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Improving Agricultural Sustainability in Bosnia and Herzegovina through Renewable Energy Integration

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Abstract: With the development of agricultural production, the demand for electricity correspondingly increases. To sustainably meet this demand, renewable energy sources (RESs) can be utilized. This paper explores the application of RES alternatives in agriculture to provide guidelines for enhancing sustainable agricultural practices in Bosnia and Herzegovina. The study employs expert decision making using fuzzy multi-criteria decision-making (MCDM) methods. A decision-making model incorporating nine criteria and six alternatives was developed. Using the direct weight calculation (DiWeC) approach, the findings indicate that economic criteria are prioritized over other sustainability criteria. The results from the fuzzy RAWEC (ranking of alternatives with weights of criteria) method reveal that solar energy has the greatest potential for advancing sustainable agricultural production in Bosnia and Herzegovina. For practical implementation of RES alternatives, active involvement from state institutions and local communities is essential.

Keywords: renewable energy; sustainable energy sources; agricultural production; fuzzy logic; Bosnia and Herzegovina; enhancing sustainable agriculture

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1. Introduction

Electricity is a key factor influencing the growth and development of economic activities globally (Yücenur et al. 2020). The demand for electricity is rising due to advancements in technology, information technology, and population growth (Lange et al. 2020). Consequently, the need for increased electricity production is evident, as consumption has surged by 4.5 times over the past 60 years (Sadeghi and Larimian 2018). Predominantly, fossil fuels are still used for electricity production, adversely impacting the environment by increasing greenhouse gas and CO_2 emissions, which contribute to environmental problems. To mitigate this, efforts are being made to introduce alternative methods for electricity generation (Dluhopolskyi et al. 2023).

These shifts in electricity production have led to a growing focus on sustainable energy sources (RESs). The adoption of RESs reduces the dependency on fossil fuels and minimizes environmental harm (Shakeyev et al. 2023). Utilizing RESs decreases greenhouse gas emissions, mitigating negative effects on the atmosphere and climate change. Many countries have strategic policies promoting the increased use of RESs in practice. However, the implementation of RESs is less common in rural areas compared to urban regions (Clausen and Rudolph 2020), thus prompting a greater focus on rural areas, which hold significant potential for RES-based electricity production.

In rural areas, agriculture is the predominant activity (Rathi 2022). Agricultural production is susceptible to global factors that heighten risks and uncertainty (Darnhofer 2014).

To address these challenges, farmers are increasingly modernizing their operations and incorporating various technical innovations (Andrianarison et al. 2022). This development is crucial for societal advancement (de Janvry and Sadoulet 2020), as agriculture produces raw materials for the food industry and finished products for consumption. In agriculture, electricity is essential for irrigation, soil preparation, fertilization, and livestock breeding (Babatunde et al. 2019). Additionally, electricity is used for water pumping, cooling, and drying agricultural products. The rising demand for these products has made agriculture more energy-intensive (Chen et al. 2020), leading to expansion into less ideal areas. These regions require more fertilizers and irrigation, with water often needing to be pumped from greater depths during dry periods. Consequently, the demand for electricity in agriculture is growing. Increasingly, rural electricity is generated from RESs, helping farmers to reduce their reliance on fossil fuels (Tesfamichael et al. 2020).

Agriculture is a crucial sector with significant potential for sustainable economic growth (Odeim et al. 2015; Zhang and Li 2024). Therefore, it is vital to develop this economic branch. Bosnia and Herzegovina, a developing country, faces a trade deficit due to the import of agricultural products. To foster economic growth, Bosnia and Herzegovina must enhance and focus on its agricultural sector. Sustainable agricultural practices are necessary to preserve resources for future generations. Implementing RESs in agriculture is one viable strategy for achieving this goal. In the presented research, we aim to provide guidelines on which RES alternatives should be utilized to improve sustainable agricultural production and contribute to the country's economic development. Additionally, our aim is to identify the most effective RES alternatives for enhancing agricultural output. The research objectives include evaluating the application of RES in sustainable agricultural production (1), providing guidelines for their selection (2), and applying a methodology based on fuzzy logic and multi-criteria decision-making (MCDM) (3).

Achieving these goals will enhance sustainable agricultural production in Bosnia and Herzegovina and foster economic growth. Furthermore, these objectives contribute to: understanding the application of renewable energy source (RES) alternatives in agricultural production to facilitate improvement (1), ranking RES alternatives based on their significance for agricultural production (2), guiding farmers towards specific RES alternatives for practical implementation (3), and developing a methodology to prioritize RES alternatives by their importance (4).

The remainder of the paper is organized into four main sections, in addition to the introduction. Section 2 details the research methodology, including the methods, procedures, criteria, and alternatives used in the decision-making model. Section 3 presents the implementation of the methodology and decision-making model through the research results. Section 4 discusses the research findings in detail and provides guidelines for improving agricultural production using RES alternatives. Section 5 focuses on the key results and conclusions drawn from the research.

