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Research Article

A Holistic Framework for Environment Conscious Based Material Selection and Experimental Assessment Using Digraph-Based Expert System

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Finding a suitable biomass sample for the pyrolysis process with proper physicochemical properties is a challenging one as it has several criteria and attributes. Multicriteria decision-making (MCDM) represents a systematic approach for helping decision makers in diversified field. In this study, the application of the digraph and matrix approach is described for the selection of the most appropriate biomass material for yielding more liquid oil via thermochemical conversion. A biomass material selection index (BMSI) is proposed that evaluates and ranks the selected materials. The index is derived from a material selection attributes function and acquired from a material selection attributes digraph. The digraph is developed making an allowance for material selection attributes and its relative importance related to pyrolysis. A sequential procedure to assess the biomass material selection index is recommended in this study. Among the selected materials, this study demonstrated a sunflower shell with a higher index. At the end of the study, the prediction is also validated by conducting the experimental research.

1. Introduction

Fossil fuels make up a large part of the world's current energy source. The combustion of fossil fuels, on the other hand, results in a massive release of greenhouse gases into the environment [1]. It is very important and critical to find possible alternate sources to meet the global energy demand [2]. It is also very essential to use agricultural wastes without affecting the food chain [3]. Agricultural wastes for sustainable energy production not only fulfil the energy needs but also deal the waste disposal problems. The lower density, shapeless structure, higher moisture content, and poor calorific value are the significant problems to deal with agricultural residues. Lignocellulosic biomass is renewable material available abundant for the production of biofuels. The design of biomass processing facilities needs a thorough understanding of the physicochemical characteristics of lignocellulosic material [4]. They are the low-value outcomes from agricultural products and industrial sectors gaining importance for energy recovery [5, 6]. Many works of literature reported the recovery of energy-rich oil from various seeds and utilized it for engine operation [7]. The use of these oils for direct heating and cooling leads to horrific environmental impacts [8]. Pyrolysis is the kind of thermochemical conversion process of heating feedstock material in oxygen-absent conditions at elevated temperatures and for high-energy biofuels and chemicals [9]. This is the only thermochemical conversion technology used since millennia yielding high-quality biofuels such as oil char and gas with increased heating value [10]. This process can produce maximum liquid fuels (pyrolysis oil or bio-oil) from biomass, which is easy to store and transport. The percentage of yield and its compositions are mainly dependent upon the characteristics of feedstock and operating procedure. The presence of basic components such as volatile contents, moisture, and ash in the feedstock are the key parameters to determine the characteristics of the product yields [11]. During pyrolysis, the lignocellulosic content of the biomass materials is devolatilized and gives a variety of compositions and complexity to the final products [12]. Previously, Madhu et al. [11], Kan et al. [13], and Xu et al. [14] studied the fundamental relationship between the properties of various agricultural residues using various techniques including infrared and reported the progress of pyrolysis whereas Lin et al. [15] studied the relationship between the bio-oil products with feedstock compositions. Isikgor and Becer [16] summarized the effects of lignin, cellulose, and hemicellulose contents of various biomasses such as softwood, hardwood, grasses, and agricultural residues on the pyrolysis process. Vassilev et al. [17] focused on the effect of various elemental compositions of feedstock on biofuel yield and its chemical properties. During pyrolysis, lignin content present in the biomass interacts with cellulose and prevents the polymerisation resulting in lower biochar yield [18]. The hemicellulose breakdown normally takes place at the temperature of 300°C, and cellulose decomposition takes place around 350°C [19]. Lignin is the most stable component, decomposing only at temperatures between 300 and 550°C [20]. By considering all the above factors, material selection is a key process for pyrolysis. Choosing the right material for this application gives maximum conversion efficiency up to 60 wt%

MCDM is the fastest growing technique used to identify the suitable material for many engineering applications when large numbers of factors are interfering with the selection [21]. It is an important technique to consider the typical properties by consigning the weight to select an appropriate alternative for maximum efficiency. Madhu et al. [11] employed the TOPSIS method for the selection of biomass materials. The TOPSIS, on the other hand, is less efficient than the analytic hierarchy process (AHP) and its updated version [22]. Holloway (1998) highlighted the significance of material selection for various engineering applications, as well as the environmental consequences of poor material selection [23]. The conventional trial and error method of selecting the biomass material for any thermochemical conversion process has been proven to be ineffective in several cases. As a result, a proper scientific method for selecting the feedstock is required. Some effort will be required to identify the elements that influence biomass selection for pyrolysis to eliminate inappropriate biomass selection and enhance the present selection method. A digraph model is used to represent abstract data that take into consideration all of the effective variables. In order to pick the optimal biomass material, the digraph model is transformed into a matrix for processing. The matrix assessment gives an index value, which indicates the efficacy of the material. This approach has been used by various works of literature since it is more adaptable for various applications [24–29].

