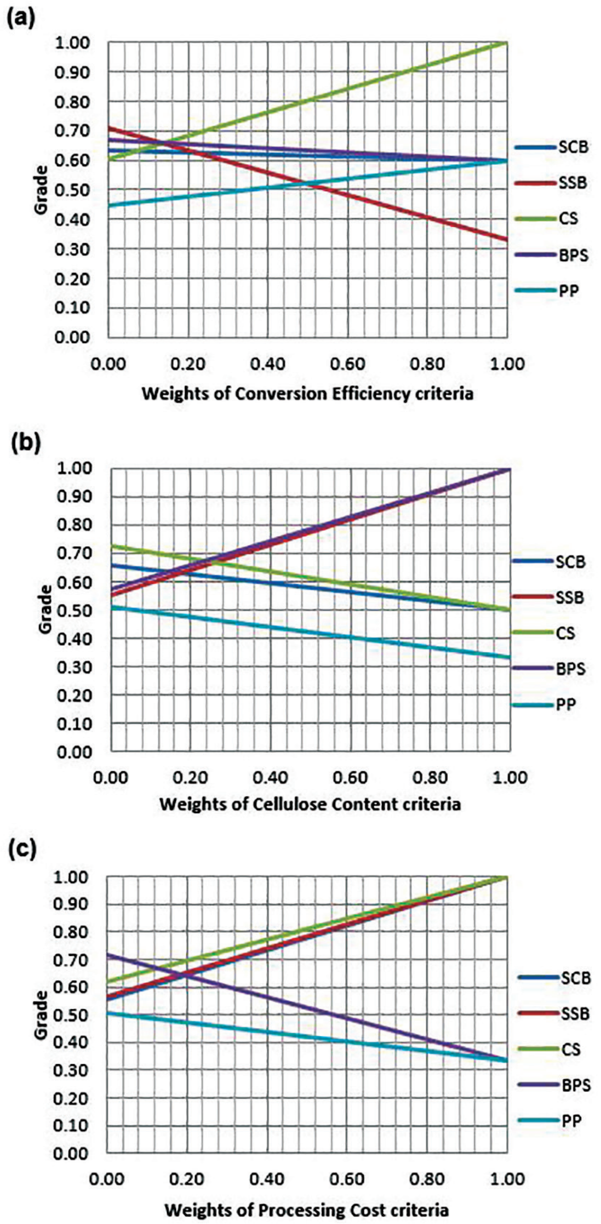

**Figure 2.** Sensitivity analysis of the priority weights of the alternatives for feedstock selection for sustainable PHA production at various criteria weights intervals: (a) conversion efficiency, (b) cellulose content, and (c) processing cost. Note: SCB – sugarcane bagasse, SSB – sweet sorghum bagasse, CS – corn stover, BPS – banana pseudostem, and PP – pineapple peelings.

selection. Banana pseudostem is favorable because of its relatively high cellulose content and conversion efficiency, but it can also be one of the least satisfactory alternatives if processing cost is given a higher importance. It can also be concluded that sweet sorghum bagasse also bears a potential for sustainable PHA production, but its use is mainly limited by its conversion efficiency and current availability in the Philippines. These variations in the ranking of alternatives show that feedstock selection is mainly reliant on priorities and importance assigned to the criteria used in evaluating each feedstock alternative.

## CONCLUSIONS

The study identified the best agricultural residue that can be used as feedstock for sustainable PHA production by surveying a pool of experts. Responses were evaluated using MCDA methods. The AHP was used to evaluate the criteria used in the selection process. The results of the study showed that feedstock composition criterion was given a higher importance over the economic criterion. Furthermore, the cellulose content criterion received the highest overall weight among all the criteria, followed by processing cost and conversion efficiency. Based on the responses of the experts, the availability of sugars for bacterial PHA production – as well as the accessibility to efficient pretreatment and hydrolysis methods – were the main considerations in feedstock selection.

