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Application of Multicriteria Decision-Making Methods in Lettuce Production Based on Agronomic and Economic Criteria

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ABSTRACT
Lettuce (*Lactuca sativa* L.) is an annual leafy vegetable crop from the Asteraceae family with the possibility to grow all year round. Two lettuce cultivars (red 'Murai' and green 'Aleppo') were cultivated in a greenhouse using two biofertilizers (a mixture of different effective microorganisms and *Trichoderma* spp. fertilizer), and their combination, during three consecutive growing seasons. This study aimed to find the optimal combination of fertilization treatments and growing seasons depending on different production criteria, using a multi-criteria decision-making (MCDM) method, Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS). A total number of 12 lettuce production models (alternatives) were proposed regarding fertilization treatments and planting dates. The study analyzed 12 criteria, which were divided into three groups: quantity, quality, and economic criteria. Weight coefficients were determined using the Analytic Hierarchy Process (AHP) method while, the stability of the obtained ranking list was investigated by applying comparative analysis using four other MCDM methods, as well as by performing sensitivity analysis through four scenarios. Cultivar 'Murai' showed the best results in the winter growing season with the application of *Trichoderma* spp. fertilizer, while cultivar 'Aleppo' in the spring with the combined fertilizers (effective microorganisms + *Trichoderma* spp). This study supports farmers and agricultural companies in optimizing planting schedules and biofertilizer selection tailored to specific cultivars, integrating quantity, quality, and economic criteria to enhance productivity and sustainability. Furthermore, it reveals the significant role of cultivar choice in optimizing biofertilizer type and growing season selection for lettuce production, demonstrating the MARCOS method's robustness as a decision-support tool in agricultural planning and management.

Keywords: Lettuce, Biofertilizer, Seasonality, MARCOS method, AHP, Sensitivity analysis

1. Introduction

Lettuce (*Lactuca sativa* L.) is a leafy vegetable crop from the Asteraceae family. It can be consumed as a whole head or as a fresh-cut vegetable mixed in ready-to-eat products. Consumers can choose different types determined by a variety of colors, textures, sizes, tastes, and nutritional values which ultimately define market price and preference (Mampholo et al. 2016). The health benefits originate from bioactive compounds such as vitamins, phenolic acids, flavonoids, carotenoids, and sesquiterpene lactones (Yang et al. 2022). The perception of "healthy food" is connected with its high antioxidant potential, contributing to a lower risk of diseases, leading to increased lettuce production and consumerism globally (Qin et al. 2018). Green leafy vegetables, including lettuce, are prone to nitrate accumulation despite containing healthy compounds. Nitrate, *per se* is non-toxic but can be converted into nitrite, leading to possible harmful effects.

Different production systems (open-field, covered systems or hydroponics) provide harvesting lettuce throughout the whole year in multiple cycles with an average vegetation period of 70-100 days. Lettuce is a cool-season crop, with the optimal day (21-23 °C) and night (15-18 °C) temperature during cultivation. In continental moderate climates, covered systems provide an opportunity to extend lettuce cultivation over the winter and early spring seasons, without using additional heating and lighting.

Excessive and uncontrolled usage of chemical fertilizers has adverse effects, leading to soil, water and air pollution, and deterioration of soil fertility, which has become one of the biggest threats in vegetable production. Recent life cycle assessment research on lettuce production found that chemical fertilizers, pesticides, and agricultural machinery contribute the most to

environmental impact and energy consumption (Mousavi et al. 2022). This study suggests reducing chemicals through biological approaches and integrated pest management to alleviate ecological and economic issues.

Single or mixed culture preparations (microbiological fertilizers, biofertilizers) contain different effective microorganisms found in natural habitats. They can be used to improve physical and biological soil properties, increase the diversity of microflora, and stimulate plant growth and yield through enhanced nutrient availability and uptake (Ibáñez et al. 2023). Among different beneficial fungus genera, *Trichoderma* spp. stands out as a biofertilizer, biopesticide, and soil improver. Previous studies have shown the positive impact of different biofertilizers on lettuce quantitative and qualitative traits (Avio et al. 2017; Ayuso-Calles et al. 2020). Biofertilizers are crucial for sustainable agriculture, improving environmental health, soil fertility and biodiversity, and pollution prevention, and can be applicable in conventional, organic, and integrated farming. With a better understanding of plant-microbe-environment interactions, biofertilizers can be cost-effective, eco-friendly, and a renewable nutrient source (Kumar et al. 2022).