Among the various material selection issues, there should be a requirement for a systematic tool for decision-making processes. The digraph and matrix approach is effective because it examines all influencing parameters related to material characteristics (attributes) as well as the relative significance of each other. The current study on the subject of pyrolysis processes only provides different conversion strategies. However, using a digraph and matrix method to choose the best biomass material for pyrolysis is a novel idea that is explored in this work. Five alternatives, such as rice straw (M1), sunflower shell (M2), hardwood (M3), wheat straw (M4), and palm shell (M5), and seven evaluation parameters, such as lignin (L), cellulose (C), hemicellulose (H), volatile matter (VM), fixed carbon (FC), moisture content (MC), and ash contents (AC), are considered for the assessment.

2. Materials and Methods

2.1. Materials. A detailed study about the constituents of the biomass material for energy recovery is the important one that should be studied at the laboratory level. The choice of conversion methods will be dependent on the application and the parameters such as biomass feedstock, heat transfer rate, and particle size [30]. Several works of literature are available explaining the reaction of lignin [31], cellulose [32], and hemicelluloses [33] related to the composition of yield, and these studies are focused on the properties of biomass during various types of pyrolysis processes [34].

The higher cellulose content in the biomass material improves the pyrolysis rate whereas the domination of lignin makes a negative impact on the process [35]. Volatile matter is one of the most common parameters measured in the biomass. It is used for the production of condensable vapour and permanent gases when it is heated. The volatile matter in the biomass material favours the percentage of energy conversion during pyrolysis. Based on the study conducted by Singh et al. [36], the presence of more volatiles in the sample increases the bio-oil production. Fixed carbon is another combustible element enhancing the production of condensable gases during pyrolysis [37]. It is calculated by the following equation:

$$FC = 1 - MC - AC - VM. \quad (1)$$

The moisture content is represented by the quality of biomass. The higher level of moisture content is influenced by the heat transfer process and affects the efficiency of the pyrolyzer unit. Hence, it is not suitable for many applications [38, 39]. Some proportion of the biomass materials has incombustible mineral elements which is commonly referred to as ash content. It denotes the amount of solid matters left over after it burnt completely. Knowledge about the quantity of ash in the material is more helpful to guess the propensity regarding deposits in the pyrolyzer equipment such as reactor, cyclone separator, condenser, and tubes [40]. From the above discussions, the feedstock for maximum liquid oil yield should have the higher proportions of fractionable volatiles with lower lignin, moisture, and ash contents. Figure 1 shows the evaluation of material properties, and Figure 2 shows the amount of elements present in the feedstock material.

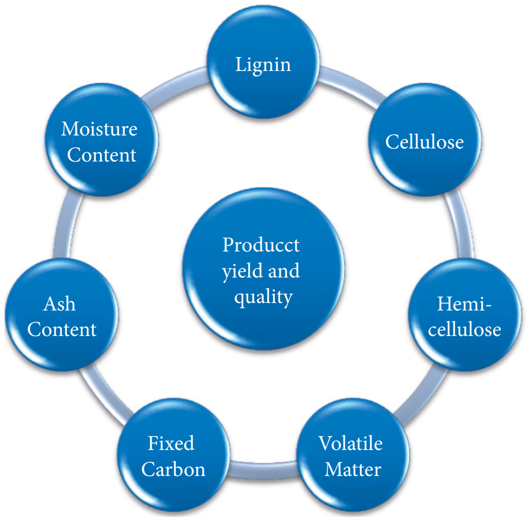

Figure 1: Properties evaluation.

