

## Article

# Integrating Fuzzy Rough Sets with LMAW and MABAC for Green Supplier Selection in Agribusiness

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**Abstract:** The evolving customer demands have significantly influenced the operational landscape of agricultural companies, including the transformation of their supply chains. As a response, many organizations are increasingly adopting green supply chain practices. This paper focuses on the initial step of selecting a green supplier, using the case study of the Semberka Company. The objective is to align the company with customer requirements and market trends. Expert decision making, grounded in linguistic values, was employed to facilitate the transformation of these values into fuzzy numbers and subsequently derive rough number boundaries. Ten economic-environmental criteria were identified, and six suppliers were evaluated against these criteria. The fuzzy rough LMAW (Logarithm Methodology of Additive Weights) method was employed to determine the criteria weights, with emphasis placed on the quality criterion. The fuzzy rough MABAC (Multi-Attributive Border Approximation Area Comparison) method was then utilized to rank the suppliers and identify the top performer. The validity of the results was established through validation techniques and sensitivity analysis. This research contributes a novel approach to green supplier selection, employing the powerful tool of fuzzy rough sets. The flexible nature of this approach suggests its potential application in future investigations. The limitation of this study is more complicated calculations for the decision maker. However, this approach is adapted to human thinking and minimizes ambiguity and uncertainty in decision making, and in future research, it is necessary to combine this approach with other methods of multi-criteria analysis.

**Keywords:** green supplier; agribusiness; sustainable selection; fuzzy rough sets; LMAW; MABAC

**MSC:** 90C29



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## 1. Introduction

In recent years, there has been a growing emphasis on sustainability in various industries, including agriculture and agribusiness. As concerns about environmental degradation, resource scarcity, and social responsibility continue to escalate [1–3], the need for sustainable practices in supplier selection becomes increasingly crucial [4–6]. Optimizing the selection of green suppliers has become a primary objective for organizations operating in the agricultural sector [7], as it allows them to align their supply chain practices with sustainable development goals [8].

The concept of sustainable sourcing has gained significant attention in recent years due to its potential to mitigate the adverse environmental and social impacts associated

with traditional supply chain practices. By adopting sustainable sourcing strategies, organizations can not only reduce their ecological footprint but also contribute to the well-being of local communities and enhance their brand reputation [9]. Therefore, it is crucial to analyze and understand the supplier selection strategies employed in agribusiness to foster sustainable sourcing.

In this study, we propose the integration of a fuzzy rough set with the Logarithm Methodology of Additive Weights (LMAW) and the Multi-attributive Border Approximation Area Comparison (MABAC) as a novel approach to sustainable supplier selection in the agricultural sector. Fuzzy rough sets provide a robust framework for handling imprecise and uncertain data, allowing for a more realistic representation of the complexities and uncertainties inherent in supplier selection processes [10]. The LMAW is employed to assign weights to the evaluation criteria based on their relative importance, capturing the additive nature of decision making [11,12]. Furthermore, MABAC provides a comparative analysis that allows for the ranking and comparison of potential suppliers based on their performance across various criteria [13].

The integration of these methods aims to overcome the limitations of traditional supplier selection approaches, which often fail to consider the multi-dimensional nature of sustainability criteria and the inherent uncertainties in decision making. By incorporating a fuzzy rough set, the LMAW, and MABAC, we can enhance the accuracy and effectiveness of supplier selection, ultimately promoting sustainability in agribusiness.

This research will contribute to the existing body of knowledge by providing a comprehensive evaluation framework that addresses the unique challenges and requirements of sustainable supplier selection in agribusiness. The findings will not only benefit agricultural organizations seeking to optimize their supplier selection processes but also contribute to the broader goal of fostering sustainability within the industry.

The remaining part of this paper is structured as follows: Section 2 provides a literature review on green supplier selection in agribusiness, emphasizing the significance of sustainability criteria and the limitations of traditional approaches. Section 3 outlines the preliminary details of the research methodology. This section elaborates on the integration of fuzzy rough sets, LMAW, and MABAC. Section 4 presents a case study conducted to evaluate potential suppliers. Section 5 presents the application of selected methods to the case study and obtaining results of which supplier best helps achieve the set goals. In addition, validation and sensitivity analysis of the findings is conducted in this section. A discussion of these findings is in Section 6. Finally, Section 7 concludes the paper by summarizing the key findings, discussing their implications, and suggesting directions for future research.

## 2. Literature Review

When conducting the literature review, keywords were first defined, i.e., sustainability, economic–ecological criteria, and the choice of suppliers. These keywords were applied using Google Scholar and certain papers were found that were used for the literature review. Papers that did not use these keywords in their abstract were excluded.

Sustainability criteria have garnered significant attention in the agricultural sector, reflecting the growing awareness among organizations of the urgent need to align their supply chain practices with sustainable development goals [14–16]. These criteria encompass environmental, social, and economic dimensions [17–19], with the overarching objective of reducing ecological footprints [20], ensuring social responsibility [21], and maintaining economic viability [22]. The integration of sustainability criteria into supplier selection processes represents a fundamental shift in the way organizations approach sourcing strategies [23], placing emphasis on responsible and sustainable practices in agribusiness.

Traditionally, supplier selection in the agricultural sector has been primarily driven by economic considerations, such as cost, quality, and delivery performance [24–26]. While these factors are undeniably important, they tend to overshadow broader sustainability considerations. The exclusive focus on economic metrics can inadvertently neglect

vital environmental and social aspects, leading to adverse environmental impacts, reputational risks, and strained stakeholder relationships [27–29]. Furthermore, the subjective nature of qualitative assessments employed in traditional approaches introduces biases and inconsistencies, making it challenging to objectively evaluate suppliers' sustainability performance [30–33].

In recent years, a growing body of research [34–40] has recognized the need to incorporate ecological criteria into green supplier selection in agribusiness. This shift reflects an increased understanding of the environmental challenges faced by the sector and the necessity of integrating environmental considerations into sourcing decisions. Ecological criteria provide a comprehensive framework for assessing suppliers' environmental impact, resource conservation efforts, and compliance with environmental regulations and standards [41–43]. These criteria encompass a wide range of factors, including energy efficiency, waste management, carbon footprint, water usage, and biodiversity conservation [44–50]. Given the substantial reliance of the agricultural sector on natural resources and its potential to impact ecosystems, the inclusion of ecological criteria is crucial for promoting sustainable practices, reducing environmental degradation, and supporting biodiversity conservation efforts [51].

The literature on green supplier selection in agribusiness underscores the increasing importance of sustainability criteria and the limitations of traditional approaches that primarily prioritize economic factors. The inclusion of ecological criteria in supplier selection has emerged as a crucial component, promoting sustainable sourcing practices and addressing environmental challenges in the agricultural sector [52,53]. However, despite the recognition of sustainability criteria in supplier selection, there remains a notable research gap concerning the integration of economic and ecological dimensions within a cohesive evaluation framework. This research aims to fill this gap by developing an integrated evaluation framework that combines economic and ecological criteria, providing valuable insights and guidance for sustainable supplier selection in agribusiness.

### 3. Preliminaries

When making decisions, various approaches and methods are utilized. Decision making in situations involving multiple decision makers and criteria is achieved by reconciling their perspectives. To bring decision making closer to human thinking, fuzzy sets are employed. This concept was first introduced by Zadeh [54], providing a solution for decision making when approximate values are available instead of precise values. This approach bridges the gap between decision-making processes and human perception, as it is often challenging to obtain all the necessary information to assign precise ratings. Fuzzy sets allow for the use of linguistic values instead of numerical evaluations [55]. By employing these values, fuzzy sets are utilized to find compromise solutions based on imprecise information [56,57]. These linguistic values do not have precise boundaries; thus, during transformation, they encompass multiple values represented by fuzzy numbers.

