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Selection of Biomass Resources with Fuzzy Multi-Criteria Decision-Making Methods: Alternatives for Sustainable Energy Production

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ABSTRACT

Selecting the most sustainable and efficient biomass resource for energy production requires a strategic multi-criteria decision-making approach. This study evaluates four biomass alternatives—plant-based, forest/wood-based, animal-based, and urban/industrial waste biomass—across economic, environmental, technical, and social dimensions, using twelve sub-criteria. The Fuzzy Bonferroni Aggregation Operator consolidated data, while the Fuzzy Weight by Envelope and Slope (F-WENSLO) method prioritized main and sub-criteria, and the Fuzzy Ranking Alternatives with Weights of Criterion (F-RAWEC) method ranked alternatives. Results identified animal-based biomass (Q_i = 1.1228) as the optimal choice due to its superior energy efficiency and economic benefits, followed by plant-based (Q_i = 1.0989), forest/wood-based (Q_i = 1.0919), and urban/industrial waste biomass (Q_i = 1.0848). The latter's low ranking reflects environmental and compatibility challenges. The study underscores the need for holistic biomass selection, balancing economic, technical, environmental, and social factors to inform sustainable energy policies.

1. Introduction

Biomass can be defined as the total mass of living organisms belonging to one or more species. Biomass energy is renewable energy derived from living or recently living organisms. Biomass is a significant resource for renewable energy production and has the potential to replace fossil fuels as natural materials. The processes involved in biomass conversion are classified, and their respective methods and final products are illustrated in Figure 1.

Figure 1 demonstrates how biomass resources are converted into energy or fuel using different technologies. The choice of method depends on the type of biomass and the desired end product.

These resources include energy forms derived from the transformation of organic matter, plant-based, animal-based, and industrial waste [2,3]. The increasing energy demand and environmental concerns have made it more essential to utilize the potential of biomass energy. However, the

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selection of biomass resources is a critical step for the efficient and sustainable production of this energy.

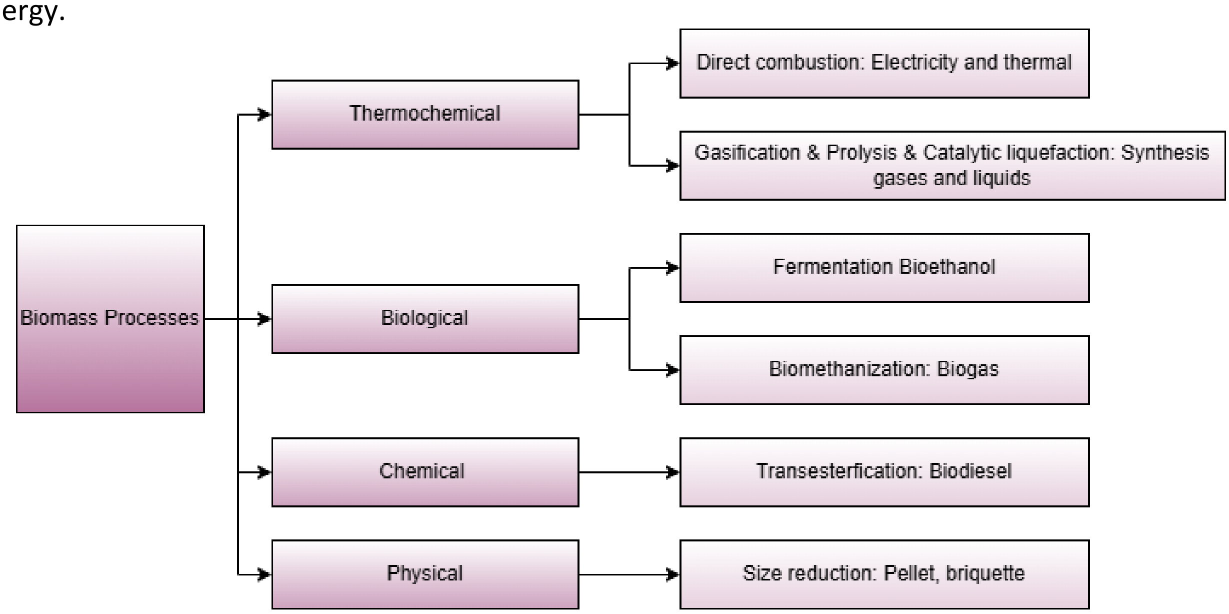

Fig. 1. Fuel Types Derived from Biomass
Source: Ministry of Energy and Natural Resources of the Republic of Turkey, [1].

The selection of biomass resources should be based on economic, environmental, technical, and social criteria. These criteria help evaluate the environmental impacts, costs, energy efficiency, transportability, and effects on local communities [4]. However, uncertainties and conflicts often exist among these criteria. For example, some biomass resources may be more environmentally sustainable but more costly. This is where multi-criteria decision-making (MCDM) methods come into play.

Fuzzy MCDM (F-MCDM) methods are effective tools to support decision-making processes in situations involving uncertainties and complexities [5-7]. These methods enable the weighting of different criteria and the comparison of various alternatives [8,9]. In cases where numerous factors need to be considered, such as the selection of biomass resources, fuzzy MCDM techniques allow for the identification of the most suitable option among various alternatives.

The aim of this study is to examine the use of F-MCDM methods in determining the most suitable alternatives for biomass resource selection. In this process, comparisons will be made among plant-based biomass, animal-based biomass, and biomass derived from urban-industrial waste based on various criteria, and the most appropriate biomass resource will be selected to contribute to sustainable energy production.

1.1. Objective of the Study

The primary objective of this study is to determine the most suitable biomass resource for sustainable energy production by using F-MCDM methods in the selection of biomass resources. Biomass resources consist of various materials derived from plant-based, animal-based, and industrial waste, and each resource has numerous criteria such as energy production potential, environmental impacts, economic costs, and social effects. In this study, fuzzy MCDM methods will be applied to compare biomass resources, taking into account the uncertainties and differences of each of these criteria.

Another objective of the study is to investigate how uncertainties and conflicts encountered in the selection of biomass resources can be managed more efficiently. In this regard, the study aims to identify biomass resources that are more suitable in terms of sustainability and to select more efficient and environmentally friendly alternatives for energy production processes.

1.2. Contributions and Innovations

The contributions and innovations of this study are listed below:

i. Application of F-MCDM Methods: This study will comprehensively apply F-MCDM methods for the first time in the selection of biomass resources. The study presents a new method for evaluating biomass resources based on economic, environmental, technical, and social criteria.
ii. Identification of Alternative Biomass Resources and Criteria: The study will extensively analyze alternative biomass resources derived from plant-based, animal-based, and industrial waste, ensuring diversity among biomass resources. At the same time, the criteria (economic, environmental, technical, and social) for evaluating each resource will be determined, enabling more effective management of uncertainties in the biomass selection process.
iii. Contribution to Sustainable Energy Production: This study contributes to the more sustainable selection of biomass resources and their integration into energy production processes, offering significant benefits for reducing environmental impacts and increasing efficiency.
iv. Innovative Approach to Decision-Making Processes: The F-MCDM methods used in this study will enable more objective and efficient solutions in complex and multi-dimensional decision-making processes, such as the selection of biomass resources. Additionally, considering uncertainties will allow for more robust and reliable decisions.

These contributions provide a significant innovation to the literature, aiming to ensure the efficient use of biomass energy and support the development of sustainable energy policies.

2. Literature Review

This study aims to determine the most suitable alternatives for biomass resource selection using fuzzy MCDM methods. The literature reveals that various methods have been employed to evaluate biomass selection and energy production.