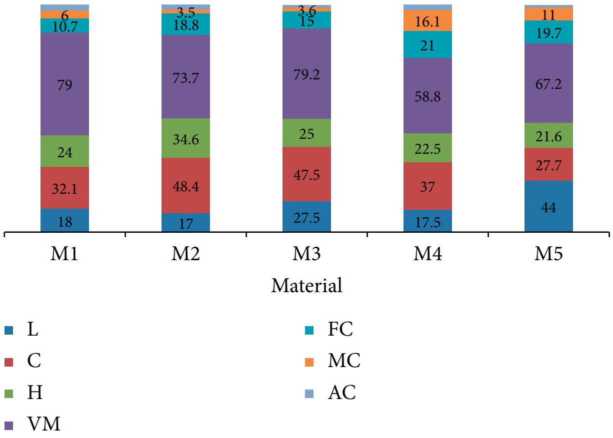

Figure 2: Properties of the selected materials.

2.2. Methods

2.2.1. Material Characterization. The analyses of all the selected samples are done by the equipment with Si'Tarc, Coimbatore. The tests have been done according to ASTM standards. For the determination of moisture content, the ASTM standard D3173 has been adopted. In this process, the biomass samples are heated up to 100°C in a muffle furnace for 3 hours and weighed after cooling. The weight loss during this process represents the evaporation of moisture content. The volatile matter in the sample is determined by ASTM D3175 indicates that the sample is kept in a vessel and heated to 900°C for devolatilization. After that, it was free from the vessel and kept in a room. The weight loss during the devolatilization process represents the total volatile matters. The ash content present in the samples was measured by combusting the samples in a furnace at around 500°C for 2 hours and cooled and weighed. ASTM standard D3174 is employed for this process [41].

2.2.2. Design Evaluation Digraph. A digraph is used to represent the selection criteria and their interdependences in the form of nodes and edges. It consists of a set of nodes, $N = \{n_i\}$ with $i = 1, 2, \ldots.., M$ and set of directed edges $E = \{e_{ij}\}$. Where n_i represents i^{th} material selection attributes and e_{ij} represents relative importance. The number of nodes M equals to the number of material selection attributes taken into account while making a decision. If a node "i" in the selection has higher relative significance than another node "j," a directed edge (arrow) is drawn from "i" to "j" (r_{ij}). If "j" has relative importance, then it is drawn as r_{ji}. In order to quickly visualize the evaluation, attributes and their interdependences are presented in a graphical form (Figure 3).

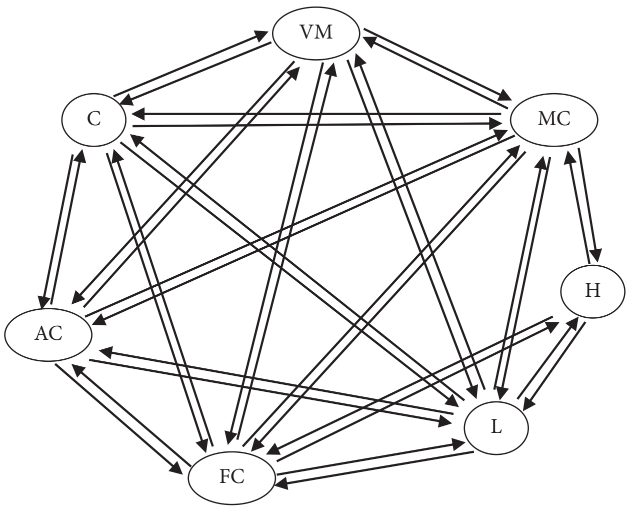

Figure 3: Material selection attributes digraph.

There are seven nodes in this case, and it becomes increasingly complicated as increased nodes and their relationships. As a result, the examination of the digraph will be complicated, making it more difficult to interpret. To get around these constraints, the digraph is represented as a matrix form.

2.2.3. Matrix Representation. The one-to-one depiction among various responsible criteria for producing higher amount of liquid yield is given by a matrix representation. The performance value of the criteria (*Ai*) and its relative weights (*aij*) is used to formulate $M \times M$ matrix, and it is shown as follows:

$$\mathrm{Ji} = \begin{array}{c|ccccc|}
 & 1 & 2 & 3 & - & \mathrm{M} \\ \cline{2-6}
1 & \mathrm{A}_1 & \mathrm{a}_{12} & \mathrm{a}_{13} & - & \mathrm{a}_{1\mathrm{m}} \\
2 & \mathrm{a}_{21} & \mathrm{A2} & \mathrm{a}_{23} & - & \mathrm{a}_{2\mathrm{m}} \\
3 & \mathrm{a}_{31} & \mathrm{a}_{32} & \mathrm{A3} & - & \mathrm{a}_{3\mathrm{m}} \\
- & - & - & - & - & - \\
\mathrm{M} & \mathrm{a}_{\mathrm{m}1} & \mathrm{a}_{\mathrm{m}2} & \mathrm{a}_{\mathrm{m}3} & - & \mathrm{Am} \\ \cline{2-6}
\end{array} \tag{2}$$

where 1, 2, 3,. . ., M are different criteria.