Unlike fuzzy sets, a rough set is a means of addressing uncertainty issues without the subjective influence of decision makers [58]. In previous applications, a rough set has proven successful in situations involving imprecision, ambiguity, and uncertainty during decision making [59]. Thus, the use of rough sets is justified when dealing with unclear and inaccessible data.

By combining these two approaches, an attempt is made to leverage the strengths of each [60,61]. A fuzzy rough number is essentially an extension of a rough number, where a rough number is expanded to incorporate fuzzy sets [62]. The procedure is as follows: First, the evaluation of criterion and alternative values is performed using linguistic values. Second, the transformation of these values into fuzzy numbers is carried out using membership functions. Third, individual fuzzy numbers are utilized to conduct rough set operations. Fourth, the steps of the rough set method are applied. Finally, the rough approach is reconciled, and the final result is obtained. The choice of which fuzzy form to use determines the number of rough sets employed. In this research, triangular

fuzzy numbers will be used, and based on that, three rough sets will be applied and eventually merged.

By employing this approach, it is necessary to determine the lower and upper bounds of rough sets [63,64]. The lower bound of a rough set is defined as follows:

$$\underline{Lim}(c_i^l) = \frac{1}{N^l} \sum_{i=1}^{N^l} \varphi \in \underline{Apr}(c_i^l), \tag{1}$$

$$\underline{Lim}(c_i^m) = \frac{1}{N^l} \sum_{i=1}^{N^m} \varphi \in \underline{Apr}(c_i^m) \tag{2}$$

$$\underline{Lim}(c_i^u) = \frac{1}{N^l} \sum_{i=1}^{N^u} \varphi \in \underline{Apr}(c_i^u) \tag{3}$$

These values represent the lower bounds for fuzzy numbers ( $l, m, u$ ). Similarly, the upper bounds of rough sets are defined as follows:

$$\overline{Lim}(c_i^l) = \frac{1}{N^l} \sum_{i=1}^{N^l} \varphi \in \overline{Apr}(c_i^l), \tag{4}$$

$$\overline{Lim}(c_i^m) = \frac{1}{N^l} \sum_{i=1}^{N^m} \varphi \in \overline{Apr}(c_i^m), \tag{5}$$

$$\overline{Lim}(c_i^u) = \frac{1}{N^l} \sum_{i=1}^{N^u} \varphi \in \overline{Apr}(c_i^u), \tag{6}$$

By establishing the lower and upper bounds, fuzzy rough sets  $\tilde{C}_i$  are defined as:

$$FR(\tilde{C}_i) = \left( [c_i^{lL}, c_i^{lU}], [c_i^{mL}, c_i^{mU}], [c_i^{uL}, c_i^{uU}] \right) = \left( [\underline{Lim}(c_i^l), \overline{Lim}(c_i^l)], [\underline{Lim}(c_i^m), \overline{Lim}(c_i^m)], [\underline{Lim}(c_i^u), \overline{Lim}(c_i^u)] \right) \tag{7}$$

This formulation yields rough numbers. When dealing with two sets and rough numbers, i.e.,  $FR(\bar{\alpha}) = \left( [\alpha^{lL}, \alpha^{lU}], [\alpha^{mL}, \alpha^{mU}], [\alpha^{uL}, \alpha^{uU}] \right)$  and  $FR(\bar{\beta}) = \left( [\beta^{lL}, \beta^{lU}], [\beta^{mL}, \beta^{mU}], [\beta^{uL}, \beta^{uU}] \right)$  the basic operations are as follows:

Addition:

$$FR(\bar{\alpha}) + FR(\bar{\beta}) = \left( [\alpha^{lL}, \alpha^{lU}], [\alpha^{mL}, \alpha^{mU}], [\alpha^{uL}, \alpha^{uU}] \right) + \left( [\beta^{lL}, \beta^{lU}], [\beta^{mL}, \beta^{mU}], [\beta^{uL}, \beta^{uU}] \right) = [\alpha^{lL} + \beta^{lL}, \alpha^{lU} + \beta^{lU}], [\alpha^{mL} + \beta^{mL}, \alpha^{mU} + \beta^{mU}], [\alpha^{uL} + \beta^{uL}, \alpha^{uU} + \beta^{uU}]. \tag{8}$$

Subtraction:

$$FR(\bar{\alpha}) - FR(\bar{\beta}) = \left( [\alpha^{lL}, \alpha^{lU}], [\alpha^{mL}, \alpha^{mU}], [\alpha^{uL}, \alpha^{uU}] \right) + \left( [\beta^{lL}, \beta^{lU}], [\beta^{mL}, \beta^{mU}], [\beta^{uL}, \beta^{uU}] \right) = [\alpha^{lL} - \beta^{uU}, \alpha^{lU} - \beta^{uL}], [\alpha^{mL} - \beta^{mU}, \alpha^{mU} - \beta^{mL}], [\alpha^{uL} - \beta^{lU}, \alpha^{uU} - \beta^{lL}]. \tag{9}$$

Multiplication:

$$FR(\bar{\alpha}) \times FR(\bar{\beta}) = \left( [\alpha^{lL}, \alpha^{lU}], [\alpha^{mL}, \alpha^{mU}], [\alpha^{uL}, \alpha^{uU}] \right) + \left( [\beta^{lL}, \beta^{lU}], [\beta^{mL}, \beta^{mU}], [\beta^{uL}, \beta^{uU}] \right) = [\alpha^{lL} \times \beta^{lL}, \alpha^{lU} \times \beta^{lU}], [\alpha^{mL} \times \beta^{mL}, \alpha^{mU} \times \beta^{mU}], [\alpha^{uL} \times \beta^{uL}, \alpha^{uU} \times \beta^{uU}]. \tag{10}$$

Division:

$$FR(\bar{\alpha}) \div FR(\bar{\beta}) = \left( [\alpha^{lL}, \alpha^{lU}], [\alpha^{mL}, \alpha^{mU}], [\alpha^{uL}, \alpha^{uU}] \right) + \left( [\beta^{lL}, \beta^{lU}], [\beta^{mL}, \beta^{mU}], [\beta^{uL}, \beta^{uU}] \right) = [\alpha^{lL} \div \beta^{uU}, \alpha^{lU} \div \beta^{uL}], [\alpha^{mL} \div \beta^{mU}, \alpha^{mU} \div \beta^{mL}], [\alpha^{uL} \div \beta^{lU}, \alpha^{uU} \div \beta^{lL}]. \tag{11}$$

Scalar multiplication:

$$\begin{aligned} \lambda \times FR(\bar{\alpha}) &= \lambda \times \left( [\alpha^{lL}, \alpha^{lU}], [\alpha^{mL}, \alpha^{mU}], [\alpha^{uL}, \alpha^{uU}] \right) \\ &= \left( [\lambda \times \alpha^{lL}, \lambda \times \alpha^{lU}], [\lambda \times \alpha^{mL}, \lambda \times \alpha^{mU}], [\lambda \times \alpha^{uL}, \lambda \times \alpha^{uU}] \right). \end{aligned} \tag{12}$$

The specificity of these operations is that during Addition and Multiplication operations, operations are performed on the same fuzzy rough numbers, while during Subtraction and Division operations, operations are performed on reciprocal numbers: the first fuzzy rough number of the set  $\bar{\alpha}$  with the sixth number of the fuzzy rough set  $\bar{\beta}$ , and the second fuzzy rough of the set  $\bar{\alpha}$  with the fifth number of the fuzzy rough set  $\bar{\beta}$ . Operations with all numbers of fuzzy rough sets are performed in the specified manner. The reason for these operations should be found in the fact that the first fuzzy rough should always be smaller than the second, the second more difficult, and whatever numbers these sets have. These operations are applied to existing methods, which will be explained in the following sections.