For example, in the study by Dovichi Filho *et al.,* [10] Geographic Information Systems (GIS) and multi-criteria decision-making (MCDM) methods were used to assess the suitability of biomass residues for electricity generation. The application in the Minas Gerais region identified eucalyptus residues as having the highest potential. The study highlighted that technical criterion were the most important factors, with CO2 emissions and electricity demand emerging as the most critical sub-criteria. Similarly, Deb *et al.,* [11] used the AHP and TOPSIS methods to determine the most suitable biomass fuel for a natural convection dryer. The study found that the best option among the tested biomass pellets was a mixture of 80% wood chips, 10% coal, and 10% burnt engine oil. Boonman *et al.,* [12] proposed a two-stage model to design sustainable supply chains for community-scale biomass power plants in Thailand. The study used spatial MCDM and location-allocation models for site selection, identifying the five most suitable locations for biomass power plants.

Fang *et al.,* [13] employed multi-objective uncertain optimization methods to optimize biomass supply chains from an energy-land-carbon perspective. In the study by [14], the PSI method was used to evaluate sustainable energy technologies, with geothermal energy identified as the best alternative. Murtaja *et al.,* [15] developed a TOPSIS-based MCDM approach to analyze the impact of social factors on the selection of renewable energy sources in India. This study emphasized the importance of social factors in the decision-making process.

These studies demonstrate the advantages of using different MCDM methods in the selection of biomass resources. In particular, they highlight the importance of environmental and technical criteria and show that integrating spatial analyses enhances the effectiveness of the decision-making process.

3. Materials and Methods

3.1. Fuzzy Theory Set

Zadeh [16] established fuzzy set theory, which is a system that represents uncertainty while also allowing decision makers to make judgments using linguistic variables. Fuzzy numbers can exist in theory and practice in a variety of forms. These are idioms used to represent unknown numbers. However, triangular fuzzy numbers are the most common kind. Triangular fuzzy numbers have been used in various studies to translate qualitative comments into quantitative ones. Triangular fuzzy numbers portray each number as three numbers. The first, second, and third integers that characterize a fuzzy number represent the lowest, most likely, and biggest possible values, respectively.

Suppose $\tilde{A} = (a_l, a_m, a_u)$ and $\tilde{B} = (b_l, b_m, b_u)$ are two triangular fuzzy numbers. The mathematical computations for these integers are described in Eqs. (1)-(4).

$$\tilde{A} + \tilde{B} = (a_l + b_l, a_m + b_m, a_u + b_u) \tag{1}$$

$$\tilde{A} - \tilde{B} = (a_l - b_u, a_m - b_m, a_u - b_l) \tag{2}$$

$$\tilde{A} x \tilde{B} = (a_l b_l, a_m b_m, a_u b_u) \tag{3}$$

$$\frac{\tilde{A}}{\tilde{B}} = \left(\frac{a_l}{b_u}, \frac{a_m}{b_m}, \frac{a_u}{b_l}\right) \tag{4}$$

Triangular fuzzy numbers can be converted to crisp numbers using a variety of formulae. In this study, Eq. (5) is used to defuzzify a fuzzy integer, such as $\tilde{A} = (a_l, a_m, a_u)$.

$$A = \frac{a_l + 4a_m + a_u}{6} \tag{5}$$

3.2 Fuzzy Bonferroni Aggregation Operator

Aggregation operators, which are mathematical functions, aggregate group members' individual preferences, evaluations, or judgments to form a common conclusion throughout the group decision-making process. The Bonferroni Mean (BM) aggregation operator is provided by Eq. (6) [17].

$$BM^{p,q}(a_1, a_2, \dots, a_n) = \left(\frac{1}{n(n-1)} \sum_{i,j=1\ (i \neq j)}^{n} a_i^p a_j^q\right)^{\frac{1}{p+q}} \tag{6}$$

3.3. F-WENSLO method for prioritization of criteria affecting strategies

Pamučar *et al.,* [18] presented the WENSLO technique for determining weight coefficients of criterion (crisp version). In this work, the WENSLO technique is fuzzification using triangular fuzzy numbers.

Step 1. Construction of the initial decision matrix

The selected experts prioritized the criteria using linguistic phrases from the fuzzy scale in Table 1.

Table 1
Fuzzy scale, linguistic expressions and triangular numbers

Fuzzy Linguistic Descriptive	Abbreviation	Fuzzy Number
Absolutely low	AL	(1,1,1)
Very low	VL	(1,1.5,2)
Low	L	(1.5,2,2.5)
Medium	M	(2,2.5,3)
Equal	E	(2.5,3,3.5)
Medium-high	MH	(3,3.5,4)
High	H	(3.5,4,4.5)
Very high	VH	(4,4.5,5)
Absolutely high	AH	(4.5,5,5)

Source: Božanić *et al.,* [19]

The combined decision matrix ($\tilde{Z}$) is obtained using Eq. (7).

$$\tilde{Z} = \left[\tilde{z}_{ij}\right]_{kxn} = \begin{bmatrix} \tilde{z}_{11} & \cdots & \tilde{z}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{z}_{k1} & \cdots & \tilde{z}_{kn} \end{bmatrix} \tag{7}$$

$\tilde{z}_{ij} = \left(z_{ij}^{l}, z_{ij}^{m}, z_{ij}^{u}\right)$ represents fuzzy value of criterion j. in alternative i.

Step 2. Creating the normalization matrix $\left(\tilde{\mathrm{T}}\right)$.

Eq. (8) is used to normalise the combined decision matrix.

$$\tilde{t}_{ij} = \left(t_{ij}^{l}, t_{ij}^{m}, t_{ij}^{u}\right) = \frac{\tilde{z}_j}{\sum_{j=1}^{n} \tilde{z}_j} = \left(\frac{z_j^{l}}{\sum_{j=1}^{n} z_j^{u}}, \frac{z_j^{m}}{\sum_{j=1}^{n} z_j^{m}}, \frac{z_j^{u}}{\sum_{j=1}^{n} z_j^{l}}\right) \tag{8}$$

Step 3. Calculation of criterion class interval ($\tilde{\rho}_j$).

The size of the j-th criteria class interval is determined using Sturges' rule, Eq. (9):

$$\tilde{\rho}_j = \left(\rho_j^{l}, \rho_j^{m}, \rho_j^{u}\right) = \left(\frac{max(z_j^{l}) - min(z_j^{l})}{1 + 3.322 * log(k)}, \frac{max(z_j^{m}) - min(z_j^{m})}{1 + 3.322 * log(k)}, \frac{max(z_j^{u}) - min(z_j^{u})}{1 + 3.322 * log(k)}\right) \tag{9}$$

Step 4. Determination of the criterion slope ($tan\tilde{\varphi}_j$).