Table 1: Normalised decision matrix.

Alternatives	Criteria						
	C1:L	C2:C	C3:H	C4: VM	C5: FC	C6: MC	C7: AC
$M1$	0.944	0.663	0.694	0.997	0.510	0.583	0.488
$M2$	1.000	1.000	1.000	0.931	0.895	1.000	0.525
$M3$	0.618	0.981	0.723	1.000	0.714	0.972	0.955
$M4$	0.971	0.764	0.650	0.742	1.000	0.217	0.512
$M5$	0.386	0.572	0.624	0.848	0.938	0.318	1.000

$$\mathrm{Ji} = \begin{array}{c|ccccc|}
 & 1 & 2 & 3 & - & \mathrm{M} \\ \cline{2-6}
1 & \mathrm{A}_1 & 1\text{-}\ \mathrm{a}_{21} & 1\text{-}\ \mathrm{a}_{31} & - & 1\text{-}\ \mathrm{a}_{\mathrm{m}1} \\
2 & \mathrm{a}_{21} & \mathrm{A2} & 1\text{-}\ \mathrm{a}_{32} & - & 1\text{-}\ \mathrm{a}_{\mathrm{m}2} \\
3 & \mathrm{a}_{31} & \mathrm{a}_{32} & \mathrm{A3} & - & 1\text{-}\ \mathrm{a}_{\mathrm{m}3} \\
- & - & - & - & - & - \\
\mathrm{M} & \mathrm{a}_{\mathrm{m}1} & \mathrm{a}_{\mathrm{m}2} & \mathrm{a}_{\mathrm{m}3} & - & \mathrm{Am} \\ \cline{2-6}
\end{array} \tag{3}$$

Here, A_i is representing the value of ith criterion by node n_i, and a_{ij} is the relative magnitude of the ith criterion over the jth criterion. The permanent function Ji is the biomass material selection function. It is a benchmark employed in combinatorial mathematics [42, 43]. The permanent function is determined by taking all the determinants as positive, and hence, there no information is missing. This assumption led to a better understanding of material selection characteristics [44]. The permanent function $\operatorname{per}(J)$ is given by

$$\begin{aligned}
& \sum_{i=1}^{M-3}\sum_{j=i+1}^{M-1}\sum_{k=i+1}^{M}\sum_{l=j+1}^{M}\cdots\sum_{M=t+1}^{M}\left(a_{ij}a_{jk}a_{kl}a_{li}+a_{il}a_{lk}a_{kj}a_{ji}\right)A_mA_nA_o\ldots A_tA_M, \\
& k,l,\ldots M \neq \text{pus} + \sum_{i=1}^{M-2}\sum_{j=i+1}^{M-1}\sum_{k=j+1}^{M}\sum_{l=k+1}^{M}\cdots\sum_{M=t+1}^{M}\left(a_{ij}a_{jk}a_{kl}a_{li}+a_{il}a_{lk}a_{kj}a_{ji}\right)A_mA_nA_o\ldots A_tA_M, \\
& k,l,\ldots M \neq \text{pus} + \sum_{i=1}^{M-4}\sum_{j=i+1}^{M-1}\sum_{k=i+1}^{M}\sum_{l=k+1}^{M}\sum_{m=j+1}^{M}\cdots\sum_{M=t+1}^{M}\left(a_{ij}a_{jk}a_{kl}a_{lm}a_{mi}+a_{im}a_{ml}a_{lk}a_{kj}a_{ji}\right)A_nA_o\ldots A_tA_M, \\
& k,l,m\ldots,M \neq \text{pus} + \sum_{i=1}^{M-3}\sum_{j=i+1}^{M-1}\sum_{k=i+1}^{M}\sum_{l=j+1}^{M}\sum_{m-1}^{M-1}\sum_{n=m+1}^{M-1}\cdots\sum_{M=t+1}^{M}\left(a_{ij}a_{jk}a_{kl}a_{li}a_{li}+a_{li}a_{il}a_{lk}a_{kj}a_{ji}\right)A_o\ldots A_tA_M, \\
& k,l,m,n\ldots,M \neq \text{pus} + \sum_{i=1}^{M-5}\sum_{j=i+1}^{M-1}\sum_{k=j+1}^{M}\sum_{l=1}^{M-2}\sum_{m=l+1}^{M-1}\sum_{n=m+1}^{M}\cdots\sum_{M=t+1}^{M}\left(a_{ij}a_{jk}a_{ki}+a_{ik}a_{kj}a_{ji}\right)\left(a_{lm}a_{mn}a_{nl}+a_{lm}a_{mn}a_{nl}\right)A_o\ldots A_tA_M, \\
& k,l,m,n\ldots,M \neq \text{pus} + + \sum_{i=1}^{M-5}\sum_{j=i+1}^{M}\sum_{k=j+1}^{M-3}\sum_{l=i+2}^{M}\sum_{m=k+1}^{M-1}\sum_{n=k+2}^{M}\cdots\sum_{M=t+1}^{M}\left(a_{ij}a_{ji}\right)\left(a_{kl}a_{lk}\right)A_o\ldots A_tA_M, \\
& k,l,m,n\ldots,M \neq \text{pus} + \sum_{i=1}^{M-5}\sum_{j=i+1}^{M-1}\sum_{k=i+1}^{M}\sum_{l=i+1}^{M}\sum_{m=i+1}^{M}\sum_{n=j+1}^{M}\cdots\sum_{M=t+1}^{M}\left(a_{ij}a_{jk}a_{kl}a_{lm}a_{mn}a_{ni}+a_{in}a_{nm}a_{ml}a_{kl}a_{kj}a_{ji}\right)A_o\ldots A_tA_M, \\
& k,l,m,n\ldots,M \neq \text{pus}+,
\end{aligned} \tag{4}$$