2. Methodology

To achieve the objectives of this paper, a model based on multi-criteria decision making (MCDM) was employed. This model was chosen to evaluate how renewable energy source (RES) alternatives can be applied in agricultural production using defined criteria. To implement this effectively, expert decision making based on linguistic evaluations was utilized. The research process was divided into four phases: an initial phase, data collection, research results, and a discussion of the results phase.

The initial phase involved crucial steps necessary to conduct this research, including the selection of experts and the formation of a model based on the chosen criteria and alternatives. Initially, a list of potential experts in the field of agriculture, specifically those with knowledge of RES alternatives, was compiled. University professors were included to ensure unbiased evolutions. These experts were selected to ensure objectivity in the research, as they were not directly involved in agricultural production but contributed indirectly through various research initiatives, including the study of RES applications in agriculture. Direct agricultural producers were not included in the research because the use of RES alternatives in agricultural production is currently limited to a few isolated cases. Additionally, practical experience among agricultural producers with RES alternatives was generally restricted to one or two options, and they did not have exposure to a broader range of alternatives. Out of 12 experts contacted, eight agreed to participate in the study.

After identifying the experts, the Delphi technique was employed to determine the criteria and alternatives for this research, which comprised a range of aspects including economic, technical, ecological, and social factors. In this process, extended sustainability criteria were integrated with technical considerations, as economic, ecological, and social criteria form the foundation of sustainability (Saqlain 2023). Furthermore, achieving economic growth requires the application of sustainability principles (Škuflić et al. 2024). By defining the criteria in this manner, an effort was made to incorporate sustainability into the selection process for RES alternatives and with their selection, the focus was on options that can be utilized in agricultural production. Consequently, six RES alternatives were chosen. These alternatives included natural resources such as solar, water, and wind energy (Rahman et al. 2022), while some alternatives utilized waste from agricultural production or agricultural products themselves (Elahi et al. 2022; Rimantho et al. 2024). These selected alternatives leveraged both natural and agricultural resources to produce electricity. Based on the findings from this technique, nine criteria were selected for evaluating RES alternatives, as shown in Table 1. These criteria included extended sustainability criteria alongside technical criteria. Criteria C1 and C3 refer to economic criteria, criteria C2 and C6 refer to ecological criteria, criterion C5 refers to social criteria, while criteria C4, C7, C8, and C9 refer to technical criteria. By applying these criteria, it can be seen that there was a greater focus on technical criteria than on sustainable criteria.

Table 1. Criteria for evaluating RES alternatives.

Id	Criteria	Description	References
C1	Investment costs	Financial expenses for implementing the RES alternative	Razmjoo et al. (2021), Karatop et al. (2021), Bilgili et al. (2022)
C2	Impact on ecology	Assessment of the RES alternative's impact on the environment	Karatop et al. (2021), Bilgili et al. (2022), Taylan et al. (2020)
C3	Return on investment time	Time required to recover the initial investment costs	Razmjoo et al. (2021), Alkan and Albayrak (2020), Bilgili et al. (2022)
C4	System efficiency	Potential for maximum use of RES with minimal costs	Bilgili et al. (2022), Taylan et al. (2020)
C5	User friendliness	Ease of use and management by end users	Karatop et al. (2021), Taylan et al. (2020)
C6	Land requirement	Total land area required to implement the RES alternative	Karatop et al. (2021), Alkan and Albayrak (2020), Bilgili et al. (2022)
C7	Integration with other systems	Ability to interconnect different RES alternatives	Bilgili et al. (2022), Taylan et al. (2020)
C8	Maintenance costs	Expenses for maintenance, repairs, and servicing of the RES alternative	Razmjoo et al. (2021), Bilgili et al. (2022)
C9	Lifetime	Operational lifespan of the RES alternatives	Alkan and Albayrak (2020), Taylan et al. (2020)

For the evaluation of RES alternatives, six options were selected due to their applicability in the agriculture of Bosnia and Herzegovina. These alternatives were:

- Solar energy (RES 1): utilizes sunlight to generate electricity using solar panels.

- Wind energy (RES 2): harnesses the kinetic energy of the wind to produce electricity via wind turbines.
- Biomass (RES 3): converts organic material from plants or agricultural waste into hot water and electricity.
- Biogas (RES 4): produced by anaerobic decomposition of organic plant materials or waste to generate gas.
- Geo energy (RES 5): uses geothermal heat from the Earth's interior to produce electricity and hot water.
- Hydropower (RES 6): generates electricity from the kinetic energy of watercourses, typically using dams.

Once the criteria and alternatives were chosen, they formed the basis of the decision-making model for further research.