On the other hand, GRA was combined with AHP results to assess the suitability of proposed feedstocks. Combined MCDA results showed that corn stover was the most suitable agricultural feedstock for PHA production. This is mainly due to its favorable cellulose content, processing cost, and conversion efficiency. As indicated by the sensitivity analysis, it is also a strong candidate for sustainable PHA production, especially if conversion efficiency and processing cost criteria are given higher weights. Moreover, banana pseudostem and sugarcane bagasse respectively received the second and third highest ratings in the selection process. Together with various studies related to PHA production such as economic feasibility, life cycle analysis, and researches on enhanced fermentation and extraction processes, the results of this study may be useful in the commercialization of the polymer. Also, this study of biomass selection for PHA production might be useful in other biological conversion processes that require carbon sources as main metabolic precursors to produce high-value products, such as organic acids, biomethane, biohydrogen, or bio-alcohol production.

## ACKNOWLEDGMENTS

This study would like to acknowledge DOST-PCIEERD for financially supporting our research project. Likewise, to all experts surveyed in this study, thank you very much for your time and effort.

## NOTES ON APPENDICES

The complete appendices section of the study is accessible at http://philjournalsci.dost.gov.ph.

## REFERENCES

ANTONIO RMDR, DELA CRUZ AAC, QUINTO ASJ, CORDERO PR, DIMAANO MNR. 2015. Bioethanol production from pineapple (*Ananas comosus*) peelings using *Saccharomyces cerevisiae* as fermenting yeast with focus on fermentation pH. Int J Eng Res Technol 4(5): 356–360.

CASTILHO LR, MITCHELL DA, FREIRE DMG. 2009. Production of polyhydroxyalkanoates (PHAs) from waste materials and by-products by submerged and solid-state fermentation. Bioresour Technol 100: 5996–6009.

COBULOGLU HI, BÜYÜKTAHTAKIN IE. 2015. A stochastic multi-criteria decision analysis for sustainable biomass crop selection. Expert Syst Appl 42: 6065–74.

[DBP] Development Bank of the Philippines. 2015. One-pager information on current developments in agriculture: Sugarcane industry. Industry Monitor: Strategic Planning and Research. Retrieved from https://www.devbnkphl.com/UserFiles/IndustryMonitorSugarCaneIndustry2015.pdf on 02 Jun 2017.

DENG J. 1982. Control problems of grey systems. Syst Control Lett 1: 288–294.

ESPINO RRC, ESPINO MRC. 2014. The status of the fruit industry in the Philippines. Food and Fertilizer Technology Center. Retrieved from http://www.fftc.agnet.org/library.php?func=view&style=type&id=20150810090507 on 02 Jun 2017.

FEIZ R, AMMENBERG J. 2017. Assessment of feedstocks for biogas production, part I – A multi-criteria approach. Resour Conserv Recycl 122: 373–387.

GERPACIO RV, LABIOS JD, LABIOS RV, DIANGKINAY EI. 2004. Maize in the Philippines: Production systems, constraints, and research priorities. Mexico: International Maize and Wheat Improvement Center (CIMMYT). 37p.

GETACHEW A, WOLDESENBET F. 2016. Production of biodegradable plastic by polyhydroxybutyrate (PHB) accumulating bacteria using low cost agricultural waste material. BMC Res Notes 9 (509): 1–9.

GOURMELON G. 2015. Global plastic production rises, recycling lags: New Worldwatch Institute analysis explores trends in global plastic consumption and recycling. Retrieved from http://www.worldwatch.org/global-plastic-production-rises-recycling-lags-0 on 02 Jun 2017.

HAAS R, JIN B, ZEPF FT. 2008. Production of poly(3-hydroxybutyrate) from waste potato starch. Biosci Biotechnol Biochem 72(1): 253–256.

HO W. 2008. Integrated analytic hierarchy process and its applications – A literature review. Eur J Oper Res 186: 211–228.

HUANG C, WU X, HUANG Y, LAI C, LI X, YONG Q. 2016. Prewashing enhances the liquid hot water pretreatment efficiency of waste wheat straw with high free ash content. Bioresour Technol 219: 583–588.

JAMBECK JR, GEYER R, WILCOX C, SIEGLER MP, ANDRADY A, NARAYAN R, LAW KL. 2015. Plastic waste inputs from land into the ocean. Science 347(6223): 768–771.

JIANG G, HILL DJ, KOWALCZUK M, JOHNSTON B, ADAMUS G, IRORERE V, RADECKA I. 2016. Carbon sources for polyhydroxyalkanoates and an integrated biorefinery. Int J Mol Sci 17(1157): 1–21.