Before these operations can be applied to certain methods, it is necessary to choose the appropriate methods. The choice of methods used in papers is usually the choice of the authors. It should be noted that all methods have their advantages and disadvantages. When choosing a method for determining the weights of the criteria, the authors Ayan et al. [65] performed an overview of certain methods and determined the advantages and disadvantages of these methods. Thus, these methods must compare criteria in pairs [66,67]; that is, compare criteria in relation to the first or last criteria, and the like. In this paper, the LMAW method will be used, where it is not necessary to compare the criteria, but it is enough to determine the importance of an individual criterion. However, the disadvantage of this method is the application of the Bonferroni aggregator, which complicates the calculation of criteria weights. When choosing the method for ranking the alternative, the MABAC method was chosen. There are several reasons for using this method: ease of use, the development of the fuzzy rough approach in this method, and the acceptance of this method in practice. However, this method also has certain limitations, which is why it is used in the results and validation of the results of this method to make the decision even more certain.

### 3.1. Fuzzy Rough LMAW Method

The LMAW method has been developed to determine not only the weight of criteria but also the ranking order of alternatives [68]. In this paper, a part of this method responsible for determining the criteria weights will be used. The steps for implementing this method are as follows:

Step 1: Formation of the initial decision matrix. This matrix is constructed by experts who assess the criteria based on linguistic ratings (Table 1). They determine the perceived importance of each criterion.

**Table 1.** Linguistic values representing the importance of criteria.

Linguistic Values	Fuzzy Numbers
Absolutely low (AL)	1, 1, 1
Very low (VL)	1, 1.5, 2
Low (L)	1.5, 2, 2.5
Medium-low (ML)	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

Step 2: Transformation of linguistic values into fuzzy numbers. This is carried out based on the membership function of the fuzzy number (Table 1).

Step 3: Determination of the lower and upper bounds of the rough number for individual fuzzy numbers. This is achieved using the definitions for establishing the lower and upper bounds of rough numbers (Expressions (1)–(6)).

$$\tilde{\gamma}_{C_n}^e = \left( [\alpha^{lL}, \alpha^{lU}], [\alpha^{mL}, \alpha^{mU}], [\alpha^{uL}, \alpha^{uU}] \right) \tag{13}$$

Step 4: Definition of the absolute anti-ideal point. This value is determined based on the minimum value among the fuzzy rough number values. It represents a value that is lower than the minimum value.

Step 5: Definition of the ratio vector. In this step, the values of the fuzzy rough numbers are divided by the absolute anti-ideal point.

$$\tilde{\mu}_{C_n}^e = \left( \frac{\tilde{\gamma}_{C_n}^e}{\tilde{\gamma}_{AIP}} \right) = \left( \left[ \frac{\alpha^{lL}}{\tilde{\gamma}_{AIP}} \cdot \frac{\alpha^{lU}}{\tilde{\gamma}_{AIP}} \right], \left[ \frac{\alpha^{mL}}{\tilde{\gamma}_{AIP}} \cdot \frac{\alpha^{mU}}{\tilde{\gamma}_{AIP}} \right], \left[ \frac{\alpha^{uL}}{\tilde{\gamma}_{AIP}} \cdot \frac{\alpha^{uU}}{\tilde{\gamma}_{AIP}} \right] \right) \tag{14}$$

Step 6: Determination of the vector of weight coefficients. This step is performed separately for each expert.

$$\begin{aligned} \tilde{\omega}_j^e &= \left( \frac{\ln(\tilde{\mu}_{C_n}^{LU})}{\ln(\prod_{j=1}^n \tilde{\mu}_{C_n}^{LU})} \right) \\ &= \left( \left[ \frac{\ln(\tilde{\mu}_{C_n}^{lL})}{\ln(\prod_{j=1}^n \tilde{\mu}_{C_n}^{uL})}; \frac{\ln(\tilde{\mu}_{C_n}^{lU})}{\ln(\prod_{j=1}^n \tilde{\mu}_{C_n}^{uL})} \right]; \left[ \frac{\ln(\tilde{\mu}_{C_n}^{mL})}{\ln(\prod_{j=1}^n \tilde{\mu}_{C_n}^{mU})}; \frac{\ln(\tilde{\mu}_{C_n}^{mU})}{\ln(\prod_{j=1}^n \tilde{\mu}_{C_n}^{mL})} \right]; \left[ \frac{\ln(\tilde{\mu}_{C_n}^{uL})}{\ln(\prod_{j=1}^n \tilde{\mu}_{C_n}^{uL})}; \frac{\ln(\tilde{\mu}_{C_n}^{uU})}{\ln(\prod_{j=1}^n \tilde{\mu}_{C_n}^{lL})} \right] \right) \end{aligned} \tag{15}$$

Step 7: Calculation of the aggregated vectors of weight coefficients. The calculation of this coefficient is conducted using the Bonferroni aggregator. It is performed by individually calculating the weights for each fuzzy rough number based on the expression:

$$\tilde{\omega}_j = \left( \frac{1}{k(k-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^k \tilde{\omega}_i^{(UL)p} \tilde{\omega}_i^{(UL)q} \right)^{\frac{1}{p+q}} \tag{16}$$

In this research, the final weights will not be computed as the weights obtained for individual fuzzy rough numbers will be retained. Thus, Step 7 serves as the final step of the fuzzy rough LMAW method.

### 3.2. Fuzzy Rough MABAC Method

The MABAC method was developed by Pamučar and Čirović [69]. This method ranks alternatives based on their deviations from the average values. The steps of this method are presented in the paper by Pamučar et al. [59], and here we will provide a brief overview of these steps.

Step 1: Formation of the initial decision matrix. This matrix is formed by experts who assess the alternatives according to observed criteria using linguistic evaluations (Table 2).

**Table 2.** Linguistic values for alternative assessment.

Linguistic Values	Fuzzy Numbers
Very bad (VB)	(0, 0, 1)
Bad (B)	(0, 1, 3)
Medium bad (MB)	(1, 3, 5)
Medium (M)	(3, 5, 7)
Medium good (MG)	(5, 7, 9)
Good (G)	(7, 9, 10)
Very good (VG)	(9, 10, 10)

Step 2: Transformation of linguistic values from the initial decision matrix into fuzzy numbers. This is done based on the membership function of the fuzzy number (Table 2).

Step 3: Determination of the lower and upper bounds of the rough number for individual fuzzy numbers. This is performed in the same manner as in the fuzzy rough LMAW method.