Since the 1950s, several scientists have examined multi-criteria decision-making methods (MCDM) toward mathematical modeling capability to provide a base for structuring decision-making problems and creating preferences from alternatives (Taherdoost & Madanchian 2023), these methods found multiple applications in different disciplines and areas, including health care, the energy sector, engineering and optimizing production, human resources, supply chain management, corporate and enterprise sustainability and selection process, transportation systems and logistics, civil engineering, education, and portfolio management in finance. Taherdoost & Madanchian (2023) examined the popularity of various MCDM methods in different fields from 2012-2022. AHP, FST (Fuzzy Set Theory), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), and GP (Goal programming) were prominent, with 3.442 scientific papers from the engineering sector and only 471 in agricultural and biological sciences.

The decision-making process to choose an adequate biofertilizer depends on its influence on quantitative, qualitative, and economic results in lettuce production. Along with the type of fertilizer, the growing season is one of the most important parameters. The more criteria considered when choosing the most favorable solution, the higher the possibility of encountering conflicting (contradictory) conclusions. This significantly complex choice, and in such situations, MCDM methods can provide significant help by making the decision-making process more explicit, rational, and efficient. These methods involve evaluating multiple alternatives and criteria to make a decision and select the final solution. Accordingly, MCDM methods are increasingly being used to solve complex problems in agriculture (Vico et al. 2020). The application of MCDM methods in vegetable production and their inclusion in the decision process has not been extensively used in previous studies. Regarding lettuce production, MCDM methods can provide significant contributions to solving various decision-making problems. For example, Vico et al. (2017), using two MCDM methods-SAW (Simple Additive Weighting) and TOPSIS-selected the most favorable mulching method in winter production of the 'Santoro' lettuce cultivar, considering economic and nutritional parameters. Stojanović et al. (2024a), applying MABAC (Multi-Attributive Border Approximation Area Comparison) and AHP methods, chose the most favorable cultivar among five observed lettuce cultivars in summer production, taking into account morphological parameters. Additionally, Stojanović et al. (2024b) used the MCDM method WASPAS (Weighted Aggregates Sum Product Assessment) to select the most favorable among six lettuce cultivars, considering morphological parameters important for the fresh market or processing industry for ready-to-eat products. On the other hand, despite the known benefits of biofertilizers, there is a scarcity of literature that explores their use in lettuce greenhouse production through MCDM analysis; moreover, in the literature, there is little information on the economic and financial aspects of using biofertilizers in lettuce greenhouse production, taking into account production costs, yield, quality properties, and environmental viability.

Therefore, the objective of this study was to determine the most favorable alternative (in terms of choosing the appropriate type of biofertilizer and planting date-season) in two different lettuce cultivars using the above-mentioned methods, considering different quantitative, qualitative, and economic criteria taken into account for each of them.

In line with the defined research objective, the following hypotheses have been formulated and will be tested in this study: H1: By applying MCDM ranking methods that consider multiple criteria simultaneously, it is possible to select the most favorable production method, which remains optimal even when the relative importance of the selected criteria varies. H2: When choosing the most favorable alternative, taking into account the type of fertilizer used and the planting time, the cultivar will significantly influence the evaluated criteria and thus the highest-ranked alternative.

2. Material and Methods

The schematic diagram below illustrates the complete lettuce research design, accompanied by detailed explanations of each phase of the decision-making process and methodology (Figure 1).