The second phase involved data collection based on the defined research model. A questionnaire was developed consisting of two parts. The first part focused on evaluating the importance of each criterion according to the experts. The second part assessed the selected RES alternatives against these criteria. To facilitate the evaluation of criteria and alternatives, a linguistic rating scale was created (Table 2). This scale, which had seven levels, was used for both the criteria and alternative evaluations. However, in order for this linguistic scale of values to be applied for the calculation of the importance of the criteria and the ranking of alternatives, it was necessary to assign them certain values using a defined membership function (Table 2). The membership function was formed in such a way that there were three values of fuzzy numbers, the first of which could not be greater than the second value, and the second value could not be greater than the third value. Using this rule, a membership function was formed in this paper that indicated the value of the fuzzy numbers. The questionnaire was then distributed to the selected experts for completion. Upon receiving the completed questionnaires, the responses were processed and prepared for analysis.

Table 2. Linguistic values and corresponding fuzzy numbers.

Linguistic Values	Fuzzy Numbers
Absolutely bad (AB)	(0, 0, 1)
Very bad (VB)	(0, 1, 3)
Bad (B)	(1, 3, 5)
Acceptable (A)	(3, 5, 7)
Good (G)	(5, 7, 9)
Very good (VG)	(7, 9, 10)
Absolutely good (AG)	(9, 10, 10)

The third phase involved the analysis of the research results. After collecting and processing the filled questionnaires, the results were calculated. Since the ratings were expressed in linguistic terms, it was necessary to convert these into numerical values for further analysis. This conversion was performed using fuzzy logic, which allowed the transformation of linguistic values into corresponding fuzzy numbers through the application of a membership function (Sarfraz and Azeem 2024). The membership function assigned a fuzzy value to each linguistic term, converting it into a fuzzy number (Lazarashouri and Najafi 2024). Once this transformation was complete, a multi-criteria decision-making (MCDM) method was used to analyze the data. Although fuzzy logic was not the main focus of this research, it served as an essential tool for obtaining the results. For this study, the direct weight calculation (DiWeC) method was used to calculate the importance of criteria, and the ranking of alternatives with weights of criterion (RAWEC) method was employed to select the RES alternatives with the highest applicability in agriculture.

2.1. Application of the DiWeC Method

The DiWeC method was used to calculate weights directly based on the experts' evaluations. It involved the following steps:

Step 1. Evaluation of criteria importance using linguistic ratings. In this step, experts assess the importance of each criterion using linguistic terms.

Step 2. Transformation of linguistic ratings into fuzzy numbers. In this step, linguistic values are transformed into fuzzy numbers using the defined membership function (Table 2), where "l" represents the first, "m" the second, and "u" the third fuzzy number. The transformation formula is as follows:

$$\tilde{x}_{ij} = \left(x_{ij}^{l}, x_{ij}^{m}, x_{ij}^{u}\right) \quad (1)$$

Step 3. Aggregation of ratings by criterion. This step is designed to aggregate the weights for each criterion. This involves summing up the fuzzy numbers assigned by each expert to a given criterion, thereby ensuring equal weightage for all experts. The formula for aggregation is as follows:

$$\tilde{v}_j = \sum_{j=1}^{n} \tilde{x}_j \quad (2)$$

Step 4. Calculation of criteria weights. Finally, the weights for each criterion are calculated by dividing the aggregate fuzzy values by the total aggregate weights. The formula for calculating weights is as follows:

$$\tilde{w}_j = \frac{v_i^l}{\sum_{j=1}^{n} v_j^u}, \frac{v_j^m}{\sum_{j=1}^{n} v_j^m}, \frac{v_j^u}{\sum_{j=1}^{n} v_j^l} \quad (3)$$

By applying these steps, the final weights of the criteria are formed. To obtain an assessment of the significance of each alternative, the steps of the fuzzy RAWEC method are applied.

2.2. Step-by-Step Application of the Fuzzy RAWEC Method

The RAWEC method, as suggested by its name, calculates the deviation of the alternatives relative to the weight of the criteria (Petrović et al. 2024; Trung et al. 2024). The fuzzy RAWEC method modifies the steps of the classic RAWEC method (Puška et al. 2024) by incorporating fuzzy logic. These steps are as follows:

Step 1. Formation of the initial decision matrix. In this step, the alternatives are evaluated using linguistic values according to the observed criteria. This forms the initial decision-making matrix in linguistic terms. The matrix provides a qualitative assessment of each alternative based on the criteria set earlier.

Step 2. Transformation of linguistic values into fuzzy numbers. The linguistic values from the initial decision matrix are then transformed into fuzzy numbers using a membership function. This step converts the qualitative assessments into quantitative fuzzy values that can be used for further analysis.