Step 4: Normalization of the fuzzy rough decision matrix. This is done using the following expressions:

For benefit criteria:

$$\bar{z}_{ij} = \left( \left[ \frac{\alpha_{ij}^{lL} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \cdot \frac{\alpha_{ij}^{lU} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \right] \cdot \left[ \frac{\alpha_{ij}^{mL} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \cdot \frac{\alpha_{ij}^{mU} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \right] \cdot \left[ \frac{\alpha_{ij}^{uL} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \cdot \frac{\alpha_{ij}^{uU} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \right] \right) \quad (17)$$

For cost criteria:

$$\bar{z}_{ij} = \left( \left[ 1 - \frac{\alpha_{ij}^{lL} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \cdot 1 - \frac{\alpha_{ij}^{lU} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \right] \cdot \left[ 1 - \frac{\alpha_{ij}^{mL} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \cdot 1 - \frac{\alpha_{ij}^{mU} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \right] \cdot \left[ 1 - \frac{\alpha_{ij}^{uL} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \cdot 1 - \frac{\alpha_{ij}^{uU} - \alpha_{i \min}^{lL}}{\alpha_{i \max}^{uU} - \alpha_{i \min}^{lL}} \right] \right) \quad (18)$$

Step 5: Weighting the normalized fuzzy rough numbers. This is accomplished using the following expression:

$$\bar{v}_{ij} = \bar{w}_j = \bar{z}_{ij} + \bar{w}_j \quad (19)$$

Step 6: Determining the border approximation area matrix (G). This is essentially the geometric mean of the criterion values for individual fuzzy rough number values. It is calculated using the following expression:

$$\bar{g}_j = \left( \prod_{i=1}^n (\bar{v}_{ij}) \right) \quad (20)$$

Step 7: Calculating the elements of the matrix for the distance of the alternatives from the border approximation area (Q). In this step, the deviation of the weighted normalized fuzzy rough numbers from the values of the border approximation area matrix (G) is calculated.

$$\bar{q}_{ij} = \left( \left[ (v_{ij}^{lL} - g_j^{uU}) \cdot (v_{ij}^{iU} - g_j^{uL}) \right] \cdot \left[ (v_{ij}^{mL} - g_j^{mU}) \cdot (v_{ij}^{mU} - g_j^{mL}) \right] \cdot \left[ (v_{ij}^{uL} - g_j^{lU}) \cdot (v_{ij}^{uU} - g_j^{lL}) \right] \right) \quad (21)$$

Step 8: Ranking the alternatives. The ranking of alternatives is done by summing all the deviation values of alternatives from the border approximation area.

$$\bar{S}_j = \left( \sum_{i=1}^n (\bar{q}_{ij}) \right) \quad (22)$$

The best alternative is the one with the highest value according to the MABAC method, and vice versa.

#### 4. Case Study

The company “Semberka” from Janja is located in the Semberija plain in Bosnia and Herzegovina. The favorable climate and land have influenced intensive agricultural activities in this area. Consequently, it was economically justified to establish processing facilities to obtain a final product, thus completing the agricultural production cycle from farm to table. The “Semberka” company from Janja represents a market-recognized brand that continues to make significant investments in production resources. Its main activity is the production of spices, food additives, and the processing of dried vegetables from its own production. The company places great emphasis on products that meet health, hygiene, and microbiological standards, as evidenced by continuous monitoring of raw materials throughout the entire process, from planting and drying to grinding and mixing according to recipes. In recent years, the company “Semberka” has focused on the production of its branded “Semberski” soups, thereby completing the production process of the factory. Due to increased production and expansion of the product range, there is a need for additional quantities of specific vegetables from other suppliers in the local and wider area. However, the products from these suppliers must meet all the specified quality standards to maintain the quality of the final product and uphold the existing brand.

The company employs several dozen workers whose main activities involve the processing and refinement of a range of dried vegetables. Among these employees are engineers (agriculture, technology, and protection) whose task is to monitor and control the work processes. Due to the need for additional raw material quantities, Semberka decided to conduct research to identify the supplier that best meets their objectives, which is the production of high-quality products with an emphasis on human health. This is due to the increasing number of people turning to a healthy lifestyle in order to improve their quality of life and extend their lifespan. The research was conducted by engaging external experts, professors from the Faculty of Agriculture in Bijeljina, in addition to the company’s own experts. Thus, five experts were involved to assess the suppliers and select the one that best meets the objectives. Among the five experts, the company employed two employees with extensive experience in raw material processing, who are technology engineers, and then three experts, holders of doctoral degrees in agricultural sciences, with years of experience in agricultural activities. This way, two segments were covered, namely raw material processing technology and agricultural production technology.

In order to select the supplier, the task of the experts was to determine the criteria by which the selected suppliers would be evaluated. They decided to apply economic–environmental criteria (Table 3). These criteria aim to choose a green supplier. The economic criteria encompass economic parameters such as costs, quality, production innovation, technological capacities, and delivery. The environmental criteria cover aspects related to environmental management standards, environmental product design, eco-friendly materials, and resource consumption reduction to optimize the production process of the Semberka company. These criteria were selected from existing similar research studies. It is important to note that in practice, there are numerous other criteria, but the experts considered these criteria to be the most suitable for this research.



**Table 3.** Criteria for supplier selection.

<b>Id</b>	<b>Criteria</b>	<b>These Criteria Will Enable:</b>	<b>References</b>
C1	Costs	Reducing costs and ensuring favorable resources	[70–73]
C2	Quality	Ensuring good resources to maintain product quality	[72–75]
C3	Production innovation	Providing innovative resources to improve products	[76–79]
C4	Delivery	Ensuring timely resource delivery	[6,72,73,80]
C5	Technological capacities	Providing an adequate quantity of resources	[71,81,82]
C6	Environmental management standards	Implementing systems for environmental protection	[5,73,83,84]
C7	Pollution control	Reducing all negative effects on the environment	[71,72,74,85–87]
C8	Environmental product design	Sourcing resources that help reduce environmental impact	[72,74,76,86,88]
C9	Eco-friendly materials	Sourcing resources that use environmentally friendly materials	[82,84,89]
C10	Resource consumption reduction	Enabling resource consumption reduction.	[74,77,90]

After selecting the criteria by which to evaluate suppliers, the experts have chosen six suppliers from the Semberija region who would assist them in producing additional and new products. These suppliers will be labeled as S1–S6. In addition to that, these suppliers will help Semberka Company improve its production, which will provide them with an additional quantity of raw materials for future manufacturing. The goal is to select one of these six suppliers with whom Semberka Company will establish partnership relations to mutually enhance their business. Since the criteria and potential suppliers have been selected, the task of the experts was to assess the criteria first using linguistic values (Table 1) and then to evaluate the suppliers using these criteria with linguistic values (Table 2). In order to select the supplier, a fuzzy rough approach will be used, which enables decision-making in the case of imprecise evaluations by applying a fuzzy approach while reducing ambiguity and uncertainty in decision making through a rough approach. This way, a more reliable decision will be made for the decision maker.

**5. Results**

When selecting a green supplier for Semberka Company’s needs, the weights of the criteria are first determined using expert assessments. In determining the weights of the criteria, the first step is to establish a linguistic assessment of the criteria. This is carried out by having each expert rate the criteria on a scale ranging from absolutely low (AL) to absolutely high (AH). The criteria that are more significant to them will receive higher ratings from the expert. As can be seen from these ratings (Table 4), there is no single criterion that is considered the best by all experts. Therefore, in this case, the ratings are harmonized to obtain a compromise solution. This solution is the one that best reconciles the different assessments.

**Table 4.** Initial decision matrix.

	<b>C1</b>	<b>C2</b>	<b>C3</b>	<b>C4</b>	<b>C5</b>	<b>C6</b>	<b>C7</b>	<b>C8</b>	<b>C9</b>	<b>C10</b>
Expert 1	VH	AH	H	MH	MH	MH	MH	E	H	E
Expert 2	H	VH	E	H	E	MH	MH	ML	MH	E
Expert 3	AH	AH	MH	H	MH	H	AH	MH	VH	MH
Expert 4	H	AH	MH	H	E	H	AH	MH	VH	E
Expert 5	H	VH	VH	H	E	ML	AH	ML	VH	MH

After forming the initial linguistic decision matrix, the next step is to transform these linguistic assessments into fuzzy numbers using membership functions (Table 1). The specificity of these fuzzy numbers is that they do not have clear boundaries and the boundaries of individual fuzzy numbers overlap. In this way, imprecise assessments are used to evaluate the weights of the criteria. By transforming linguistic values into fuzzy numbers, a triangular fuzzy number is formed for each value (Table 5).