where pus means the previously used subscripts.

The permanent function includes the relative significance measurements of criteria. As a result, it may be used to assess the performance of the alternatives. The best alternative is the one having a higher value of the permanent function.

2.2.4. Biomass Material Section Illustration. The normalized decision is shown in Table 1. For which C, H, VM, and FC are taken as beneficial criteria, and *L*, MC, and AC are taken as nonbeneficial criteria. Let *Xij* be the decision matrix's preference value related to material selection, and then, the below equation is used for normalisation.

$$\begin{aligned} \overline{X}_{ij} &= \frac{X_{ij}}{X_j^{\mathrm{Max}}}\ \text{for} \quad \text{beneficial criteria,} \\ \overline{X}_{ij} &= \frac{X_j^{\mathrm{min}}}{X_{ij}}\ \text{for} \quad \text{nonbeneficial criteria.} \end{aligned} \tag{5}$$

2.3. Pyrolysis Process

2.3.1. Reactor Setup. The confirmation experiments were carried out in a fluidized bed reactor (diameter: 150 mm, length: 1 m). The reactor temperature was controlled by a PID controller and measured with five thermocouples. The reactor is well insulated. For the fluidization, nitrogen gas was admitted through a perforated plate fixed at the bottom of the reactor, and its admitted velocity is maintained more than the minimum fluidization velocity. The sand used for fluidization was 0.75 mm in size. The reactor is vertical, and the samples are fed at the rate of 20 g/min. The condensed liquid oil and char were collected and weighed. The mass balance method was used to calculate the yield of uncondensable gas emitted throughout the process. The experiments have been carried out at the fixed temperature of 450°C. The particle sizes used for all the experiments were kept below 1.0 mm. All the samples used for the experimentation purpose were crushed and sieved to attain below 1.0 mm. A dedicated ball mill and sieve shaker were utilized for this purpose. The small size of the particle always leads to maximum heat transfer during pyrolysis and promotes maximum decomposition at a lower temperature.

3. Results and Discussion

3.1. Biomass Material Selection Index. A digraph with directed edges towards a node that has the same number of selection criteria shows the interrelationship between multiple criteria [45]. A $7 * 7$ criterion matrix (*J*) is constructed. Where $m = 7$ denotes the number of evaluation criteria, and *Ai* denotes the criterion's performance value in comparison to the alternative. The relative significance value here is assigned using Table 2.