Step 3. Normalization of the fuzzy decision matrix. The specificity of the RAWEC method is that it involves two types of normalization: maximum normalization for benefit criteria and minimum normalization for cost criteria.

Maximum normalization is expressed as follows:

$$n_{ij} = \frac{x_{ij}^l}{\max x_j^u}, \frac{x_{ij}^m}{\max x_j^u}, \frac{x_{ij}^u}{\max x_j^u};\ \text{for benefit criteria} \quad (4)$$

$$n_{ij} = \frac{\min x_j^l}{x_{ij}^u}, \frac{\min x_j^l}{x_{ij}^m}, \frac{\min x_j^l}{x_{ij}^l};\ \text{for cost criteria} \quad (5)$$

Minimum normalization is expressed as follows:

$$n\prime_{ij} = \frac{\min x_j^l}{x_{ij}^u}, \frac{\min x_j^l}{x_{ij}^m}, \frac{\min x_j^l}{x_{ij}^l};\ \text{for benefit criteria} \tag{6}$$

$$n\prime_{ij} = \frac{x_{ij}^l}{\max x_j^u}, \frac{x_{ij}^m}{\max x_j^u}, \frac{x_{ij}^u}{\max x_j^u};\ \text{for cost criteria} \tag{7}$$

Here, $x_{j\ min}$ represents the minimum value of a particular criterion, and $x_{j\ max}$ represents the maximum value of a particular criterion.

Step 4. Calculating the deviation from the criterion weight. Using the weights obtained from the DiWeC method, the deviation from these weights is calculated. This involves summing the deviations for all alternative values, as follows:

$$\tilde{v}_j = \sum_{i=1}^{n} \tilde{w}_j \cdot \left(1 - \tilde{n}_{ij}\right) \tag{8}$$

$$\tilde{v}\prime_j = \sum_{i=1}^{n} \tilde{w}_j \cdot \left(1 - \tilde{n}\prime_{ij}\right) \tag{9}$$

where $\tilde{w}_j$ represents the weight of the criterion.

Step 5. Defuzzification of the deviation from the criterion weight. This step transforms the fuzzy numbers into crisp numbers, making them easier to interpret and use in further calculations, as follows:

$$v_{ij\ def} = \frac{v_i^l + 4v_i^m + v_i^u}{6} \tag{10}$$

$$v\prime_{ij\ def} = \frac{v\prime_i^l + 4v\prime_i^m + v\prime_i^u}{6} \tag{11}$$

Step 6. Calculating the value of the RAWEC method. In this step, the final values of the alternatives are calculated, and a ranking order is formed, as follows:

$$Q_i = \frac{v'_{ij} - v_{ij}}{v'_{ij} + v_{ij}} \tag{12}$$

The best alternative is the one with a value closest to one (1), indicating the highest suitability, while the worst alternative is the one with a value closest to minus one (−1). Based on these values, a ranking of alternatives is established.

After obtaining the alternative rankings, which indicated the suitability of each alternative for agricultural production based on the experts' evaluations, a sensitivity analysis was performed. This analysis examined the impact of each criterion on the final ranking of alternatives (Krstić and Tadić 2023). By identifying which criteria significantly influenced the ranking, guidelines can be provided on how to improve the ranking of certain alternatives.

The final stage of this research was the discussion of the results. Based on the conducted analyses, the results obtained from the DiWeC and RAWEC methods were explained in detail. The sensitivity analysis provided additional insight, highlighting the importance of various criteria and their impact on the rankings. This phase involved a thorough explanation of why certain criteria were deemed more important than others and why specific alternatives were preferred for agricultural applications in Bosnia and Herzegovina. Each result was analyzed to provide a comprehensive understanding of the findings and their implications for future research and practical applications in the field of renewable energy sources (RESs) in agriculture.

3. Results

When choosing which RES alternative would yield the best results in agricultural production, the first step was to determine the importance of each criterion. This importance was calculated using the DiWeC approach. The initial step in this approach involved experts evaluating the significance of each criterion. These evaluations were provided in the form of linguistic values, which were then used to form the initial decision-making matrix (Table 3).

Table 3. Initial decision matrix for criteria.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
Expert 1 (E1)	AG	AG	AG	VB	A	G	B	G	G
Expert 2 (E2)	VG	VG	VG	G	G	G	G	VG	VG
Expert 3 (E3)	AG	AG	AG	VG	VG	AG	G	AG	VG
Expert 4 (E4)	AG	AG	AG	G	A	A	A	AG	AG
Expert 5 (E5)	VG	AG	VG	G	A	B	A	AG	AG
Expert 6 (E6)	AG	AG	G	G	A	A	A	AG	AG
Expert 7 (E7)	AG	G	VG	A	A	A	B	AG	AG
Expert 8 (E8)	AG	VB	G	VB	AB	VG	A	B	AB

The linguistic values obtained were first transformed using the membership function, assigning each linguistic value a corresponding fuzzy number. For example, the linguistic value "Good" was transformed into a fuzzy number (7, 9, 10). By applying the defined membership function (Table 2), a fuzzy decision matrix was created (Table 4).