**Table 5.** Initial fuzzy decision matrix.

	C1		C2		C3		C4		...	C10						
Expert 1	4	4.5	5	4.5	5	5	3.5	4	4.5	3	3.5	4	...	2.5	3	3.5
Expert 2	3.5	4	4.5	4	4.5	5	2.5	3	3.5	3.5	4	4.5	...	2.5	3	3.5
Expert 3	4.5	5	5	4.5	5	5	3	3.5	4	3.5	4	4.5	...	3	3.5	4
Expert 4	3.5	4	4.5	4.5	5	5	3	3.5	4	3.5	4	4.5	...	2.5	3	3.5
Expert 5	3.5	4	4.5	4	4.5	5	4	4.5	5	3.5	4	4.5	...	3	3.5	4

Then, individual lower and upper bounds of rough numbers are determined based on these numbers. For the first fuzzy number in the first criterion, it looks like this:

$$\underline{Lim}(1) = \frac{1}{4}(4 + 3.5 + 3.5 + 3.5) = 3.63; \quad \overline{Lim}(1) = \frac{1}{2}(4 + 4.5) = 4.25;$$

$$\underline{Lim}(2) = \frac{1}{4}(4 + 3.5 + 3.5 + 3.5) = 4.125; \quad \overline{Lim}(2) = \frac{1}{2}(4.5 + 5) = 4.75;$$

$$\underline{Lim}(3) = \frac{1}{4}(5 + 4.5 + 5 + 4.5 + 4.5) = 4.7; \quad \overline{Lim}(3) = \frac{1}{2}(5 + 5) = 5.$$

It is important to mention that for each expert, the lower and upper bounds are determined by considering the value they provided. To determine the lower bound, all smaller values are compared among that expert and other experts, while for the upper bound, all larger and equal values are considered among that expert and other experts. In this way, these bounds are formed, as shown in Table 6.

Table 6. Initial fuzzy rough decision matrix for criteria.

	C1				C2				C10									
	l	u	l	u	l	u	l	u	l	u	l	u	l	u				
E1	3.63	4.25	4.25	4.75	4.75	5.00	4.30	4.50	4.80	5.00	5.00	5.00	2.50	2.70	3.00	3.20	3.50	3.70
E2	3.50	3.80	3.80	4.30	4.50	4.70	4.00	4.30	4.50	4.80	5.00	5.00	2.50	2.70	3.00	3.20	3.50	3.70
E3	3.80	4.50	4.30	5.00	4.70	5.00	4.30	4.50	4.80	5.00	5.00	5.00	2.70	3.00	3.20	3.50	3.70	4.00
E4	3.50	3.80	4.00	4.30	4.50	4.70	4.30	4.50	4.80	5.00	5.00	5.00	2.50	2.70	3.00	3.20	3.50	3.70
E5	3.50	3.80	4.00	4.30	4.50	4.70	4.00	4.30	4.50	4.80	5.00	5.00	2.70	3.00	3.20	3.50	3.70	4.00

By using these rules, lower and upper bounds of rough numbers are determined for all experts and criteria. This forms the initial fuzzy rough decision matrix, which serves as the starting point for applying the fuzzy rough method (Table 6). In this case, the steps of the fuzzy rough LMAW method are applied.

The first step of this method is to define the absolute anti-ideal point. When considering all lower values of the first fuzzy numbers, since these values are the smallest, it can be observed that the minimum value is two (2). Therefore, the value chosen for the absolute anti-ideal point is a value smaller than two. In this example, the value of 1.9 is taken. The next step of this method is to define the relationship vector. In this step, the division of all values in the fuzzy rough decision matrix by the values of the absolute anti-ideal point is performed (Equation (14)). The subsequent step is to determine the vector of weight coefficients. Here, the natural logarithm is calculated for each value, and that value is divided by the natural logarithm of the product of weight coefficient vectors for the corresponding fuzzy numbers and the limits of rough numbers (Table 7).

Table 7. Matrix of weight coefficient vectors.

	C1				C2				C10									
	l	u	l	u	l	u	l	u	l	u	l	u	l	u				
E1	0.08	0.11	0.11	0.14	0.15	0.22	0.10	0.11	0.12	0.15	0.16	0.22	0.03	0.05	0.06	0.08	0.10	0.15
E2	0.08	0.09	0.10	0.14	0.16	0.22	0.09	0.11	0.12	0.16	0.17	0.24	0.03	0.05	0.07	0.09	0.11	0.16
E3	0.08	0.11	0.10	0.14	0.14	0.18	0.09	0.11	0.12	0.14	0.15	0.18	0.04	0.06	0.07	0.09	0.10	0.14
E4	0.07	0.09	0.10	0.12	0.14	0.18	0.10	0.11	0.12	0.15	0.16	0.19	0.03	0.04	0.06	0.08	0.10	0.13
E5	0.07	0.09	0.10	0.13	0.14	0.20	0.09	0.11	0.12	0.14	0.16	0.21	0.04	0.06	0.07	0.09	0.11	0.16

Finally, the Bonferroni aggregator is applied to harmonize the weights of the experts. Using this aggregator, the weights of the criteria are obtained, which are used to adjust the initial decision matrix. Based on this approach, weights are obtained where the upper limit of the first fuzzy number cannot be greater than the lower limit of the second fuzzy number, and the upper limit of the second fuzzy number cannot be greater than the lower limit of the third fuzzy number. When examining these results (Table 8), criterion C2 (quality) received the highest weight, followed by criterion C1 (costs), while criterion C8 (environmental product design) received the lowest weight.

After determining the weights of the criteria, the ranking of alternatives is performed. The first step in the fuzzy rough MABAC method is the same, and the initial decision matrix with linguistic values is formed (Table 9). Then, the transformation of these linguistic values into fuzzy numbers is carried out using the membership function (Table 2).

**Table 8.** Final weights of criteria.

	<b>l</b>	<b>u</b>	<b>l</b>	<b>u</b>	<b>l</b>	<b>u</b>
C1	0.08	0.10	0.10	0.14	0.15	0.20
C2	0.09	0.11	0.12	0.15	0.16	0.21
C3	0.05	0.08	0.08	0.12	0.12	0.19
C4	0.07	0.08	0.09	0.12	0.14	0.18
C5	0.04	0.05	0.07	0.09	0.10	0.15
C6	0.04	0.07	0.07	0.11	0.11	0.17
C7	0.07	0.10	0.11	0.14	0.15	0.20
C8	0.02	0.05	0.05	0.08	0.09	0.15
C9	0.07	0.09	0.10	0.13	0.14	0.20
C10	0.04	0.05	0.07	0.09	0.10	0.15