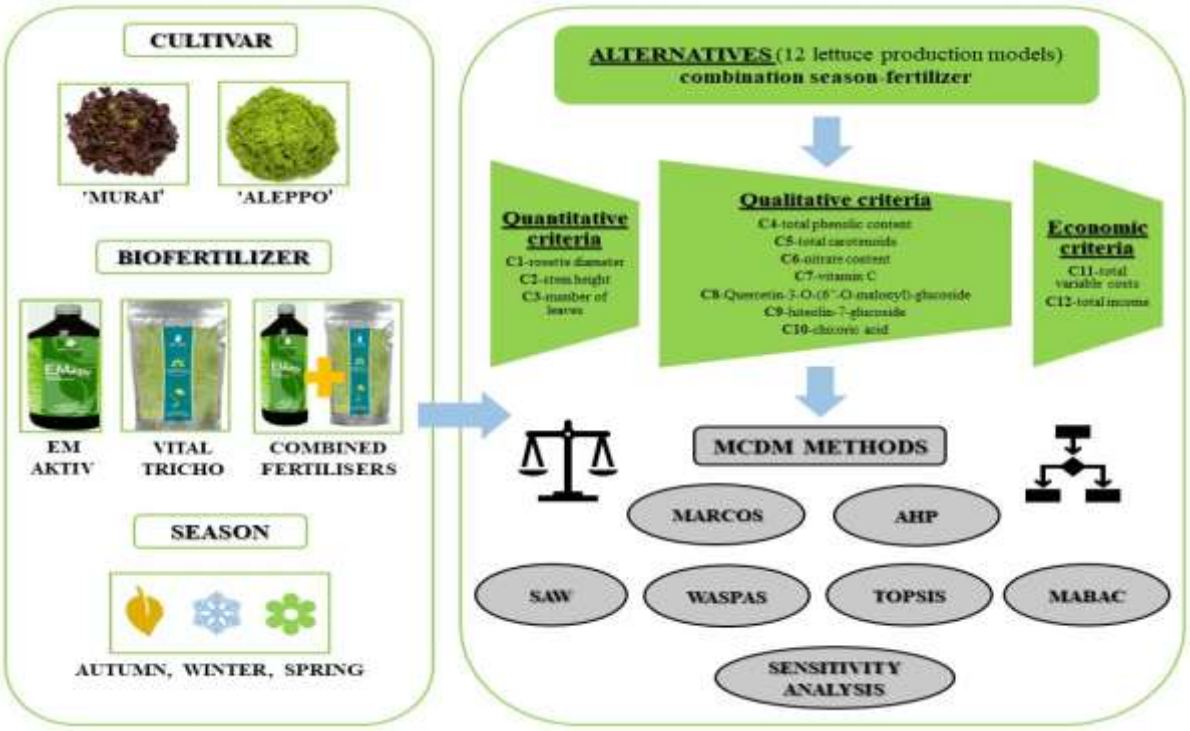


Figure 1- Schematic overview of the experimental design and methodology used in the lettuce study

2.1. Plant material and biofertilizers

The experiments included two lettuce Rijk Zwaan (De Lier, the Netherlands) cultivars belonging to two different types: Oak (red 'Murai' -*L. sativa* var. *crispa*) and Lollo (green 'Aleppo'-*L. sativa* var. *crispa*). Two different biofertilizers were studied. EM Aktiv (Candor, Em tehnologija, Valpovo, Croatia) is a liquid formulation that contains organic matter produced from the microbiological fermentation of molasses from sugar cane using effective microorganisms. Vital Tricho (Candor, Em tehnologija, Valpovo, Croatia) is a powder formulation of both *Trichoderma asperellum* and *Trichoderma viride* (5×10^9 CFU mL^{-1}). The third treatment is a combination of both fertilizers, EM Aktiv and Vital Tricho.

2.2. Experimental design and growing data

Lettuce experiments were organized in three successive growing seasons (autumn, winter, and spring) in the company Iceberg Salat Centar (Surčin, Serbia). Plants were cultivated in the greenhouse, an area of 256 m^2, without additional heating and lighting, in a fertile soil, covered with black mulch film. Before experiments, chemical soil analysis showed sufficient levels of macronutrients and humus. For that reason, mineral fertilizers were not applied. Trials were set up in a complete block design with four treatments (control - without fertilization, a fertilizer EM Aktiv, a fertilizer Vital Tricho, and a combination of EM Aktiv and Vital Tricho), in three replications. Main plots were sized 2 × 1 m with 32 plants in each plot and with 25 × 25 cm density. Biofertilizers were applied, via battery sprayer, in the soil before transplanting (150 mL EM Aktiv, 21 g Vital Tricho, and 150 mL + 21 g EM Aktiv and Vital Tricho, where each of the treatments was dissolved in 10 L of water). During the vegetation period, plants were treated foliarly four times (30 mL EM Aktiv, 12 g Vital Tricho, and 30 mL + 12 g EM Aktiv and Vital Tricho, where each of the treatments was dissolved in 6 L of water).