Table 4. Initial fuzzy decision matrix for criteria.

	C1	C2	C3	C4	C5	...	C9
E1	(9, 10, 10)	(9, 10, 10)	(9, 10, 10)	(0, 1, 3)	(3, 5, 7)	...	(5, 7, 9)
E2	(7, 9, 10)	(7, 9, 10)	(7, 9, 10)	(5, 7, 9)	(5, 7, 9)	...	(7, 9, 10)
E3	(9, 10, 10)	(9, 10, 10)	(9, 10, 10)	(7, 9, 10)	(7, 9, 10)	...	(7, 9, 10)
E4	(9, 10, 10)	(9, 10, 10)	(9, 10, 10)	(5, 7, 9)	(3, 5, 7)	...	(9, 10, 10)
E5	(7, 9, 10)	(9, 10, 10)	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)	...	(9, 10, 10)
E6	(9, 10, 10)	(9, 10, 10)	(5, 7, 9)	(5, 7, 9)	(3, 5, 7)	...	(9, 10, 10)
E7	(9, 10, 10)	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)	(3, 5, 7)	...	(9, 10, 10)
E8	(9, 10, 10)	(0, 1, 3)	(5, 7, 9)	(0, 1, 3)	(0, 0, 1)	...	(0, 0, 1)
Sum	(68, 78, 80)	(57, 67, 72)	(58, 71, 78)	(30, 44, 59)	(27, 41, 55)	...	(55, 65, 70)

The next step in this approach was to calculate the sum of the rating values (Table 4). Following this, the sum of all ratings for individual fuzzy numbers was computed. Finally, the total values were divided from that amount to form the final ranking order. For example, the calculation for criterion C1 (Investment Costs) was performed as follows:

$$\tilde{w}_1 = \frac{68}{608} = 0.112, \frac{78}{526} = 0.148, \frac{80}{413} = 0.194$$

Applying this calculation to all criteria, fuzzy criteria weights were derived, representing the importance of these criteria (Table 5). The results indicated that, according to the evaluations, the most important criterion was C1 (Investment Costs) for evaluating RES alternatives, followed by criterion C3 (Return on investment time). Conversely, the least important criterion was C7 (Integration with other systems). This suggested that the experts considered investment costs to be more crucial than other criteria when selecting RES alternatives.

Table 5. Criterion importance values.

C	$\widetilde{w}_j$
C1	(0.112, 0.148, 0.194)
C2	(0.094, 0.127, 0.174)
C3	(0.095, 0.135, 0.189)
C4	(0.049, 0.084, 0.143)
C5	(0.044, 0.078, 0.133)
C6	(0.059, 0.097, 0.155)
C7	(0.039, 0.076, 0.136)
C8	(0.095, 0.131, 0.179)
C9	(0.090, 0.124, 0.169)

Once the importance of the criteria was calculated, the significance of individual RES alternatives for agricultural production was determined based on the experts' opinions (Table 6). Using the same steps as in the DiWeC approach, the alternatives were first evaluated according to criteria based on linguistic evaluations. These linguistic values were then transformed into fuzzy numbers in the same manner. Subsequently, a summary fuzzy decision matrix was formed by calculating the average values for all alternatives across the observed criteria. This ensured that each expert's opinion was weighted equally in the decision-making process.

Table 6. Initial decision matrix for alternatives.

E1	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
RES 1	A	AG	VG	VG	VG	AG	AG	VB	AG
RES 2	B	VG	VG	AG	VG	B	B	AB	G
RES 3	VB	VB	G	AG	AG	A	G	B	AG
RES 4	A	B	A	B	A	VB	G	G	B
RES 5	B	AG	AG	A	VG	AB	B	AB	VG
RES 6	A	AG	AG	G	VG	AB	B	B	VG
E2	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
RES 1	G	G	VG	AG	G	A	VG	VB	AG
RES 2	G	A	VG	G	G	A	VG	B	VG
RES 3	A	B	A	B	A	B	G	A	G
RES 4	A	B	A	B	A	B	G	A	G
RES 5	A	B	B	B	A	B	G	A	G
RES 6	B	B	G	G	A	A	G	B	VG
E8	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
RES 1	G	VG	VG	AG	VG	VG	AG	VG	AG
RES 2	A	VG	VG	VG	VG	G	A	VG	AG
RES 3	A	B	G	G	A	A	AG	G	AG
RES 4	G	G	A	G	G	AG	AG	G	AG
RES 5	B	A	A	A	VG	B	AG	A	A
RES 6	AB	VB	VG	VB	B	AB	A	B	VB