**Table 9.** Initial linguistic decision matrix.

<b>E1</b>	<b>C1</b>	<b>C2</b>	<b>C3</b>	<b>C4</b>	<b>C5</b>	<b>C6</b>	<b>C7</b>	<b>C8</b>	<b>C9</b>	<b>C10</b>
A1	B	MB	MG	MG	MG	G	MG	M	M	MB
A2	M	M	MG	MG	MB	G	MG	MG	MG	MG
A3	MG	M	M	M	B	MG	M	M	MG	MG
A4	M	MB	M	MB	MB	M	MB	M	M	M
A5	M	M	M	MB	M	M	B	M	M	MG
A6	M	MB	M	M	M	M	B	MB	MB	M
<b>E2</b>	<b>C1</b>	<b>C2</b>	<b>C3</b>	<b>C4</b>	<b>C5</b>	<b>C6</b>	<b>C7</b>	<b>C8</b>	<b>C9</b>	<b>C10</b>
A1	M	B	M	M	M	MG	M	M	MB	MB
A2	MG	M	MG	MG	MB	G	MG	G	MG	M
A3	M	MG	G	M	MB	G	MG	M	M	MG
A4	MG	M	M	M	MB	M	MB	MG	M	MG
A5	G	MG	MG	MB	M	MG	MB	M	MG	MG
A6	M	M	M	M	MG	M	MB	MG	M	MG
<b>E3</b>	<b>C1</b>	<b>C2</b>	<b>C3</b>	<b>C4</b>	<b>C5</b>	<b>C6</b>	<b>C7</b>	<b>C8</b>	<b>C9</b>	<b>C10</b>
A1	MG	MB	M	MG	G	MG	G	M	MG	M
A2	M	MG	MG	MG	MB	G	MG	MG	MG	MG
A3	MB	MG	M	G	MB	M	M	G	MG	G
A4	M	MG	MB	MB	MB	M	MG	M	MG	M
A5	MG	M	M	MB	M	M	B	MG	M	G
A6	M	MG	M	MG	G	M	B	MB	M	M
<b>E4</b>	<b>C1</b>	<b>C2</b>	<b>C3</b>	<b>C4</b>	<b>C5</b>	<b>C6</b>	<b>C7</b>	<b>C8</b>	<b>C9</b>	<b>C10</b>
A1	MG	M	MG	MG	MG	MG	G	MB	M	MG
A2	MB	MG	G	M	MB	G	MG	MG	MG	MG
A3	MG	M	M	M	M	M	MG	M	M	G
A4	MG	MG	M	MG	MB	M	MB	MG	M	M
A5	G	M	G	MB	M	M	MB	G	M	MG
A6	MG	MG	M	M	MG	MG	M	MB	MG	G
<b>E5</b>	<b>C1</b>	<b>C2</b>	<b>C3</b>	<b>C4</b>	<b>C5</b>	<b>C6</b>	<b>C7</b>	<b>C8</b>	<b>C9</b>	<b>C10</b>
A1	MG	MB	MG	MG	MG	G	MG	MB	M	MB
A2	G	MG	MG	MG	MB	MG	MG	MG	MG	G
A3	G	M	M	M	M	G	G	M	MG	MG
A4	G	MG	M	MG	MG	M	MB	G	M	M
A5	MG	M	MG	MB	M	M	B	M	MG	MG
A6	M	MB	M	M	M	M	B	MB	MB	G

After that, the lower and upper bounds are determined for each fuzzy number and each expert. This is performed in the same way as in the fuzzy rough LMAW method. Then, the aggregate decision matrix is formed by calculating the average values of the lower and upper bounds of the rough numbers, and the initial joint fuzzy rough decision matrix is

created (Table 9). This matrix is fundamental for conducting the steps of the fuzzy rough MABAC method. When forming this decision matrix, it is important to ensure that the upper bound of the first fuzzy number is not greater than the lower bound of the second fuzzy number and that the upper bound of the second fuzzy number is not greater than the lower bound of the third fuzzy number. Therefore, where this is the case, adjustments are made to this fuzzy rough decision matrix, so that the upper bound of the first fuzzy number becomes the lower bound of the second fuzzy number, and the upper bound of the second fuzzy number becomes the lower bound of the third fuzzy number. These adjustments are marked in Table 10.

**Table 10.** Initial fuzzy rough decision matrix for alternatives.

	C1				C2				...	C10									
	l	u	l	u	l	u	l	u		l	u	l	u						
S1	2.5	4.6	4.6	6.6	6.6	8.6	0.7	1.7	2.3	3.7	4.3	5.7	...	1.3	3.1	3.3	5.1	5.3	7.1
S2	2.5	5.2	5.2	7.2	7.2	8.7	3.7	4.7	5.7	6.7	7.7	8.7	...	4.3	5.7	6.3	7.7	8.3	9.3
S3	2.8	5.5	5.5	7.5	7.5	9.1	3.3	4.3	5.3	6.3	7.3	8.3	...	5.7	6.7	6.7	8.3	8.3	9.6
S4	3.7	5.5	5.7	7.5	7.7	9.1	2.9	4.7	4.9	6.7	6.9	8.7	...	3.1	3.7	5.1	5.7	7.1	7.7
S5	4.5	6.3	6.5	8.3	8.3	9.6	3.1	3.7	5.1	5.7	7.1	7.7	...	5.1	5.7	7.1	7.7	9.0	9.4
S6	3.1	3.7	5.1	5.7	7.1	7.7	1.9	4.1	4.1	6.1	6.1	8.1	...	3.9	6.1	5.9	8.1	8.1	9.4

Once this decision matrix is formed, the steps of the fuzzy rough MABAC method are carried out. The first step is to normalize this initial fuzzy rough decision matrix. Since the linguistic scale is in a form where all criteria are transformed into benefit criteria, normalization is applied for the benefit criteria (Expression (17)). When performing normalization, the minimum value of the lower bound of the first fuzzy number is first identified, followed by the maximum value of the upper bound of the third fuzzy number. For example, for the first supplier, the lower bound of the first fuzzy number will be  $(2.5 - 2.5)/(9.3 - 2.5) = 0$ . In this way, the other values of the normalized decision matrix are calculated. The minimum and maximum values for each criterion are taken, and the normalization process is applied.

Then, the weighting of this normalized decision matrix is performed (Expression (19)). Weighting is done by multiplying the normalized values with the corresponding weights and summing them with those weights (Table 11). After that, the border approximation area matrix (g) is formed, which represents the geometric mean value for each boundary of the fuzzy numbers. Then, the values of the weighted decision matrix are subtracted from the values of the border approximation area matrix. For example, the value of the lower bound of the first fuzzy number is subtracted from the value of the border approximation area matrix of the upper bound of the third fuzzy number, the upper bound of the first fuzzy number is subtracted from the lower bound of the third fuzzy number, and so on. In this way, the values of the matrix for the distance of the alternatives from the border approximation area (Q) are calculated.