BMSI is a numerical value that indicates how successfully the material was selected for maximum efficiency. The biomass material selection attributes function is used to evaluate BMSI since it provides measurements of qualities and their relative importance. The higher *Ai* and *Aij* values will result in a higher BMSI value. BMSI is obtained from (4) by putting the values *Ai* and a_{ij}.

$$\mathrm{Ji} = \begin{array}{c|ccccccc|} & \mathrm{C1} & \mathrm{C2} & \mathrm{C3} & \mathrm{C4} & \mathrm{C5} & \mathrm{C6} & \mathrm{C7} \\ \mathrm{C1} & - & 1\text{-}0.65 & 1\text{-}0.55 & 1\text{-}0.75 & 1\text{-}0.55 & 1\text{-}0.45 & 1\text{-}0.55 \\ \mathrm{C2} & .65 & - & 1\text{-}0.45 & 1\text{-}0.55 & 1\text{-}0.4 & 1\text{-}0.4 & 1\text{-}0.45 \\ \mathrm{C3} & .55 & .45 & - & 1\text{-}0.6 & 1\text{-}0.45 & 1\text{-}0.4 & 1\text{-}0.45 \\ \mathrm{C4} & .75 & .55 & .6 & - & 1\text{-}0.3 & 1\text{-}0.25 & 1\text{-}0.35 \\ \mathrm{C5} & .55 & .4 & .45 & .3 & - & 1\text{-}0.4 & 1\text{-}0.55 \\ \mathrm{C6} & .45 & .4 & .4 & .25 & .4 & - & 1\text{-}0.6 \\ \mathrm{C7} & .55 & .45 & .45 & .35 & .55 & .6 & - \end{array} \tag{6}$$

$$\mathrm{Ji} = \begin{array}{c|ccccccc|} & \mathrm{C1} & \mathrm{C2} & \mathrm{C3} & \mathrm{C4} & \mathrm{C5} & \mathrm{C6} & \mathrm{C7} \\ \mathrm{C1} & A_1 & .35 & .45 & .25 & .45 & .55 & .45 \\ \mathrm{C2} & .65 & A_2 & .55 & .45 & .6 & .6 & .55 \\ \mathrm{C3} & .55 & .45 & A_3 & .4 & .55 & .6 & .55 \\ \mathrm{C4} & .75 & .55 & .6 & A_4 & .7 & .75 & .65 \\ \mathrm{C5} & .55 & .4 & .45 & .3 & A_5 & .6 & .45 \\ \mathrm{C6} & .45 & .4 & .4 & .25 & .4 & A_6 & .4 \\ \mathrm{C7} & .55 & .45 & .45 & .35 & .55 & .6 & A_7 \end{array}$$

Table 2: Relative importance.

Class description	Relative importance (a_{ij})
Two equal criteria	0.5
One criterion is somewhat important	0.6
One criterion is sturdily more significant	0.7
One criterion is very strongly important	0.8
One criterion is extremely important	0.9
One criterion is exceptionally more important	1

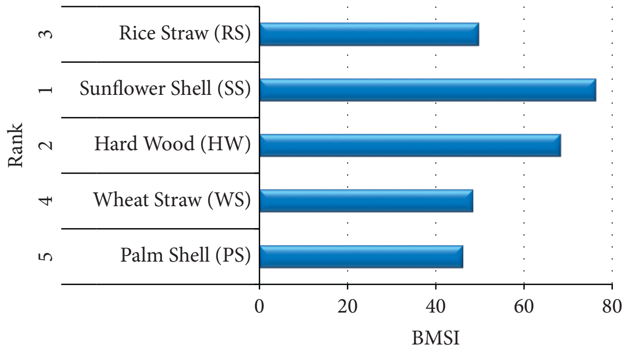

Figure 4: Ranking of biomass alternatives.

Table 3: BMSI with ranking.

Alternatives	BMSI	Rank
$M1$	49.7323	3
$M2$	76.3339	1
$M3$	68.2903	2
$M4$	48.4130	4
$M5$	46.1427	5

The permanent function of matrix J_1 is used to find BMSI for RS.