The slope of the criterion is calculated by Eq. (10).

$$tan\tilde{\varphi}_j = \frac{\sum_{i=1}^{k} \tilde{z}_j}{(k-1)\tilde{\rho}_j} = \left(\frac{\sum_{i=1}^{k} z_j^{l}}{(k-1)\rho_j^{u}}, \frac{\sum_{i=1}^{k} z_j^{m}}{(k-1)\rho_j^{m}}, \frac{\sum_{i=1}^{k} z_j^{u}}{(k-1)\rho_j^{l}}\right) \tag{10}$$

Step 5. Determination of the criterion envelope ($\tilde{\varepsilon}_j$)

Eq. (11) calculates the total of the partial Euclidean distances between two consecutive criteria.

$$\tilde{\varepsilon}_j = \left(\sum_{i=1}^{k-1} \sqrt{\left(z_{i+1,j}^{l} - z_{ij}^{l}\right)^2 + \left(\rho_j^{l}\right)^2}, \sum_{i=1}^{k-1} \sqrt{\left(z_{i+1,j}^{m} - z_{ij}^{m}\right)^2 + \left(\rho_j^{m}\right)^2}, \sum_{i=1}^{k-1} \sqrt{\left(z_{i+1,j}^{u} - z_{ij}^{u}\right)^2 + \left(\rho_j^{u}\right)^2}\right) \tag{11}$$

Step 6. Determine the envelope slope ratio ($\tilde{\delta}_j$)

The ratio of the total Euclidean distance to the criteria slope is calculated using Eq. (12).

$$\tilde{\delta}_j = \frac{\tilde{\varepsilon}_j}{tan\tilde{\varphi}_j} = \left(\frac{\varepsilon_j^l}{tan\varphi_j^u}, \frac{\varepsilon_j^m}{tan\varphi_j^m}, \frac{\varepsilon_j^u}{tan\varphi_j^l}\right) \quad (12)$$

Step 7. Obtaining fuzzy weights $(\tilde{w}_j)$ of each of the criterion

Weights are determined using Eq. (13) depending on the criteria's significance coefficients.

$$\tilde{w}_j = \left(w_j^l, w_j^m, w_j^u\right) = \frac{\tilde{\delta}_j}{\sum_{j=1}^n \tilde{\delta}_j} = \left(\frac{\delta_j^l}{\sum_{j=1}^n \delta_j^u}, \frac{\delta_j^m}{\sum_{j=1}^n \delta_j^m}, \frac{\delta_j^u}{\sum_{j=1}^n \delta_j^l}\right) \quad (13)$$

3.4. F-RAWEC Method for Ranking Strategies

Puška *et al.,* [20] presented the RAWEC technique for ranking alternatives (crisp version). In this study, the RAWEC technique is fuzzified using triangular fuzzy numbers.

Step 1. Construction of the initial decision matrix

The selected experts prioritized the criteria using linguistic phrases from the fuzzy scale in Table 1.

The combined decision matrix $(\tilde{X})$ is obtained using Eq. (14).

$$\tilde{X} = \left[\tilde{x}_{ij}\right]_{kxn} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{k1} & \cdots & \tilde{x}_{kn} \end{bmatrix} \quad (14)$$

$\tilde{x}_{ij} = \left(x_{ij}^l, x_{ij}^m, x_{ij}^u\right)$ represents fuzzy value of criterion j. in alternative i.

Step 2. Creating the normalization matrix $(\tilde{N})$.

When normalising the initial decision matrix, double normalisation is performed with Eq. (15) for the benefit normalization $(\tilde{n}_{ij})$ and Eq. (16) for the cost normalization $(\tilde{n}_{ij})'$.

$$\tilde{n}_{ij} = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \frac{\tilde{x}_j}{max(\tilde{x}_{ij})} = \left(\frac{x_{ij}^l}{max(x_{ij}^u)}, \frac{x_{ij}^m}{max(x_{ij}^u)}, \frac{x_{ij}^u}{max(x_{ij}^u)}\right) \quad (15)$$

and

$$\left(\tilde{n}_{ij}\right)' = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \frac{min(\tilde{x}_{ij})}{\tilde{x}_{ij}} = \left(\frac{min(x_{ij}^l)}{x_{ij}^u}, \frac{min(x_{ij}^l)}{x_{ij}^m}, \frac{min(x_{ij}^l)}{x_{ij}^l}\right) \quad (15)$$

$$\tilde{n}_{ij} = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \frac{min(\tilde{x}_{ij})}{\tilde{x}_{ij}} = \left(\frac{min(x_{ij}^l)}{x_{ij}^u}, \frac{min(x_{ij}^l)}{x_{ij}^m}, \frac{min(x_{ij}^l)}{x_{ij}^l}\right) \quad (16)$$

and

$$\left(\tilde{n}_{ij}\right)' = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \frac{\tilde{x}_j}{max(\tilde{x}_{ij})} = \left(\frac{x_{ij}^l}{max(x_{ij}^u)}, \frac{x_{ij}^m}{max(x_{ij}^u)}, \frac{x_{ij}^u}{max(x_{ij}^u)}\right) \quad (16)$$

Step 3. Calculate the deviation from the criteria weight

Eqs. (17) and (18) yield the total deviation from the weight of the criterion after first calculating the deviations of the normalized data from the maximum values denoted by the number 1. The deviation is then multiplied by the weights of the criteria.

$$\tilde{\vartheta}_{ij} = \left(\sum_{i=1}^n \left[\left(1 - n_{ij}^u\right) * w_j^l\right], \sum_{i=1}^n \left[\left(1 - n_{ij}^m\right) * w_j^m\right], \sum_{i=1}^n \left[\left(1 - n_{ij}^l\right) * w_j^u\right]\right) \quad (17)$$

$$\left(\tilde{\vartheta}_{ij}\right)' = \left(\sum_{i=1}^n \left[\left(1 - \left(n_{ij}^u\right)'\right) * w_j^l\right], \sum_{i=1}^n \left[\left(1 - \left(n_{ij}^m\right)'\right) * w_j^m\right], \sum_{i=1}^n \left[\left(1 - \left(n_{ij}^l\right)'\right) * w_j^u\right]\right) \quad (18)$$

Step 4. Calculation of the value of the RAWEC method

The value of the RAWEC method obtained by Eq. (19) takes a value between (-1,1).

$$\tilde{Q}_i = \frac{(\tilde{\vartheta}_{ij})' - \tilde{\vartheta}_{ij}}{(\tilde{\vartheta}_{ij})' + \tilde{\vartheta}_{ij}} = \left(\frac{(\vartheta_{ij}^{l})' - \vartheta_{ij}^{u}}{(\vartheta_{ij}^{u})' + (\vartheta_{ij}^{u})}, \frac{(\vartheta_{ij}^{m})' - \vartheta_{ij}^{m}}{(\vartheta_{ij}^{m})' + (\vartheta_{ij}^{m})}, \frac{(\vartheta_{ij}^{u})' - \vartheta_{ij}^{l}}{(\vartheta_{ij}^{l})' + (\vartheta_{ij}^{l})} \right) \tag{19}$$

The degree to which the value of an alternative's technique is high determines its superiority. The best option is indicated by the alternative with the highest value.

4. Case Study

To form a decision-making group for working on the selection of biomass resources, individuals from various fields of expertise were brought together. Table 2 shows the structure of the decision-making group, which includes representatives from each area of expertise.

Table 2
Structure of the Decision-Making Group

Expert Group Member	Role	Responsibilities
E1	Energy Efficiency Expert	Analyzing the energy production efficiency of biomass sources, comparing energy conversion rates of different sources, and recommending suitable energy production methods.
E2	Environmental Science Expert	Evaluating the environmental impacts of biomass sources, measuring carbon footprint, developing waste management strategies, and suggesting eco-friendly biomass options.
E3	Economics Expert	Conducting cost analyses of biomass sources, assessing market value and economic returns, and examining the effects of incentives and subsidies.
E4	Agricultural and Forestry Engineering Expert	Evaluating the sustainability of agricultural biomass sources, analyzing the efficiency of forest products, and examining the environmental impacts of these resources.
E5	Social Sciences Expert	Assessing local community acceptance of biomass projects, analyzing the social impacts of biomass sources, evaluating food security risks, and contributing to regional development.