KHAIRA A, DWIVEDI RK. 2017. A state-of-the-art review of analytic hierarchy process. Mater Today: Proc 5(2018): 4029–35.

KHANG DS, PROMENTILLA MAB, TAN RR, ABE N, TUAN PD, RAZON, LF. 2016. Multi-criteria approach to assess stakeholders' preferences for selection of biodiesel feedstock in Vietnam. Int. J. Business and Systems Research 10(2-4): 306–331.

KUO Y, YANG T, HUANG GW. 2008. The use of grey relational analysis in solving multiple attribute decision-making problems. Comput Ind Eng 55: 80–93.

LEBRETON LCM, VAN DER ZWEET J, DAMSTEEG J, ANDRADY A, REISSER J. 2017. River plastic emissions to the world's ocean. Nat Commun 8: 1–10.

MARTINEZ GA, BERTIN L, SCOMA A, REBECCHI S, BRAUNEGG G, FAVA F. 2015. Production of polyhydroxyalkanoates from dephenolised and fermented olive mill wastewaters by employing a pure culture of *Cupriavidus necator*. Biochem Eng J 997: 92–100.

MEDINA JD, GARCIA HS. 2005. Pineapple: Post-harvest operations. Food and Agricultural Organization of the United Nations. 38p.

MTUI GYS. 2009. Recent advances in pretreatment of lignocellulosic wastes and production of value added products. Afr J Biotechnol 8(8): 1398–1415.

NWOKOAGBARA E, OLALEYE AK, WANG M. 2015. Biodiesel from microalgae: The use of multi-criteria decision analysis for strain selection. Fuel 159: 241–249.

PANDEY A, NEGI S, BINOD P, LARROCHE C. 2014. Pre-treatment of biomass: Processes and technologies. Netherlands: Elsevier. 272p.

PANDIAN SR, DEEPA V, KALISHWARALAI K, RAMESHKUMAR N, JEYARAJ M, GURUNATHAN S. 2010. Optimization and fed-batch production of PHB utilizing dairy waste and sea water nutrient sources by *Bacillus megaterium* SRKP-3. Bioresour Technol 101: 705–711.

PROWSE W. 2013. The banana market in Asia: A market dominated by the Philippines. In: FruiTrop No. 210. France: Agricultural Research for Development (CIRAD). 92p.

ROC BFV. 2012. Investments for sweet sorghum sought. Business World Online. Retrieved from http://www.bworldonline.com/content.php?section=4&title=Investments-for-sweet-sorghum-sought&id=59048 on 02 Jun 2018.

SAATY TL. 1980. The analytic hierarchy process: Planning, priority setting, resource allocation. New York: McGraw-Hill. 287p.

SAELEE S, PAWEEWAN B, TONGPOOL R, WITOON T, TAKADA J, MANUSBOONPURMPOOL K. 2014. Biomass type selection for boilers using TOPSIS multi-criteria model. Int J Environ Sci Dev 5(2): 181–186.

SALLEHUDDIN R, SHAMSUDDIN SMH, HASHIM SZM. 2008. Application of grey relational analysis for multivariate time series. In: Eighth International Conference on Intelligent Systems Design and Applications; 26–28 Nov 2008; Kaohsiung, Taiwan: IEEE Computer Society. p. 432-437.

TAHERZADEH M, KARIMI K. 2007. Acid-based hydrolysis processes for ethanol from lignocellulosic materials: A review. Bioresources 2(3): 472-499.

TAN RR, PROMENTILLA MAB. 2013. A methodology for augmenting sparse pairwise comparison matrices in AHP: Applications to energy systems. Clean Technol Environ Policy 15: 713–719.

THOMPSON J, TYNER W. 2011. Corn stover for bioenergy production: Cost estimates and farmer supply response. Renewable Energy: Fueling and Feeding America Through Renewable Resources. Retrieved from https://www.extension.purdue.edu/extmedia/EC/RE-3-W.pdf on 02 Jun 2017.

YU J, STAHL H. 2008. Microbial utilization and biopolyester synthesis of bagasse hydrolysates. Bioresour Technol 99(17): 8042–48.