After forming the fuzzy decision matrix, normalization for the fuzzy RAWEC (ranking of alternatives with weights of criteria) method was calculated. Given the specific linguistic scale, all criteria were considered as benefit criteria, so normalization for benefit criteria was applied. For example, normalization for criterion C1 and alternative RES 1 (Solar Energy) was calculated as follows:

$$n_{11} = \frac{4.75}{8.38} = 0.57, \frac{6.63}{8.38} = 0.79, \frac{8.38}{8.38} = 1.00$$

$$n\prime_{11} = \frac{4.63}{8.38} = 0.55, \frac{4.63}{6.63} = 0.70, \frac{4.63}{4.75} = 0.97$$

Normalization ensured that the maximum value of the normalized data was one (1). This was crucial when applying the fuzzy RAWEC method, as it aligned with the method's requirement that the maximum value of normalized data should be equal to one. This was particularly important for calculating deviations from the criterion weights. The calculation of deviations for the same criterion and alternative is demonstrated as follows:

$$\widetilde{d}_{11} = 0.11{\cdot}(1-1) = 0.00,\ 0.15{\cdot}(1-0.79) = 0.06,\ 0.19{\cdot}(1-0.57) = 0.08$$

$$\widetilde{d\prime}_{11} = 0.11{\cdot}(1-0.97) = 0.00,\ 0.15{\cdot}(1-0.70) = 0.04,\ 0.19{\cdot}(1-0.55) = 0.09$$

Summing the deviations was the fourth step of this method. Following this, defuzzification was performed (expressions 10 and 11), and the final value of this method was calculated (Table 7). For instance, the final value of the fuzzy RAWEC method for alternative A1 (Solar Energy) was computed as follows:

$$Q_1 = \frac{0.458 - 0.264}{0.458 + 0.264} = 0.269$$

Table 7. Results of the fuzzy RAWEC method.

RES	$\widetilde{v}_j$	v_j	$\widetilde{v}'_j$	v'_j	Q_i	Rank
RES 1	(0.01, 0.29, 0.42)	0.264	(0.20, 0.45, 0.75)	0.458	0.269	1
RES 2	(0.04, 0.37, 0.55)	0.346	(0.16, 0.41, 0.72)	0.417	0.093	2
RES 3	(0.04, 0.37, 0.55)	0.346	(0.15, 0.40, 0.72)	0.413	0.088	3
RES 4	(0.07, 0.44, 0.65)	0.416	(0.08, 0.35, 0.68)	0.361	−0.070	5
RES 5	(0.09, 0.43, 0.64)	0.410	(0.09, 0.35, 0.66)	0.358	−0.068	4
RES 6	(0.10, 0.46, 0.68)	0.436	(0.07, 0.33, 0.65)	0.339	−0.125	6

By applying this calculation to other alternatives, the results indicated that RES 1 (Solar Energy) had the best indicators, followed by RES 2 (Wind Energy), while RES 6 (Hydropower) had the worst indicators.

To understand how specific criteria influenced this ranking, a sensitivity analysis was conducted. This analysis can be performed in various ways, either by using the existing weights of the criteria or by considering different scenarios (Radovanović et al. 2024). Some sensitivity analyses alter the importance of only one criterion, while others change the importance of all criteria (Biswas et al. 2023). In this research, the sensitivity analysis was carried out by giving greater importance to each criterion in turn compared to the other criteria (Jokić et al. 2021; Tešić et al. 2024). This was achieved by increasing the importance of an individual criterion by two, three, four, and five times, while simultaneously decreasing the importance of the other criteria by the same factor (Sarfraz 2024). Since each criterion changed four times and there were nine criteria, a total of 36 scenarios were formed.

The results of the sensitivity analysis (Figure 1) demonstrated that individual criteria significantly influenced the choice of RES alternative for agricultural production. Observing these results, it was evident that in most scenarios, alternative RES 1 (solar energy) consistently yielded the best results. However, when the importance of criteria C1 (investment costs), C3 (return on investment time), C5 (user friendliness), and C8 (maintenance costs) was altered, this alternative did not always rank as the best. This indicated that, according to the experts, there were other alternatives that performed better under these specific criteria adjustments. To enhance the value of the experts' evaluations for alternative RES 1, it was crucial to first focus on reducing the investment costs.