By clearly defining the roles and responsibilities of each expert, the decision-making process was ensured to be comprehensive and effective.

4.1. Definition and Explanation of Criteria

The criteria used in the selection of biomass resources were thoroughly explained by the decision-making group and are presented in Table 3.

Table 3
Criteria Used in the Selection of Biomass Resources

Main Criteria	Sub-Criteria	Description
Economic Criteria (C1)	Cost (C11) (min)	The cost of raw material procurement, processing, and transportation should be low.
	Market Value (C12) (max)	The selected biomass should provide high economic returns for energy production.
	Incentives and Subsidies (C13) (max)	Government incentives and subsidies supporting the biomass source should be considered.
Environmental Criteria (C2)	Carbon Footprint (C21) (min)	Emissions released during the processing and use of biomass should be low.
	Waste Management (C22) (max)	The biomass source should be sustainable in terms of waste management.
	Land and Water Usage (C23) (min)	It should not cause excessive water and fertilizer use or harm agricultural land.

Table 3
Continued

Main Criteria	Sub-Criteria	Description
Technical Criteria (C3)	Energy Efficiency (C31) (max)	A high energy conversion rate ensures efficient energy production.
	Compatibility (C32) (max)	It should be compatible with existing biomass processing facilities for easy integration.
	Storage and Transportation Ease (C33) (max)	The biomass source should be easy to transport and store.
Social Criteria (C4)	Employment Impact (C41) (max)	It should contribute to regional development by creating employment opportunities.
	Local Acceptance (C42) (max)	It should be socially acceptable and well-received by local communities.
	Food Security (C43) (min)	It should not threaten agricultural land or food production.

These criteria aim to comprehensively evaluate and prioritize the selection of biomass resources. Based on these criteria, the decision-making group will determine the most suitable option.

4.2. Biomass Resources

The alternatives proposed by the decision-making group for creating sustainable biomass resources and increasing diversity in energy production are presented in Table 4.

Table 4
Alternative Biomass Resources

Alternative Biomass Sources	Content of Alternative Biomass Source
Plant-Based Biomass Source (A1)	- Oilseed plants: Safflower, mustard, peanut - Sugar and starch plants: Sweet sorghum, cassava, oat - Fiber plants: Jute, abaca, sisal - Plant residues: Coffee husks, tea waste, fruit pulp
Alternative Biomass Sources from Forests and Forest Products (A2)	- Agroforestry residues - Sawdust and wood chips from debarked trees - Mushroom industry waste
Animal-Based Biomass Source (A3)	- Fish processing waste - Seaweed and aquatic biomass - Dairy and whey by-products
Alternative Biomass Source from Urban and Industrial Waste (A4)	- Agricultural processing waste (e.g., coffee and cocoa husks) - Bioplastic production waste - Organic waste from food processing and retail sector

Table 4 categorically breaks down biomass sources, showing examples within each type.

4.3. Data Collection and Analysis

The decision-making group evaluated both the criteria and the alternative biomass sources according to these criteria, as shown in Table 1. Based on expert opinions, the evaluation of the main criteria is presented in Table 5, the evaluation of the sub-criteria in Table 6, and the evaluation of the alternative biomass sources in Table 7.

Table 5
Experts' Evaluation of Main Criteria

Experts	C1	C2	C3	C4
E1	H	VH	AH	MH
E2	E	AH	H	VH
E3	AH	MH	E	H
E4	MH	VH	AH	E
E5	MH	H	MH	AH

Table 5 provides a summary of the scores given by experts for specific criteria. The criteria were evaluated and scored by each expert within the framework of their own area of expertise. This scoring will help determine the weights of the criteria to be used in the final decision-making process.

Table 6
Experts' Evaluation of Sub-Criteria

Experts	C11	C12	C13	C21	C22	C23	C31	C32	C33	C41	C42	C43
E1	MH	H	E	VH	H	MH	AH	VH	H	E	MH	M
E2	E	MH	H	AH	AH	VH	H	H	MH	M	VH	E
E3	AH	AH	VH	E	MH	E	MH	VH	AH	H	MH	M
E4	H	MH	MH	MH	VH	AH	H	MH	MH	VH	H	MH
E5	E	MH	MH	MH	H	H	E	MH	E	AH	AH	VH

Table 7
Experts' Evaluation of Alternatives

Experts	Alternative Biomass Source	C11	C12	C13	C21	C22	C23	C31	C32	C33	C41	C42	C43
E1	A1	VH	H	MH	H	AH	H	VH	MH	AH	H	AH	H
	A2	H	MH	VH	VH	H	VH	AH	H	VH	MH	VH	MH
	A3	VH	H	AH	H	VH	MH	VH	H	VH	H	VH	H
	A4	AH	VH	H	VH	AH	VH	VH	H	AH	VH	AH	VH
E2	A1	H	MH	VH	MH	VH	VH	H	E	VH	MH	VH	MH
	A2	MH	H	MH	H	VH	H	VH	VH	H	H	H	H
	A3	H	MH	VH	MH	H	H	H	MH	VH	MH	VH	MH
	A4	H	MH	VH	H	VH	H	H	MH	VH	MH	VH	MH
E3	A1	AH	VH	H	VH	H	MH	VH	H	VH	H	VH	H
	A2	VH	VH	H	AH	H	H	VH	H	VH	MH	VH	MH
	A3	AH	VH	H	VH	H	H	VH	H	VH	H	VH	H
	A4	AH	H	VH	VH	VH	VH	H	H	VH	H	VH	H
E4	A1	MH	E	MH	H	VH	H	MH	E	H	MH	H	MH
	A2	MH	E	MH	H	H	MH	H	VH	H	MH	H	MH
	A3	MH	E	MH	H	H	MH	H	MH	H	MH	H	MH
	A4	MH	E	H	MH	H	MH	H	MH	H	MH	H	MH
E5	A1	H	VH	H	E	MH	M	H	H	MH	VH	H	E
	A2	MH	MH	E	H	H	MH	H	VH	H	MH	MH	H
	A3	E	E	MH	MH	H	VH	MH	MH	E	E	E	MH
	A4	VH	H	AH	AH	AH	AH	VH	VH	AH	AH	AH	AH

These assessments help to understand the strengths and weaknesses of the proposed biomass resources in the decision-making process and inform the criteria to be considered in the final selection.

4.4. Determining the weights with F-WENSLO method

The initial decision matrix obtained as a result of the experts' evaluations and presented in Table 5 was normalized using Eq. (8). The resulting normalized matrix is provided in Table 8.

Table 8
Normalized decision matrix

	C1			C2			C3			C4		
E1	0.1667	0.2105	0.2727	0.1702	0.2093	0.2632	0.2045	0.2439	0.2778	0.1364	0.1750	0.2286
E2	0.1190	0.1579	0.2121	0.1915	0.2326	0.2632	0.1591	0.1951	0.2500	0.1818	0.2250	0.2857
E3	0.2143	0.2632	0.3030	0.1277	0.1628	0.2105	0.1136	0.1463	0.1944	0.1591	0.2000	0.2571
E4	0.1429	0.1842	0.2424	0.1702	0.2093	0.2632	0.2045	0.2439	0.2778	0.1136	0.1500	0.2000
E5	0.1429	0.1842	0.2424	0.1489	0.1860	0.2368	0.1364	0.1707	0.2222	0.2045	0.2500	0.2857
max	0.2143	0.2632	0.3030	0.1915	0.2326	0.2632	0.2045	0.2439	0.2778	0.2045	0.2500	0.2857
min	0.1190	0.1579	0.2121	0.1277	0.1628	0.2105	0.1136	0.1463	0.1944	0.1136	0.1500	0.2000

In Table 8, the normalized values of the evaluation of criterion C1 by E1 are obtained as follows.

$$\tilde{t}_{11} = \left(\frac{3,5}{4,5+3,5+5+4+4}, \frac{4}{4+3+5+3,5+3,5}, \frac{4,5}{3,5+2,5+4,5+3+3}\right) = (0.1667 \quad 0.2105 \quad 0.2727)$$

All elements of the matrix were calculated similarly.