Regular agricultural practices such as irrigation, ventilation, pest prevention, hoeing, and weeding were performed throughout all growing seasons. Soil cultivation was done mechanically with a tractor and tiller. Manual tasks included setting up black mulch film, planting seedlings, hoeing, weeding, and ventilating the greenhouse. A battery sprayer was used for applying biofertilizers. Plants were irrigated with sprinklers powered by an electric pump. Manual labor hours and the number of employees required for each operation were calculated, along with electricity and fuel usage.

2.3. Climatic conditions

Climatic data were measured using the RC-4HC Data Logger (Elitech Technology Inc., San Jose, CA, USA). Air temperature and air relative humidity were measured for 24 hours during all experiments (Figure 2). The photoperiod changed from the date of transplanting to harvest in autumn (11-9 h), winter (9-13 h), and spring (14-15 h).

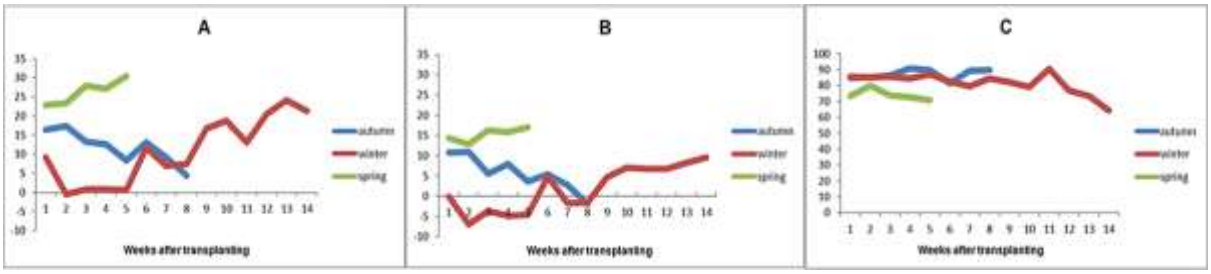


Figure 2- Climatic parameters during lettuce cultivation. A-average day temperature (°C); B-average night temperature (°C); C-average air relative humidity (%)

2.4. Data collection and MCDM analysis

Plants were harvested on the same day when both cultivars reached physiological maturity and commercial size. Morphological and quantitative parameters (rosette diameter, stem height, rosette fresh weight, and number of leaves) were measured immediately after the harvest, using a scale, ruler, and caliper.

For qualitative analysis, total phenolic content was measured spectrophotometrically (Multiskan Spectrum, Thermo Electron Corporation, Vantaa, Finland) using the Folin-Ciocalteu reagent (Dragišić Maksimović & Živanović 2012). Total carotenoids were determined spectrophotometrically (Multiskan Spectrum, Thermo Electron Corporation, Vantaa, Finland) according to Lichtenthaler & Wellburn (1983). Nitrate content was determined using rapid colorimetric determination of nitrate (UV-VIS spectrophotometer, 1166, Lamboled, Inc., Los Angeles, CA, USA) by nitration of salicylic acid reported by Cataldo et al. (1975), with nitrite removed by adding sulfamic acid (Jana & Moktan 2013). The vitamin C content was determined spectrophotometrically (Tecan Sunrise Spectrophotometer, Tecan Group, Männedorf, Switzerland) according to Stevens et al. (2006). From frozen samples homogenized in methanol (80%) acidified with formic acid, 98:2 (*v*/*v*) were determined quercetin derivate, luteolin-7-glucoside, and chicoric acid using Waters HPLC system (Waters, Milford, MA, USA).

Taking into account the planting date and biofertilizer, a total of 12 production models (alternatives) were created as presented in Table 1.

Table 1- Lettuce production models

Combination planting date-fertilizer	*Model*	*Combination planting date-fertilizer*	*Model*
Autumn - Without fertilization (control)	Model 1 (A1)	Autumn - Vital Tricho	Model 7 (A7)
Winter - Without fertilization (control)	Model 2 (A2)	Winter - Vital Tricho	Model 8 (A8)
Spring - Without fertilization (control)	Model 3 (A3)	Spring - Vital Tricho	Model 9 (A9)
Autumn - EM Aktiv	Model 4 (A4)	Autumn - EM Aktiv + Vital Tricho	Model 10 (A10)
Winter - EM Aktiv	Model 5 (A5)	Winter - EM Aktiv + Vital Tricho	Model 11 (A11)
Spring - EM Aktiv	Model 6 (A6)	Spring - EM Aktiv + Vital Tricho	Model 12 (A12)

In Table 1 models 1-3 are control variants, i.e., they represent models in which no biofertilizer was used, and differ regarding planting date-growing season. Models from 4-12 represent a combination of planting date and biofertilizer application. A total of 12 criteria were observed for each of the models used, and are represented in Table 2.