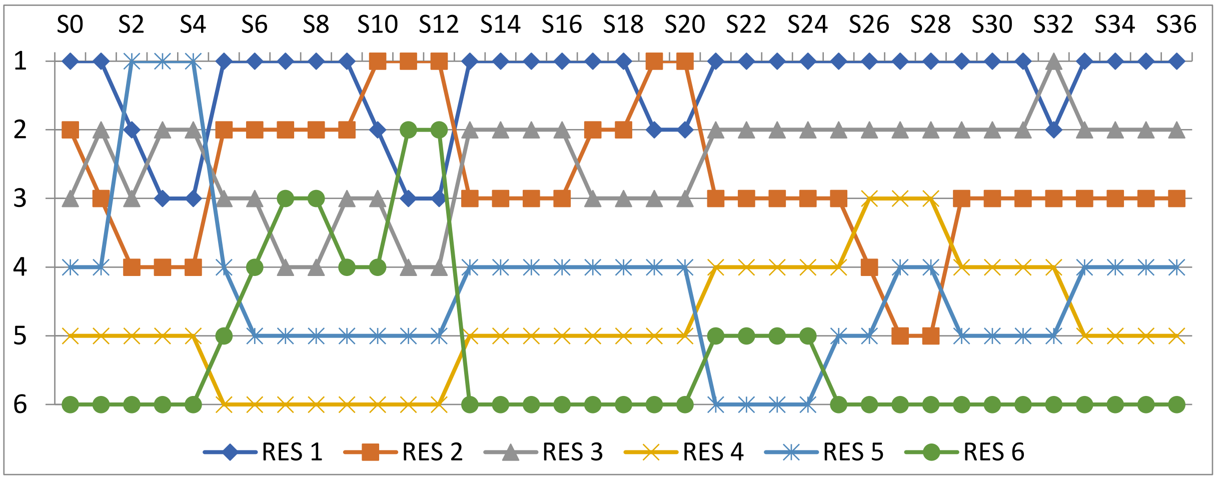

Figure 1. Results of the sensitivity analysis.

Making solar panels more affordable and improving their utilization can significantly enhance their competitiveness. Additionally, it is essential to develop new systems for energy storage, as solar energy generation is dependent on sunlight and is only feasible during daylight hours. At night, solar panels do not produce electricity due to the absence of sunlight. Reducing investment costs will also decrease the payback time, as a lower initial investment will lead to a quicker return on investment, thus shortening the payback period. With adjustments to these two criteria (C1 and C3), there was a marked trend toward improving the ranking of alternative RES 1. Regarding criteria C5 and C8, alternative RES 1 ranked second when the importance of these criteria was increased by four or five times, respectively. By examining other alternatives in a similar manner, it became clear which criteria favored each alternative and which did not. The criteria that were advantageous should maintain their high values, while those that resulted in lower scores should be improved, as illustrated in the case of alternative RES 1. Based on these results (Figure 1), it could be concluded that, in certain locations within Bosnia and Herzegovina, alternative RES options might be more suitable for agricultural production. This is because different locations offer varying conditions, and certain criteria might be more critical in these specific contexts than in the general scenario across Bosnia and Herzegovina. Therefore, it is essential to tailor the use of RESs for agricultural production to the conditions of each specific location.

4. Discussion

The tendency in every production sector is to introduce innovations through advanced technologies. These technologies are increasingly being implemented in agricultural production to improve product quality (Gzar et al. 2022). The introduction of smart systems in agriculture has led to a growing demand for electricity (Goel et al. 2021). Additionally, there is a strong trend toward adopting sustainable agricultural practices (Khan et al. 2021). Consequently, this research focused on exploring the use of RES alternatives in agriculture. By integrating these alternatives in a sustainable manner, electricity can be generated to meet the rising demands in the agricultural sector. The electricity produced from RES alternatives will facilitate the modernization of agricultural production, enabling the adoption of more innovations and thus enhancing and improving agricultural output.

In recent years, there has been a significant increase in the construction of RES-based power plants in Bosnia and Herzegovina. Traditionally, hydropower has dominated electricity production in the country (Sher et al. 2024). However, the use of other RES alternatives is becoming more prevalent. The adoption of RES alternatives in agriculture, however, remains limited and their usage is still negligible in Bosnia and Herzegovina. This neglect of RES application in rural areas is also present in other countries (Woldeyohannes et al. 2016). That is why it is necessary to pay more attention and invest in RESs so that the population of these settlements can access electricity that does not pollute the environment. In this way, RESs would be increasingly applied in rural areas (Klepacka 2019) and in agricultural production, which is the primary production in these areas.

In this paper, the use of RES alternatives in agricultural production was analyzed. The alternatives were evaluated according to extended sustainability criteria to determine which of these alternatives was most suitable for agricultural production, with a note that extended sustainability criteria combined with technical criteria are common for the evaluation of RES alternatives (Campos-Guzmán et al. 2019). Applying the DiWeC approach in this paper revealed that according to the experts' evaluations, the most critical criteria were investment costs and the investment return time. Thus, economic criteria were given greater importance compared to other sustainability criteria. Similar results were obtained by Nitsenko et al. (2018) in their research, where they observed the efficiency of energy transformation in RES. However, in their research, Elena Arce et al. (2015) showed that technological criteria were more important than sustainable ones when evaluating RES alternatives in terms of CO2 emissions. This is understandable because, for practical implementation, it is crucial to secure funding and assess the return on investment. Murphy et al. (2022) noted that this is a key factor for investments in electricity. This is because it is very important for the investor to know when they will recover their initial investment costs. If the payback time is shorter, the RES alternative is more attractive for investment. Following these economic criteria, other criteria were also deemed significant based on the experts' evaluations.