Then, the criteria class range was calculated using Eq. (9), the criteria slope was calculated using Eq. (10), the criteria envelope was calculated using Eq. (11), the envelope slope ratio was calculated using Eq. (12) and the fuzzy weight of each criterion was calculated using Eq. (13) and presented in Table 9.

Table 9
Calculations according to F-WENSLO method for criteria

	C1			C2			C3			C4		
$\tilde{\boldsymbol{\rho}}_j$	0.0287	0.0317	0.0274	0.0192	0.0210	0.0158	0.0274	0.0294	0.0251	0.0274	0.0301	0.0258
$\boldsymbol{tan\tilde{\varphi}_j}$	0.6482	0.9500	1.4848	0.7681	1.0750	1.6148	0.5932	1.0250	1.4938	0.6960	1.0000	1.5365
$\tilde{\boldsymbol{\varepsilon}}_j$	0.5856	0.6023	0.5702	0.5323	0.5451	0.5460	0.6454	0.6574	0.6252	0.6238	0.6394	0.6293
$\tilde{\boldsymbol{\delta}}_j$	0.3944	0.6340	0.8797	0.3296	0.5070	0.7108	0.4321	0.6414	1.0540	0.4060	0.6394	0.9041
$\tilde{\boldsymbol{w}}_j$	0.1111	0.2618	0.5631	0.0929	0.2094	0.4550	0.1218	0.2648	0.6747	0.1144	0.2640	0.5788

All calculations are shown specific to criteria C1.

$$\tilde{\rho}_{C1} = \left(\frac{0.2143-0.1190}{1+3.322*log5}, \frac{0.2632-0.1579}{1+3.322*log5}, \frac{0.3030-0.2121}{1+3.322*log5}\right) = (0.0287, 0.0317, 0.0274)$$

$$tan\tilde{\varphi}_{C1} = \begin{pmatrix} \dfrac{0.1667+0.1190+0.2143+0.1429+0.1429}{4*0.3030}, \\ \dfrac{0.2105+0.1579+0.2632+0.1842+0.1842}{4*0.2632}, \\ \dfrac{0.2727+0.2121+0.3030+0.2424+0.2424}{4*0.2143} \end{pmatrix} = (0.6482, 0.9500, 1.4848)$$

$$\tilde{\varepsilon}_{C1} = \begin{pmatrix} \sqrt{((0.1190-0.1667)^2+0.0287^2)+((0.2143-0.1190)^2+0.0287^2)+((0.1429-0.2143)^2+0.0287^2)+((0.1429-0.1429)^2+0.0287^2)}, \\ \sqrt{((0.1579-0.2105)^2+0.0317^2)+((0.2632-0.1579)^2+0.0317^2)+((0.1842-0.2632)^2+0.0317^2)+((0.1842-0.1842)^2+0.0317^2)}, \\ \sqrt{((0.2121-0.2727)^2+0.0274^2)+((0.3030-0.2121)^2+0.0274^2)+((0.2424-0.3030)^2+0.0274^2)+((0.2424-0.2424)^2+0.0274^2)} \end{pmatrix}$$

$$\tilde{\varepsilon}_{C1} = (0.1405 \quad 0.1552 \quad 0.1364)$$

$$\tilde{\delta}_{C1} = \left(\frac{0,1405}{1,4848}, \frac{0,1552}{0,9500}, \frac{0,1364}{0,6482}\right) = (0.0946 \;\; 0.1634 \;\; 0.2104)$$

$$\widetilde{w}_{C1} = \begin{pmatrix} \dfrac{0.0946}{0.2104 + 0.1108 + 0.2159 + 0.1893}, \\ \dfrac{0.1634}{0.1634 + 0.0924 + 0.1482 + 0.1387}, \\ \dfrac{0.2104}{0.0946 + 0.0563 + 0.0948 + 0.0821} \end{pmatrix} = (0.1302 \;\; 0.3010 \;\; 0.6420)$$

Crips weights were then obtained using Eq. (5).

$$w_{C1} = \frac{0.1302 + 4 * 0.3010 + 0.6420}{6} = 0.3294$$

Since $\sum_{j=1}^{4} w_j = 1$ for all weights, normalized weight values were obtained.

$$\omega_{C1} = \frac{0.3294}{0.3294 + 0.1828 + 0.3136 + 0.2855} = 0.2964$$

Similarly, the same procedures were performed for the other weights.

$$\omega_j = (0.2964 \;\; 0.1645 \;\; 0.2822 \;\; 0.2569)$$

According to the weights of the main criteria used in the selection of biomass resources, the most important factor seems to be Economic Criteria (C1) (0.2964). It is followed by Technical Criteria (C3) (0,2822), Social Criteria (C4) (0,2569) and Environmental Criteria (C2) (0,1645) with the lowest weight.

The procedure used to determine the weights of the main criteria was also used to determine the weights of the sub-criteria. The global weights obtained by multiplying the weights of the main criteria by the weights of the sub-criteria are shown in Table 10.

Table 10
Weights and rankings of sub-criteria

Criteria	Fuzzy weights			Local weights (normalise)	Global weights (normalise)	Rank
C1	0.1302	0.3010	0.6420	0.2964		
C11	0.0497	0.1121	0.2611	0.1130	0.1349	1
C12	0.0389	0.0858	0.1727	0.0826	0.0986	3
C13	0.0259	0.0637	0.2192	0.0744	0.0888	5
C2	0.0775	0.1703	0.3379	0.1645		
C21	0.0402	0.0887	0.1946	0.0878	0.0581	10
C22	0.0338	0.0723	0.1501	0.0704	0.0466	12
C23	0.0493	0.1077	0.2568	0.1097	0.0726	8
C3	0.1305	0.2731	0.6588	0.2822		
C31	0.0328	0.0723	0.1712	0.0734	0.0834	7
C32	0.0180	0.0425	0.1399	0.0488	0.0554	11
C33	0.0436	0.0973	0.2079	0.0953	0.1083	2
C4	0.1130	0.2556	0.5775	0.2569		
C41	0.0394	0.0879	0.2339	0.0930	0.0962	4
C42	0.0307	0.0663	0.1594	0.0678	0.0701	9
C43	0.0363	0.1035	0.1134	0.0839	0.0868	6

According to Table 10, the sub-criteria that are more important in the selection of biomass sources are shown.

Prominent Criteria: Cost (C11) (0.1349): Identified as the most important criterion. This indicates that economic factors are the most critical element in biomass selection. Ease of Storage and Transportation (C33) (0.1083): The portability and storage conditions of biomass are technically very important. Market Value (C12) (0.0986): Biomass sources with higher economic returns are preferred more. Employment Impact (C41) (0.0962): The capacity to create employment on a social level is also an important criterion in the selection process. Incentives and Support (C13) (0.0888): Incentives provided by the government and institutions are one of the factors influencing biomass projects.