$$\begin{aligned}
\operatorname{per}(J_1) = {} & \prod_{i=1}^{7} A_i + \sum_{i=1}^{6}\sum_{j=i+1}^{7} \cdots\cdots \sum_{M=t+1}^{7} \left(a_{ij}a_{ji}\right) A_k A_l A_m A_n A_o \cdots\cdots A_t A_M \\
& + \sum_{i=1}^{5}\sum_{j=i+1}^{6}\sum_{k=j+1}^{7} \cdots\cdots \sum_{M=t+1}^{7} \left(a_{ij}a_{jk}a_{ki} + a_{ik}a_{kj}a_{ji}\right) A_l A_m A_n A_o \cdots\cdots A_t A_M \\
& + \sum_{i=1}^{4}\sum_{j=i+1}^{7}\sum_{k=i+1}^{6}\sum_{l=i+2}^{7} \cdots\cdots \sum_{M=t+1}^{7} \left(a_{ij}a_{ji}\right)\left(a_{kl}a_{lk}\right) A_m A_n A_o \cdots\cdots A_t A_M \\
& + \sum_{i=1}^{4}\sum_{j=i+1}^{6}\sum_{k=i+1}^{7}\sum_{l=j+1}^{7} \cdots\cdots \sum_{M=t+1}^{7} \left(a_{ij}a_{jk}a_{kl}a_{li}\right)\left(a_{il}a_{lk}a_{kj}a_{ji}\right) A_m A_n A_o \cdots\cdots A_t A_M + \\
& + \sum_{i=1}^{5}\sum_{j=i+1}^{6}\sum_{k=j+1}^{7}\sum_{l=k+1}^{7} \cdots\cdots \sum_{M=t+1}^{7} \left(a_{ij}a_{jk}a_{kl}a_{li}\right)\left(a_{il}a_{lk}a_{kj}a_{ji}\right) A_m A_n A_o \cdots\cdots A_t A_M .
\end{aligned} \tag{7}$$

Similarly, the BMSI for other materials is found by the following matrix:

$$
\begin{gathered}
J_1 = \begin{array}{c|ccccccc}
\text{RS} & \text{C1} & \text{C2} & \text{C3} & \text{C4} & \text{C5} & \text{C6} & \text{C7} \\
\hline
\text{C1} & .944 & .35 & .45 & .25 & .45 & .55 & .45 \\
\text{C2} & .65 & .663 & .55 & .45 & .6 & .6 & .55 \\
\text{C3} & .55 & .45 & .694 & .4 & .55 & .6 & .55 \\
\text{C4} & .75 & .55 & .6 & .997 & .7 & .75 & .65 \\
\text{C5} & .55 & .4 & .45 & .3 & .510 & .6 & .45 \\
\text{C6} & .45 & .4 & .4 & .25 & .4 & .583 & .4 \\
\text{C7} & .55 & .45 & .45 & .35 & .55 & .6 & .488
\end{array} \\[2ex]
J_2 = \begin{array}{c|ccccccc}
\text{SS} & \text{C1} & \text{C2} & \text{C3} & \text{C4} & \text{C5} & \text{C6} & \text{C7} \\
\hline
\text{C1} & 1 & .35 & .45 & .25 & .45 & .55 & .45 \\
\text{C2} & .65 & 1 & .55 & .45 & .6 & .6 & .55 \\
\text{C3} & .55 & .45 & 1 & .4 & .55 & .6 & .55 \\
\text{C4} & .75 & .55 & .6 & .931 & .7 & .75 & .65 \\
\text{C5} & .55 & .4 & .45 & .3 & .895 & .6 & .45 \\
\text{C6} & .45 & .4 & .4 & .25 & .4 & 1 & .4 \\
\text{C7} & .55 & .45 & .45 & .35 & .55 & .6 & .525
\end{array} \\[2ex]
J_3 = \begin{array}{c|ccccccc}
\text{HW} & \text{C1} & \text{C2} & \text{C3} & \text{C4} & \text{C5} & \text{C6} & \text{C7} \\
\hline
\text{C1} & .618 & .35 & .45 & .25 & .45 & .55 & .45 \\
\text{C2} & .65 & .981 & .55 & .45 & .6 & .6 & .55 \\
\text{C3} & .55 & .45 & .723 & .4 & .55 & .6 & .55 \\
\text{C4} & .75 & .55 & .6 & 1 & .7 & .75 & .65 \\
\text{C5} & .55 & .4 & .45 & .3 & .714 & .6 & .45 \\
\text{C6} & .45 & .4 & .4 & .25 & .4 & .972 & .4 \\
\text{C7} & .55 & .45 & .45 & .35 & .55 & .6 & .955
\end{array} \\[2ex]
J_4 = \begin{array}{c|ccccccc}
\text{WS} & \text{C1} & \text{C2} & \text{C3} & \text{C4} & \text{C5} & \text{C6} & \text{C7} \\
\hline
\text{C1} & .971 & .35 & .45 & .25 & .45 & .55 & .45 \\
\text{C2} & .65 & .764 & .55 & .45 & .6 & .6 & .55 \\
\text{C3} & .55 & .45 & .650 & .4 & .55 & .6 & .55 \\
\text{C4} & .75 & .55 & .6 & .742 & .7 & .75 & .65 \\
\text{C5} & .55 & .4 & .45 & .3 & 1 & .6 & .45 \\
\text{C6} & .45 & .4 & .4 & .25 & .4 & .217 & .4 \\
\text{C7} & .55 & .45 & .45 & .35 & .55 & .6 & .512
\end{array} \\[2ex]
J_5 = \begin{array}{c|ccccccc}
\text{PS} & \text{C1} & \text{C2} & \text{C3} & \text{C4} & \text{C5} & \text{C6} & \text{C7} \\
\hline
\text{C1} & .386 & .35 & .45 & .25 & .45 & .55 & .45 \\
\text{C2} & .65 & .572 & .55 & .45 & .6 & .6 & .55 \\
\text{C3} & .55 & .45 & .624 & .4 & .55 & .6 & .55 \\
\text{C4} & .75 & .55 & .6 & .848 & .7 & .75 & .65 \\
\text{C5} & .55 & .4 & .45 & .3 & .938 & .6 & .45 \\
\text{C6} & .45 & .4 & .4 & .25 & .4 & .318 & .4 \\
\text{C7} & .55 & .45 & .45 & .35 & .55 & .6 & 1
\end{array}
\end{gathered}
\tag{8}
$$