Using the fuzzy RAWEC method, results were obtained that showed that alternative RES 1 (solar energy), which harnesses sunlight for electricity production, achieved the highest ratings according to the experts' assessments. This alternative performed well because the adoption of solar energy through the installation of solar panels is currently expanding (Li and Huang 2020). Solar panels can be used individually or as part of larger solar power plants (He et al. 2020). The number of sunny days, which reaches up to 270 in Bosnia and Herzegovina, enables the large-scale application of solar panels in electricity production (Džafić and Durmić 2023). In addition, lowland areas with higher agricultural production in Bosnia and Herzegovina have a higher number of sunny days compared to mountainous areas, which have fewer sunny days and lower agricultural production (Elqadhi et al. 2024). The flexibility of solar panels allows for individual installation on farms, where they can power water pumps, electronic devices for smart agricultural production, and various other equipment. During the peak agricultural production period from spring to autumn, there are usually more sunny days, maximizing the potential for electricity generation from this alternative (Škrbić et al. 2020).

Following solar energy, the second highest-rated alternative was wind energy. This alternative utilizes various sizes of wind turbines to generate electricity. The size and cost of these turbines can vary significantly (Soares-Ramos et al. 2020). Unlike solar energy, wind energy can be harnessed whenever there is sufficient wind to turn the turbine blades. Consequently, this RES alternative is most suitable for regions with consistent wind patterns to ensure continuous electricity production. However, this also presents a challenge for the widespread application of this alternative because it requires specific locations with adequate wind conditions, thereby limiting its flexibility. A similar limitation applies to the lowest-rated alternative, which was hydro energy. To generate electricity from hydro energy, a water source with sufficient hydro potential is required, typically necessitating the construction of hydro-electric power plants. However, this means that the agricultural property must possess such potential, and environmental approvals are needed to construct hydropower plants. Furthermore, substantial financial investments are required to implement this alternative.

5. Conclusions

This research, through the application of expert decision making and the fuzzy MCDM method, determined the importance of various criteria and ranked the RES alternatives. The results of the DiWeC approach indicated that economic factors play a more significant role than other sustainability criteria. Using the fuzzy RAWEC method, the findings revealed that the most favorable RES alternative for the development of agricultural production is RES 1, which involves the use of solar energy. Therefore, the practical application of RES alternatives should be tailored to specific regions, with localized research to identify the most suitable options. Different RES alternatives may yield better results than those presented in this study, especially when considering the unique climatic and geographical characteristics of particular areas within Bosnia and Herzegovina.

For the effective implementation of RES alternatives in agricultural production, state or local authorities must provide various incentives for their adoption. Without such support, farmers are less likely to choose these alternatives for electricity production. Thus, it is essential to encourage agricultural producers with institutional backing to first adopt smart approaches in agriculture, followed by the integration of RES alternatives. This comprehensive approach is crucial for enhancing agricultural production in Bosnia and Herzegovina. Many countries have implemented certain actions to use RES alternatives in agricultural production and thus improve production. To improve agricultural production using RES alternatives, Bosnia and Herzegovina should adopt the good practices from these countries.

Despite the contributions of this research, it also has certain limitations regarding the selection of experts, criteria, alternatives, methods, and other aspects that may be considered constraints. However, this study is among the first to explore the potential of integrating RES alternatives into agricultural production to enhance its efficiency and sustainability. Future research should aim to expand this approach by involving different experts to assess whether their evaluations align, selecting additional criteria for evaluating alternatives, and tailoring these criteria to specific agricultural activities. It is possible that some RES alternatives may be more pertinent than others for different agricultural operations. Moreover, as scientific advancements continue, the development of new RES alternatives is likely, and these should be incorporated into future research.

The findings from this research provide certain guidelines for further studies. Additionally, the research demonstrated that the decision-making model used here is applicable to similar and other problems involving decision making with multiple criteria and alternatives. This approach can be further developed and refined to introduce new methodologies and enhance decision-making processes in various contexts. Finally, it should be mentioned that financial resources are the biggest obstacle to the implementation of RES alternatives in agricultural production in Bosnia and Herzegovina. Therefore, it is necessary for the state to stimulate the use of RES alternatives and provide certain incentives to farmers so that they invest more in the production of electricity from RES alternatives.

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