Moderately Important Criteria: Food Security (C43) (0.0868) and Energy Efficiency (C31) (0.0834): Important from a sustainability perspective but not as decisive as cost and technical suitability. Land and Water Use (C23) (0.0726): Although its environmental impact is significant, it lags behind economic and technical criteria. Local Acceptance (C42) (0.0701): Public acceptance of biomass facilities is decisive but not among the most critical factors.

Less Important Criteria: Carbon Footprint (C21) (0.0581): Although important for environmental sustainability, it is less influential than economic and technical factors. Compatibility (C32) (0.0554): Technically important but not as dominant as other technical and economic factors. Waste Management (C22) (0.0466): Has the lowest weight value, meaning it appears to be the least influential factor in biomass selection.

In the selection of biomass sources, economic factors (cost, market value, incentives) stand out as the most decisive factors. Among technical factors, ease of storage and transportation is also highly important. Environmental factors rank lower, indicating that decision-makers primarily consider economic and logistical suitability. Based on this analysis, it can be concluded that for biomass projects to succeed, it is necessary to focus on sources that minimize costs and are efficient in terms of transportation and storage. To enhance environmental sustainability, greater emphasis could be placed on reducing the carbon footprint and improving waste management.

4.5. Fuzzy Dombi Bonferroni aggregation operator application

The decision-makers interpreted the performance of the alternatives according to Table 1. To aggregate these individual evaluations provided in Table 7, a combined fuzzy decision matrix was obtained using Eq. (3) and is presented in Table 11.

Table 11
Fuzzy decision matrix aggregated using the Fuzzy Dombi Bonferroni aggregation operator

Alternative		C11			C12			C13	
A1	3.6912	4.1923	4.5962	3.3875	3.8891	4.3903	3.3948	3.8955	4.3960
A2	3.5917	4.0927	4.4972	3.2863	3.7881	4.2895	3.5951	4.0957	4.5962
A3	3.4893	3.9906	4.3960	3.3875	3.8891	4.3903	3.3948	3.8955	4.3960
A4	3.3948	3.8955	4.3960	3.3875	3.8891	4.3903	3.3948	3.8955	4.3960
Alternative		C21			C22			C23	
A1	3.2901	3.7914	4.2924	3.7914	4.2924	4.6957	3.1820	3.6844	4.1863
A2	3.3875	3.8891	4.3903	3.5951	4.0957	4.5962	3.2787	3.7815	4.2837
A3	3.4893	3.9906	4.4917	3.5951	4.0957	4.5962	3.1820	3.6844	4.1863
A4	3.5847	4.0866	4.4917	3.5951	4.0957	4.5962	3.2825	3.7848	4.2866
Alternative		C31			C32			C33	
A1	3.5951	4.0957	4.5962	2.9917	3.4928	3.9937	3.7914	4.2924	4.6957
A2	3.6912	4.1923	4.5962	3.0903	3.5917	4.0927	3.6946	4.1952	4.6957
A3	3.7914	4.2924	4.6957	3.3912	3.8923	4.3932	3.5951	4.0957	4.5962
A4	3.7914	4.2924	4.6957	3.3912	3.8923	4.3932	3.5951	4.0957	4.5962

Table 11
Continued

Alternative		C41			C42			C43	
A1	3.3948	3.8955	4.3960	3.8955	4.3960	4.7984	3.0943	3.5951	4.0957
A2	3.2939	3.7947	4.2953	3.7980	4.2983	4.7984	2.9958	3.4964	3.9969
A3	3.3948	3.8955	4.3960	3.6980	4.1982	4.6984	3.0943	3.5951	4.0957
A4	3.2939	3.7947	4.2953	3.6980	4.1982	4.6984	2.9958	3.4964	3.9969

Table 11 combines the alternative biomass sources using the Fuzzy Dombi Bonferroni aggregation operator to evaluate them according to the determined criteria and select the most suitable source.

4.6. F-RAWEC method application results

Using Eq. (15) and Eq. (16) on Table 11, the benefit and cost normalized decision matrices are obtained. These matrices are provided in Table 12 and Table 13, respectively.

Table 12
Benefit normalization matrix

Alternative		C11			C12			C13	
A1	0.7386	0.8098	0.9197	0.7716	0.8858	1.0000	0.7386	0.8476	0.9564
A2	0.7549	0.8295	0.9452	0.7485	0.8628	0.9770	0.7822	0.8911	1.0000
A3	0.7723	0.8507	0.9729	0.7716	0.8858	1.0000	0.7386	0.8476	0.9564
A4	0.7723	0.8715	1.0000	0.7716	0.8858	1.0000	0.7386	0.8476	0.9564
Alternative		C21			C22			C23	
A1	0.7665	0.8678	1.0000	0.8074	0.9141	1.0000	0.7601	0.8636	1.0000
A2	0.7494	0.8460	0.9713	0.7656	0.8722	0.9788	0.7428	0.8415	0.9705
A3	0.7325	0.8245	0.9429	0.7656	0.8722	0.9788	0.7601	0.8636	1.0000
A4	0.7325	0.8051	0.9178	0.7656	0.8722	0.9788	0.7423	0.8407	0.9694
Alternative		C31			C32			C33	
A1	0.7656	0.8722	0.9788	0.6810	0.7951	0.9091	0.8074	0.9141	1.0000
A2	0.7861	0.8928	0.9788	0.7034	0.8176	0.9316	0.7868	0.8934	1.0000
A3	0.8074	0.9141	1.0000	0.7719	0.8860	1.0000	0.7656	0.8722	0.9788
A4	0.8074	0.9141	1.0000	0.7719	0.8860	1.0000	0.7656	0.8722	0.9788
Alternative		C41			C42			C43	
A1	0.7723	0.8861	1.0000	0.8118	0.9161	1.0000	0.2614	0.0000	0.1142
A2	0.7493	0.8632	0.9771	0.7915	0.8958	1.0000	0.2451	0.0230	0.1372
A3	0.7723	0.8861	1.0000	0.7707	0.8749	0.9792	0.2277	0.0000	0.1142
A4	0.7493	0.8632	0.9771	0.7707	0.8749	0.9792	0.2277	0.0000	0.1142

The benefit normalized values of alternative A1 for criterion C11 are obtained as follows.

$$\tilde{n}_{11} = \left(\frac{3{,}3948}{4{,}5962}, \frac{3{,}3948}{4{,}1923}, \frac{3{,}3948}{3{,}6912}\right) = (0{,}7386\ \ 0{,}8098\ \ 0{,}9197)$$

All elements of the matrix are calculated similarly.

Table 13
Cost normalization matrix

Alternative		C11			C12			C13	
A1	0.8031	0.9121	1.0000	0.7485	0.8450	0.9701	0.7723	0.8715	1.0000
A2	0.7814	0.8904	0.9785	0.7661	0.8675	1.0000	0.7386	0.8289	0.9443
A3	0.7592	0.8682	0.9564	0.7485	0.8450	0.9701	0.7723	0.8715	1.0000
A4	0.7386	0.8476	0.9564	0.7485	0.8450	0.9701	0.7723	0.8715	1.0000