**Table 11.** Weighted values of the normalized decision matrix and border approximation area matrix.

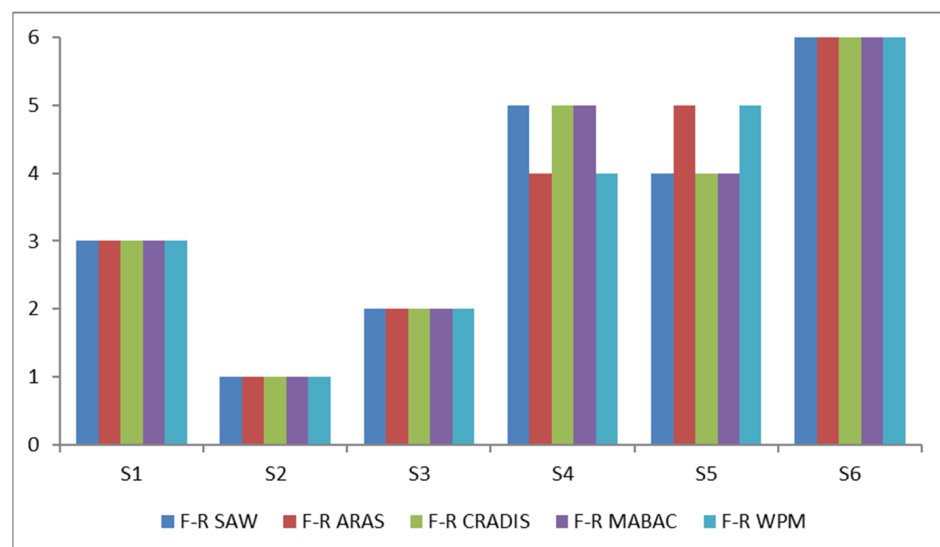
	C1				C2				...	C10									
	l	u	l	u	l	u	l	u		l	u	l	u						
S1	0.08	0.13	0.13	0.21	0.23	0.37	0.09	0.12	0.15	0.20	0.23	0.34	...	0.04	0.06	0.08	0.13	0.16	0.25
S2	0.08	0.13	0.14	0.22	0.24	0.38	0.13	0.16	0.20	0.26	0.30	0.42	...	0.05	0.08	0.10	0.15	0.19	0.29
S3	0.08	0.14	0.15	0.23	0.25	0.39	0.12	0.16	0.19	0.25	0.29	0.41	...	0.06	0.08	0.11	0.16	0.19	0.30
S4	0.09	0.14	0.15	0.23	0.25	0.39	0.12	0.16	0.19	0.26	0.28	0.42	...	0.04	0.07	0.09	0.13	0.18	0.27
S5	0.10	0.15	0.16	0.25	0.27	0.40	0.12	0.15	0.19	0.24	0.29	0.39	...	0.05	0.08	0.11	0.15	0.20	0.30
S6	0.08	0.11	0.14	0.20	0.24	0.35	0.11	0.16	0.17	0.25	0.27	0.40	...	0.05	0.08	0.10	0.16	0.19	0.30
$\bar{g}_j$	0.08	0.13	0.14	0.22	0.25	0.38	0.12	0.15	0.18	0.24	0.28	0.39	...	0.05	0.07	0.10	0.15	0.18	0.28

Then, it is necessary to sum up all the values of individual boundaries for all criteria using Expression (8). Finally, the final value of the fuzzy rough MABAC method is obtained by calculating the average value for all boundaries. The results show that supplier S2 achieves the best results (Table 12), making it the first choice for establishing partnerships, followed by supplier S3, while supplier S6 performs the poorest.

**Table 12.** Final ranking order of the fuzzy rough MABAC method.

	<b>l</b>	<b>u</b>	<b>l</b>	<b>u</b>	<b>l</b>	<b>u</b>	<b>S</b>	<b>Rank</b>
S1	−2.64	−1.10	−0.59	0.61	1.11	2.67	0.011	3
S2	−2.56	−1.03	−0.45	0.72	1.31	2.81	0.134	1
S3	−2.61	−1.05	−0.55	0.69	1.17	2.74	0.065	2
S4	−2.66	−1.15	−0.63	0.54	1.05	2.57	−0.048	5
S5	−2.64	−1.15	−0.60	0.54	1.10	2.56	−0.030	4
S6	−2.68	−1.18	−0.66	0.50	1.02	2.52	−0.079	6

To confirm these results, a validation of the results will be conducted. This validation is performed by using the same weights and the same initial decision matrix while applying other MCDM methods. In this study, the results of the fuzzy rough MABAC method will be compared with the methods: fuzzy rough SAW (Simple Additive Weighting), fuzzy rough ARAS (Additive Ratio Assessment), fuzzy rough CRADIS (compromise ranking of alternatives from distance to ideal solution), and fuzzy rough WPM (Weighted Product Method). The validation results show that the rank order differs between the fuzzy rough ARAS and fuzzy rough WPM methods for suppliers S4 and S5. When examining the results of the fuzzy rough MABAC method, it can be observed that the smallest difference occurs for these two suppliers (Figure 1). This is the reason why the rank order differs between these two methods compared to the fuzzy rough MABAC method. Additionally, these two methods also apply different normalizations. The application of different types of normalization can affect the rank order of alternatives [91,92]. The rank order does not differ from the fuzzy rough MABAC method for the other two methods. Based on these results, the obtained results of the fuzzy rough MABAC method can be confirmed.



**Figure 1.** Validation of the results.

After the validation of the results, a sensitivity analysis will be conducted. This analysis aims to demonstrate the role of individual criteria on the final rank order of alternatives and show how sensitive each supplier is to changes in the weights of individual criteria. This will help identify the areas that each supplier needs to improve in order to perform

better in the market. This will be conducted as follows. Each individual criterion will be reduced by 15% until only 10% of the initial criterion value remains [93]. In this way, 6 scenarios for each individual criterion will be applied [94]. Since there are 10 criteria, a total of 60 sensitivity analysis scenarios will be performed.

The results of the sensitivity analysis show that in all scenarios, suppliers S2, S3, and S6 did not change their rank order (Figure 2). Supplier S2 remained in the first position in all scenarios, supplier S3 in the second position, while supplier S6 was consistently ranked last for all criteria. The sensitivity analysis revealed the following: Supplier S4 has poorer indicators than supplier S5 in terms of innovativeness, so in order to be better rated than the other suppliers, this supplier needs to improve the innovativeness of their products and services. Additionally, this analysis showed that supplier S1 has better indicators than supplier S5 in terms of delivery and pollution control. For supplier S5 to be better than supplier S1, they need to adjust their delivery time and improve pollution control in their production because when the weights of these criteria were reduced, supplier S5 had a higher rank than supplier S1. In other cases and scenarios, the rank order of the suppliers remained unchanged.

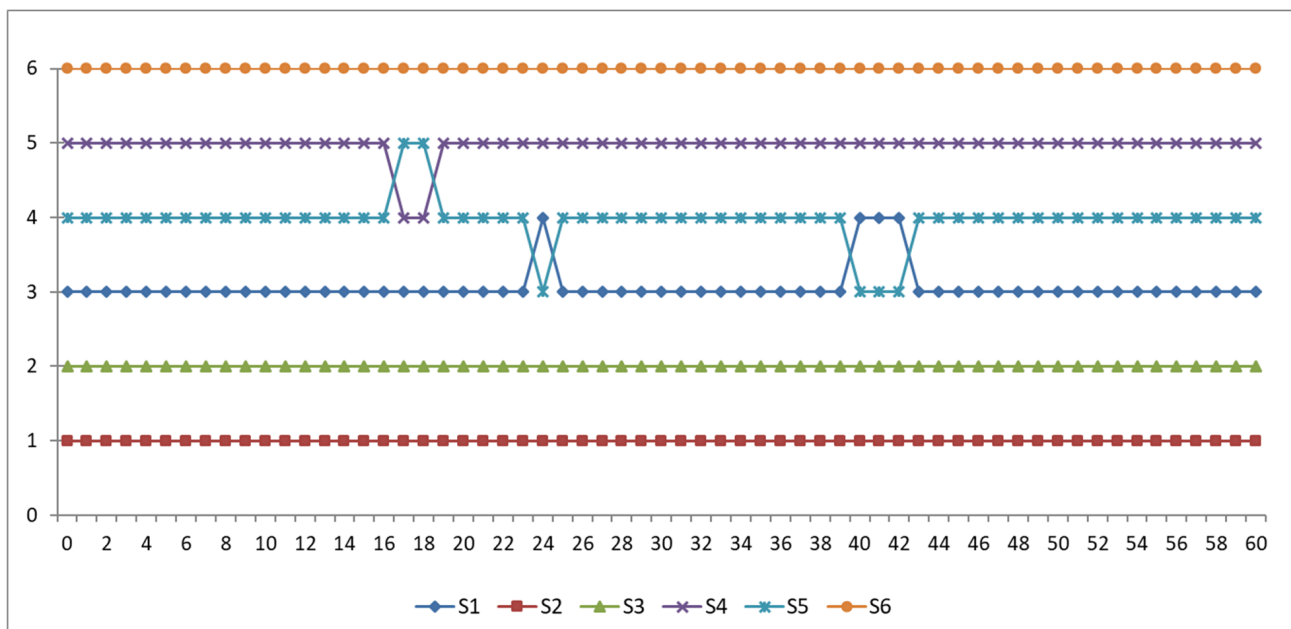


Figure 2. Sensitivity analysis.