3.2. Ranking of Biomass Alternatives. The ranking order is based on the biomass material selection index ($M2 = 76.3339 > M3 = 68.2903 > M1 = 49.7323 > M4 = 48.4130 > M5 = 46.1427$). The ranks achieved using this digraph and matrix approach are shown in Figure 4 which is specified according to BMSI.

Table 4: Yield of biofuel under selected operating conditions.

Feedstock	MCDM rank	Yield in wt%			Experimental rank
		Bio-oil	Biochar	Gas	
SS	1	46.4	23.3	30.3	1
HW	2	43.5	24.6	31.9	2

Among the list, sunflower shell (*M*2) is chosen as the best alternative using the digraph and matrix approach for better oil yield. Table 3 shows the rank of the selected biomass based on the BMSI value.

When compared to other biomass materials, SS has very low lignin content (17%) and higher cellulose content (48.4%) may be the cause for predicting rank 1 [46]. The moisture content of the SS is also minimum that can enhance the yield with higher quality with higher heating value. From the study found by Demirbas, during pyrolysis, the existence of higher moisture content in the biomass material significantly affects the thermal degradation and yields [47]. It is also proved by the previous studies that the restriction on heat transfer significantly affects the product distribution [48]. The higher lignin content in PS and lower volatile matter present in the WS lead to poor yield; hence, they are ranked five and four. Normally, in thermochemical conversion processes, 90% of the volatile contents are converted as high-energy biofuel that shows the correlation between the breakdown of volatile contents and increased product yield (bio-oil, biogas, and char) [49–51]. Even though SS has lower volatile matter than HW, the higher level of cellulose, hemicellulose, and lower level of lignin may be the reason for ranking one by this approach.

3.3. Confirmation Experiment. The confirmation experiment to assess the reliability was performed using the materials SS and HW which was ranked 1 and 2. During pyrolysis, SS and HW yielded a maximum of 46.4.5 wt% and 43.5 wt% of bio-oil, respectively. These findings proved that the bio-oil extracted from SS is superior to HW. The experimental findings predicted by the digraph and matrix approach were validated and found as accurate. The results also represent the correlation between the experimental and predicted data; thus, it also builds the integrity of the usage of MCDM techniques for material selection issues. Table 4 shows the yield of biofuel from the top two ranked biomass materials under the same operating conditions.

4. Conclusion

In this work, the digraph and matrix approach was used to establish a system for identifying appropriate biomass material for the production of maximum bio-oil. Among the selected alternatives, this technique identified a suitable biomass resource by considering various attributes and their interrelations. This method gives substantial results and also established a link between previous pyrolysis studies for appropriate material selection. The lower lignin, moisture, and higher cellulose content of sunflower shell with a BMSI value of 76.3339 may be the reason for ranking one among the other selected alternatives. This approach is having a good agreement with experimental results. Hence, the top-ranked material yielded 2.9 wt% more than the second-ranked material under the same experimental conditions. The confirmation experimental results give confidence for further research, and this approach can be extended for various engineering applications.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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