Table 13
Continued

Alternative		C21			C22			C23	
A1	0.7325	0.8441	0.9556	0.7656	0.8376	0.9482	0.7423	0.8595	0.9766
A2	0.7542	0.8658	0.9774	0.7822	0.8778	1.0000	0.7649	0.8822	0.9993
A3	0.7768	0.8884	1.0000	0.7822	0.8778	1.0000	0.7423	0.8595	0.9766
A4	0.7981	0.9098	1.0000	0.7822	0.8778	1.0000	0.7658	0.8829	1.0000
Alternative		C31			C32			C33	
A1	0.7822	0.8778	1.0000	0.7491	0.8565	1.0000	0.7656	0.8376	0.9482
A2	0.7822	0.8576	0.9740	0.7310	0.8329	0.9681	0.7656	0.8570	0.9731
A3	0.7656	0.8376	0.9482	0.6810	0.7686	0.8822	0.7822	0.8778	1.0000
A4	0.7656	0.8376	0.9482	0.6810	0.7686	0.8822	0.7822	0.8778	1.0000
Alternative		C41			C42			C43	
A1	0.7493	0.8456	0.9703	0.7707	0.8412	0.9493	0.1969	0.0299	0.1550
A2	0.7669	0.8680	1.0000	0.7707	0.8603	0.9737	0.2186	0.0000	0.1325
A3	0.7493	0.8456	0.9703	0.7871	0.8808	1.0000	0.2408	0.0299	0.1550
A4	0.7669	0.8680	1.0000	0.7871	0.8808	1.0000	0.2614	0.0299	0.1550

The cost normalized values of alternative A1 for criterion C11 are obtained as follows.

$$(\tilde{n}_{11})' = \left(\frac{3,6912}{4,5962}, \frac{4,1923}{4,5962}, \frac{4,5962}{4,5962}\right) = (0,8031 \;\; 0,9121 \;\; 1,0000)$$

All elements of the matrix are calculated in a similar way. Then, the deviations from the criteria weights are obtained by Eq. (17) and Eq. (18). These matrices are given in Table 14 and Table 15 respectively.

Table 14
Deviations from criteria weights (Benefit)

Alternative		C11			C12			C13	
A1	0.0040	0.0213	0.0683	0.0000	0.0098	0.0395	0.0011	0.0097	0.0573
A2	0.0027	0.0191	0.0640	0.0009	0.0118	0.0434	0.0000	0.0069	0.0477
A3	0.0013	0.0167	0.0595	0.0000	0.0098	0.0395	0.0011	0.0097	0.0573
A4	0.0000	0.0144	0.0595	0.0000	0.0098	0.0395	0.0011	0.0097	0.0573
Alternative		C21			C22			C23	
A1	0.0000	0.0117	0.0454	0.0000	0.0062	0.0289	0.0000	0.0147	0.0616
A2	0.0012	0.0137	0.0488	0.0007	0.0092	0.0352	0.0015	0.0171	0.0661
A3	0.0023	0.0156	0.0520	0.0007	0.0092	0.0352	0.0000	0.0147	0.0616
A4	0.0033	0.0173	0.0520	0.0007	0.0092	0.0352	0.0015	0.0171	0.0662
Alternative		C31			C32			C33	
A1	0.0007	0.0092	0.0401	0.0016	0.0087	0.0446	0.0000	0.0084	0.0400
A2	0.0007	0.0077	0.0366	0.0012	0.0077	0.0415	0.0000	0.0104	0.0443
A3	0.0000	0.0062	0.0330	0.0000	0.0048	0.0319	0.0009	0.0124	0.0487
A4	0.0000	0.0062	0.0330	0.0000	0.0048	0.0319	0.0009	0.0124	0.0487
Alternative		C41			C42			C43	
A1	0.0000	0.0100	0.0533	0.0000	0.0056	0.0300	0.0322	0.1035	0.0838
A2	0.0009	0.0120	0.0586	0.0000	0.0069	0.0332	0.0313	0.1011	0.0856
A3	0.0000	0.0100	0.0533	0.0006	0.0083	0.0366	0.0322	0.1035	0.0876
A4	0.0009	0.0120	0.0586	0.0006	0.0083	0.0366	0.0322	0.1035	0.0876

The deviations of alternative A1 from the criterion weight for criterion C11 were obtained as follows.

$$\tilde{\vartheta}_{11} = \big((1-0,9197)*0,0497 \;\; (1-0,8098)*0,1121 \;\; (1-0,7386)*0,2611\big) = (0,0040 \;\; 0,0213 \;\; 0,0683)$$

All elements of the matrix were calculated similarly.

Table 15
Deviations from criteria weights (Cost)

Alternative		C11			C12			C13	
A1	0.0000	0.0099	0.0514	0.0012	0.0133	0.0434	0.0000	0.0082	0.0499
A2	0.0011	0.0123	0.0571	0.0000	0.0114	0.0404	0.0014	0.0109	0.0573
A3	0.0022	0.0148	0.0629	0.0012	0.0133	0.0434	0.0000	0.0082	0.0499
A4	0.0022	0.0171	0.0683	0.0012	0.0133	0.0434	0.0000	0.0082	0.0499
Alternative		C21			C22			C23	
A1	0.0018	0.0138	0.0520	0.0017	0.0117	0.0352	0.0012	0.0151	0.0662
A2	0.0009	0.0119	0.0478	0.0000	0.0088	0.0327	0.0000	0.0127	0.0604
A3	0.0000	0.0099	0.0434	0.0000	0.0088	0.0327	0.0012	0.0151	0.0662
A4	0.0000	0.0080	0.0393	0.0000	0.0088	0.0327	0.0000	0.0126	0.0602
Alternative		C31			C32			C33	
A1	0.0000	0.0088	0.0373	0.0000	0.0061	0.0351	0.0023	0.0158	0.0487
A2	0.0009	0.0103	0.0373	0.0006	0.0071	0.0376	0.0012	0.0139	0.0487
A3	0.0017	0.0117	0.0401	0.0021	0.0098	0.0446	0.0000	0.0119	0.0453
A4	0.0017	0.0117	0.0401	0.0021	0.0098	0.0446	0.0000	0.0119	0.0453
Alternative		C41			C42			C43	
A1	0.0012	0.0136	0.0586	0.0016	0.0105	0.0366	0.0307	0.1004	0.0911
A2	0.0000	0.0116	0.0545	0.0008	0.0093	0.0366	0.0315	0.1035	0.0886
A3	0.0012	0.0136	0.0586	0.0000	0.0079	0.0339	0.0307	0.1004	0.0861
A4	0.0000	0.0116	0.0545	0.0000	0.0079	0.0339	0.0307	0.1004	0.0838

The deviations of alternative A1 from the criterion weight for criterion C11 were obtained as follows.

$$(\tilde{\vartheta}_{11})' = \big((1-1)*0{,}0497\ \ (1-0{,}9121)*0{,}1121\ \ (1-0{,}8031)*0{,}2611\big) = (0{,}0000\ \ 0{,}0099\ \ 0{,}0514)$$

All elements of the matrix are calculated similarly. The RAWEC method value is obtained by Eq. (19) and given in Table 16.