The validations of results and sensitivity analysis have shown that supplier S2 has the best indicators among all suppliers, making it the first choice for establishing partnerships. Following supplier S2, the next choice is supplier S3.

## 6. Discussion

The growing consumer demand for a healthier lifestyle has triggered a significant transformation in the agro-food industry [95]. Increasingly, customers are seeking out products that promote good health and contribute to environmental preservation. Consequently, ecological criteria have become integral to supplier selection [53], complementing traditional economic considerations. This study focuses on the selection of a green supplier, using the Semberka company as an example. The findings underscore the importance of incorporating ecological criteria into supplier selection processes. In response to the shifting preferences of consumers, companies are prioritizing suppliers that align with eco-friendly practices, showcasing their commitment to sustainability and catering to customer demands.

Integrating ecological criteria into supplier selection offers several advantages [96]. Firstly, it enables companies to contribute to environmental preservation by supporting suppliers that adhere to eco-friendly practices. This not only benefits the planet but also enhances a company's image and reputation, appealing to eco-conscious consumers. Secondly, choosing green suppliers can lead to the procurement of high-quality products that meet stringent health and safety standards, contributing to consumer satisfaction and trust in the company's offerings [97]. Moreover, it opens up opportunities for companies to enter new markets or expand their customer base by attracting health-conscious consumers [98]. However, the integration of ecological criteria into supplier selection is not without challenges [99]. Companies may face difficulties in identifying and evaluating suppliers' eco-friendly practices, particularly when comprehensive and standardized metrics are lacking. Additionally, there may be cost implications associated with sourcing from green suppliers, as environmentally friendly practices often require investments in sustainable technologies or processes. Striking a balance between environmental considerations and economic viability is a key aspect that companies must carefully navigate during the supplier selection process [23].

In the case of the Semberka company, the utilization of ecological criteria in the selection of a green supplier demonstrates a proactive approach to addressing customer demands and aligning with industry trends. This decision allows the company to contribute to sustainable practices and foster a positive impact on the environment [100]. The selection of a green supplier by the Semberka company was facilitated through the innovative application of expert decision making based on linguistic values. Fuzzy sets were employed to accommodate imprecise information, while rough sets addressed ambiguity and uncertainty in the decision-making process. This research utilized the fuzzy rough approach and employed the LMAW and MABAC methods.

The LMAW method was used to determine the criteria weights, with the transformation of linguistic values into fuzzy numbers and subsequent derivation of rough number boundaries being prerequisite steps. The quality criterion emerged as the most significant, while environmental product design received the lowest weight. However, the results indicate that the differences in weights between the selected criteria were not substantial, underscoring the importance of each criterion in the green supplier selection process. The MABAC method, previously adapted for the fuzzy rough approach, was further tailored for ease of use. Care was taken to ensure that the upper boundaries of preceding fuzzy numbers were not greater than the lower boundaries of subsequent fuzzy numbers when determining the rough number boundaries. This adjustment influenced the values in the initial decision matrix, to which the steps of the MABAC method were applied. Sensitivity analysis further demonstrated that even without altering the weights of individual criteria, this supplier consistently displayed the most favorable indicators.

Future research in this field should focus on exploring the long-term effects and outcomes of selecting green suppliers. Investigating the economic benefits, operational efficiency, and customer satisfaction resulting from such supplier selections would provide valuable insights for businesses aiming to incorporate ecological criteria into their decision-making processes.

## 7. Conclusions

Since many existing studies predominantly focus on either economic or environmental factors, neglecting the need for a comprehensive approach that holistically evaluates suppliers' performance in both dimensions, there is a gap that needs to be addressed. This research aims to fill that gap by developing an integrated evaluation framework that simultaneously incorporates economic and ecological criteria for green supplier selection. By merging these dimensions, organizations can make informed and sustainable supplier selection decisions that align with their overall sustainability objectives. The development of an integrated evaluation framework holds immense promise for the agricultural sector. It allows organizations to effectively balance economic and ecological considerations



in supplier selection, enabling them to identify suppliers that not only meet economic requirements but also demonstrate strong environmental stewardship and social responsibility. This comprehensive approach plays a crucial role in mitigating environmental impacts, supporting biodiversity conservation, and enhancing the overall sustainability of supply chains.

In the case of the Semberka company, this research applied an integrated fuzzy rough approach to solving the problem of selecting a green supplier. This approach was chosen to leverage the advantages offered by fuzzy and rough techniques, enhancing the decision-making process's reliability and providing decision makers with a safer and more robust framework. To implement this approach, customized versions of the LMAW and MABAC methods were utilized. The fuzzy rough LMAW method was used to determine the criteria weights, with the quality criterion receiving the highest weight. The fuzzy rough MABAC method was then employed to rank suppliers based on the observed criteria. The results indicated that supplier S2 achieved the best performance and was the preferred choice for establishing partnerships. These results were validated and further supported by sensitivity analysis. These results were confirmed through validation, wherein the same weights and initial decision matrix were utilized, employing different MCDM methods.

The advantage of applying the fuzzy rough approach lies in the fact that the combination of these approaches uses the good sides of both approaches. By applying the fuzzy approach, imprecise evaluations of decision making are used, while by applying the rough approach, the influence of subjectivity in decision making is reduced. In addition, the rough approach helps to solve the problem of uncertainty in decision making. Despite this, this approach has limitations. The application of this approach complicates calculations, as it requires transforming linguistic values into fuzzy values and determining rough number boundaries. Moreover, specific operations need to be applied to these numbers. However, despite these challenges, the fuzzy rough approach enhances the decision-making process's reliability by adapting the research to human thinking, reducing subjectivity in decision making, minimizing ambiguities, and addressing uncertainties. Furthermore, the practical example of selecting a green supplier provided a detailed explanation of this approach. Future research should focus on further applying and developing similar approaches that leverage the fuzzy rough approach. The case study of the Semberka company demonstrates the effectiveness of the fuzzy rough approach in making informed decisions that align with sustainability objectives. The research contributes to the field by addressing the limitations of existing studies and offering a comprehensive framework for green supplier selection. Further research is needed to expand the application of this approach and explore new approaches that build upon it.

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## Abbreviations

LMAW	Logarithm Methodology of Additive Weights
MABAC	Multi-attributive Border Approximation Area Comparison
AL	Absolutely low
VL	Very low
L	Low
ML	Medium-low

E	Equal
MH	Medium-high
H	High
VH	Very high
AH	Absolutely high
VB	Very bad
B	Bad
MB	Medium bad
M	Medium
MG	Medium good
G	Good
VG	Very good
SAW	Simple Additive Weighting
ARAS	Additive Ratio Assessment
CRADIS	Compromise ranking of alternatives from distance to ideal solution
WPM	Weighted Product Method

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