Table 16
Ranking of Alternative Biomass Sources

	$\tilde{\boldsymbol{\vartheta}}_{ij}$			$(\tilde{\boldsymbol{\vartheta}}_{ij})'$			$\tilde{\boldsymbol{Q}}_i$			$\boldsymbol{Q}_i$	Rank
A1	0.0396	0.2188	0.5928	0.0415	0.2273	0.6056	-0.4600	0.0190	6.9774	1.0989	2
A2	0.0411	0.2237	0.6051	0.0384	0.2236	0.5990	-0.4707	-0.0002	7.0226	1.0919	3
A3	0.0392	0.2210	0.5961	0.0401	0.2254	0.6073	-0.4620	0.0099	7.1591	1.1228	1
A4	0.0413	0.2249	0.6060	0.0378	0.2214	0.5960	-0.4727	-0.0079	7.0131	1.0848	4

The fuzzy value of alternative A1 is obtained as follows.

$$\tilde{Q}_1 = \left(\frac{0{,}0415-0{,}5928}{0{,}5928+0{,}6050}, \frac{0{,}2273-0{,}2188}{0{,}2230+0{,}2188}, \frac{0{,}6056-0{,}0396}{0{,}0415+0{,}0396}\right) = (-0{,}4600\ \ 0{,}0190\ \ 6{,}9774)$$

Using Eq. (5), the crips value of alternative A1 is obtained as follows.

$$Q_i = \frac{-0{,}4600 + 4*0{,}0190 + 6{,}9774}{6} = 1{,}0989$$

According to Table 16, A3 (Animal Biomass) ranks 1st. Animal waste (manure, slaughterhouse residues) is generally efficient in biogas production due to its high methane content. It offers sustainability and low-cost advantages as it is integrated with waste management. Its abundance as a by-product in the agricultural sector increases scalability. A1 (Plant-Based Biomass) ranks 2nd. Sources such as corn, sugarcane, or algae have high energy potential. However, the need for agricultural land and water can increase energy production costs. Seasonal variations and storage challenges may reduce performance. A2 (Forest-Based Biomass) ranks 3rd. Processing wood and forest residues typically requires high energy and time. Due to the slow regeneration rate of forests, it carries sustainability risks. Transportation costs and carbon footprint may be higher compared to other sources. A4 (Urban/Industrial Waste) ranks 4th. The heterogeneous nature of waste (mixture of plastic, food, textiles) reduces processing efficiency. Pre-processing (sorting, cleaning) costs are high. Pollution or toxic substance risks can complicate energy production.

5. Discussion, practical and managerial implications

This study presents a holistic decision-making model that considers economic, environmental, technical, and social criteria in the selection of biomass sources. By evaluating different biomass sources using multi-criteria decision-making (MCDM) methods, it was determined that animal-based biomass (A3) stands out as the most suitable alternative. This is followed by plant-based biomass (A1) and forest-derived biomass (A2). Biomass derived from urban and industrial waste (A4) showed the lowest performance.

The results emphasize the critical importance of balancing both cost and benefit factors in the evaluation of biomass sources. In particular, animal-based biomass sources demonstrated superior performance in critical criteria such as energy efficiency (C31 = 0.0834), ease of storage and transportation (C33 = 0.1083), and employment impact (C41 = 0.0962) compared to other alternatives. Additionally, in terms of environmental sustainability, plant-based and forest-based biomass sources were also found to offer notable contributions in areas such as low carbon footprint and waste management.

5.1. Practical Implications

This study provides various actionable insights for decision-makers in biomass supply chains and energy production processes:

Resource Planning: Animal-based biomass sources should be prioritized in energy investments. However, plant-based and forest-based biomass sources should also be considered as supportive alternatives.

Cost Optimization: To minimize costs in raw material procurement and processing, logistics infrastructure should be strengthened, and the establishment of regional biomass processing facilities should be encouraged.

Environmental Sustainability: Strategic planning should be undertaken to reduce carbon emissions, improve waste management processes, and maintain ecosystem balance through biomass production.

Social Acceptance: Awareness campaigns should be organized to ensure the adoption of biomass projects by local communities, and the economic and environmental benefits of biomass use should be communicated to a wider audience.

5.2. Managerial Implications

For managers and policymakers in the energy sector, the following strategic recommendations are provided for the effective management and sustainable use of biomass resources:

Policy and Incentive Mechanisms: Government policies promoting biomass-based energy production should be made more effective. Financial support programs for renewable energy investments should be increased, and environmental regulations for sustainable biomass management should be strengthened.

Supply Chain Management: Supply chain processes should be optimized for the efficient use of biomass resources, and logistical solutions to reduce transportation and storage costs should be developed.

Regional and Sectoral Strategies: Regional policies for biomass use should be established, and local agricultural and industrial collaborations should be encouraged.

Long-Term Planning: Long-term energy strategies should be developed for the sustainable management of biomass resources and integrated into national energy policies.

In this context, the findings of this study contribute to enabling decision-makers in the renewable energy sector to develop more informed and data-driven strategies. Future research could focus on a more detailed regional and sectoral evaluation of biomass sources and the analysis of the efficiency of different energy conversion technologies.

6. Results, Limitations, and Future Directions

This study provides a comprehensive evaluation of biomass source selection using a F-MCDM approach, aiming to guide decision-makers. The analysis reveals that animal-based biomass sources are more advantageous compared to other alternatives, highlighting the decisive impact of economic and environmental criteria on biomass selection. This offers significant insights for policymakers, energy managers, and industry representatives seeking to enhance the sustainability and efficiency of biomass-based energy production.

The prominence of animal-based biomass sources in criteria such as energy efficiency, ease of storage and transportation, and employment impact underscores the importance of strategic planning in the biomass supply chain. Additionally, plant-based and forest-based biomass sources offer advantages in terms of low carbon footprint and waste management, contributing to environmental sustainability.

6.1. Limitations of the Study

While this study makes significant contributions to the literature, it has certain limitations:

Dataset and Geographic Scope: The analysis was conducted using data from a specific geographic region. Similar analyses in regions with different climate and ecosystem conditions could enhance the generalizability of the results.

Criterion Selection and Weighting: The criteria used in the study were determined based on expert opinions, and their importance may vary across different sectors. For example, carbon footprint may be more critical in the industrial sector, while employment impact may be prioritized in rural areas.

Technological Changes and Dynamic Nature: The efficiency and cost parameters of biomass sources may change over time. As biotechnology, innovative biomass processing methods, and energy conversion technologies advance, the economic and environmental impacts of biomass sources may evolve. Therefore, dynamic decision models are necessary.

MCDM Method and Model Limitations: While fuzzy MCDM methods were used in this study, applying other multi-criteria decision-making approaches such as AHP, TOPSIS, VIKOR, and DEMATEL could yield alternative results and enrich the methodology.

Considering these limitations, future research should incorporate additional elements to achieve more comprehensive and realistic results in biomass source selection.

6.2. Future Directions

To enable more effective, sustainable, and economically efficient use of biomass resources, future studies could focus on the following areas:

Technical and Environmental Perspectives:

Carbon Emissions and Environmental Impacts: The effects of biomass sources on greenhouse gas emissions should be examined in greater detail. Life cycle assessment (LCA) methods should be used to evaluate the long-term environmental sustainability contributions of biomass sources. Biomass Energy Conversion Efficiency: The efficiency of different biomass types in energy conversion technologies such as biogas, biodiesel, pyrolysis, and gasification should be compared.

Economic and Policy Perspectives:

Incentive Mechanisms and Investment Strategies: Government support, financial incentives, and subsidy models should be analyzed in detail to increase the role of biomass sources in energy investments. Supply Chain Optimization: Biomass logistics, storage, and transportation processes should be made more efficient. Integration between local production centers and energy plants should be strengthened to reduce costs.

Social and Industrial Perspectives:

Biomass Use in Alternative Sectors: The potential uses of biomass resources in industries such as agriculture, pharmaceuticals, food, textiles, and chemicals, beyond energy production, should be explored. Social Acceptance of Biomass Projects: Public perceptions of biomass projects should be measured, and community-supported biomass projects should be developed. Awareness of biomass use should be increased through public relations and education programs.

By following these recommendations, future research will contribute to making biomass-based energy systems more effective, efficient, and sustainable. Additionally, these findings serve as an important guide for policymakers, industry representatives, and academics in their decision-making processes.

Conflicts of Interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The datasets generated during and/or analyzed during the current study is available from the corresponding author on reasonable request.

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