Table 2- Quantitative, qualitative, and economic criteria analyzed in the study

Quantitative criteria		**Qualitative criteria**	
C1	Rosette diameter (cm)	**C7**	Vitamin C content (mg 100 g^{-1} FW)
C2	Stem height (mm)	**C8**	Quercetin-3-O-(6″-O-malonyl)-glucoside (mg g^{-1} DW)
C3	Number of leaves	**C9**	Luteolin-7-glucoside (mg g^{-1} DW)
Qualitative criteria		**C10**	Chicoric acid (mg g^{-1} DW)
C4	Total phenolic content (µg GA eq g^{-1} FW)	**Economic criteria**	
C5	Total carotenoids (µg g^{-1} FW)	**C11**	Total variable costs (USD m^{-2})
C6	Nitrate content (mg kg^{-1} FW)	**C12**	Total income (USD m^{-2})

Economic criteria considered evaluating total variable costs and total income for all models. The total income was obtained by multiplying the harvested yield with the average sales price during the three growing seasons. Total variable costs (C11) and total income (C12) are (in used models) expressed in USD m^{-2} of the area converted at the average middle exchange rate for the specified period (1 USD=114.0608 RSD).

Solving the multi-criteria decision-making problem in this study was performed using the MARCOS method. The MARCOS method was chosen over other MCDM methods for several reasons. Firstly, the results of its application indicate less sensitivity

compared to other MCDM methods. Secondly, it defines ideal and anti-ideal solutions, providing a comprehensive basis for the evaluation of alternatives, and with its innovative approach to determining their utility, it improves the accuracy of the ranking. Thirdly, it is computationally less complex than some other methods (e.g., PROMETHEE- Preference Ranking Organization Method for Enrichment Evaluation).

The choice of MCDM methods over other multivariate statistical methods was made due to the very nature of the problem-specifically, because it involves decision-making and the evaluation of alternatives based on predefined goals and priorities, rather than just the statistical similarity or distance between data. For example, Ivanović's distance, as a multivariate method that can be used for data ranking, does not take into account the importance of individual criteria, and it is difficult to explain the importance of each one for the final rank. On the other hand, by applying an MCDM method, each criterion is explicitly defined and assigned a weight.

The method was developed by Stević et al. (2020) in the healthcare industry, and the authors compared it with other MCDM methods, MABAC, ARAS (Additive Ratio Assessment), WASPAS, SAW, TOPSIS, and EDAS (Evaluation based on Distance from Average Solution). This method is based on defining the relationship between alternatives and reference values, i.e., ideal and anti-ideal alternatives. According to the defined relationships, the utility functions of the alternatives are determined, i.e., the position of the same to the ideal and anti-ideal solution, and a compromise ranking is made, declaring the best alternative closest to the ideal, i.e., the furthest from the anti-ideal solution.

The ranking procedure using the MARCOS method consists of seven steps. In the first step, an initial decision matrix is established with *n* criteria and *m* alternatives. In the second step, the initial matrix is expanded by adding the same ideal (*AI*) and anti-ideal alternatives (*AAI*). The *AAI* represents the most unfavorable values for each observed criterion, which represents the highest values for cost criteria and the least for benefit criteria. The *AI* represents the most favorable values for each observed criterion. The third step involves the normalization of the data from the expanded matrix in such a way that the cost criteria are normalized by bringing the most favorable value of the observed criteria into relation with the value that should be normalized. In the case of the benefit criterion, the procedure is reversed, that is, normalization of the data is done by bringing the value that is normalized to the most favorable value. The next step involves determining the weight matrix by multiplying the values of the normalized matrix with weight coefficients. Then, in the fifth step, the degree of usefulness of alternative *K* is calculated to the ideal and anti-ideal solution using the following equations:

$$K_i^- = \frac{S_i}{S_{aai}} \tag{1}$$

$$K_i^+ = \frac{S_i}{S_{ai}} \tag{2}$$

Where it:

$S_i -$ represents the sum of the elements of the weight matrix

In the next step, the utility function of the alternatives is determined as a compromise of the observed alternative to the ideal and anti-ideal solutions by applying the following equation:

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1 - f(K_i^+)}{f(K_i^+)} + \frac{1 - f(K_i^-)}{f(K_i^-)}} \tag{3}$$

Where it:

$f(K_i^-)$ - represents the utility function with the anti-ideal solution
$f(K_i^+)$ - represents the utility function with the ideal solution.

The utility functions of ideal and anti-ideal solutions are determined using the following equations:

$$f(K_i^-) = \frac{\mathrm{K}_i^+}{K_i^+ + K_i^-} \tag{4}$$

$$f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^-} \quad (5)$$

In the final step, the alternatives are ranked in a way that a higher value of the utility function implies a better position in the ranking list and vice versa.

Weight coefficients were determined using the AHP method (Al-Harbi 2001). The stability of the obtained ranking list was investigated by applying comparative analysis using MCDM methods SAW (MacCrimmon 1968), WASPAS (Zavadskas et al. 2012), TOPSIS (Hwang & Yoon 1981), MABAC (Pamučar & Ćirović 2015), as well as by performing sensitivity analysis. Spearman's rank correlation coefficient was calculated for both cultivars to test possible relationships between ranking lists of the used MCDM methods.

3. Results and Discussion

The total variable costs included the costs of materials (seeds-seedlings, pesticides, biofertilizers, black mulch film, and others), labor costs, electricity costs, sales (packaging), and others. The key reasons for the distinction in the total variable costs are the differences in production technology by growing seasons, and thus the differences in labor costs, plant protection costs, as well as fertilization costs (Table 3).

Table 3- The structure of variable costs in lettuce production

	Indicator (cost type)	*USD m^{-2}*
1.	Material costs	0.84-1.20
-	*Seedlings*	0.61
-	*Biofertilizers*	0.00-0.35
-	*Preventive protection*	0.00-0.01
-	*Black mulch film*	0.05
-	*Irrigation sprinklers*	0.17
2.	Fuel costs	0.01-0.02
3.	Costs of electrical energy	0.00-0.01
4.	Labor costs	0.10-0.12
5.	Cost of sales (packaging)	0.38
6.	Other costs	0.00-0.12
7.	Total variable costs	1.33-1.84

Material costs have the largest share in total variable costs, which, depending on the production model, range from 56.40-70.56%. Seedling costs had the largest share in total material costs (51.15-73.16%). The cost of biofertilizers had the highest value when using the combination EM Aktiv + Vital Tricho (0.35 USD m^{-2}), while in the case of control alternatives, they were 0.00 USD m^{-2}. Other costs included the costs of black mulch film, rabbit nets and disinfectants, which were also only present on certain models.

Economic profitability and efficiency are one of the most important goals for farmers and the leafy vegetable processing industry. On the other hand, the market sets up different demands regarding the quantity and quality parameters of vegetables in a food supply chain, which are important for consumers. Market quality requirements can be reduced in case of a lack of lettuce on the market, or set through stricter standards control in case of surplus production (Simko et al. 2014). Lettuce breeding aims to increase yield, improve pest and physiological disorder resistance, and ensure adaptability and quality. Bodiroga et al. (2022) stated that vegetable production in a protected area without additional heating has economic validity, in the way defined by the investment models, which includes the current method of financing and risky business situations. Our study showed that seedlings and biofertilizer costs account for the largest share of variable costs in all seasons (Table 3). Globally, overreliance on chemical fertilizers has resulted in ecological and economic issues and the possible accumulation of harmful compounds. Commercial biofertilizers are gaining more attention as a cleaner alternative, but their production costs remain significant. Using low-cost materials, like agro-industrial residues enriched with rock phosphate, can help reduce these costs (Fasusi et al. 2021).

Therefore, one question arises, such as to, the economic benefit of the application of biofertilizers in lettuce greenhouse production in different growing seasons, and its optimization. The effects of biofertilizers on various quantity and quality parameters depend on the cultivar, environmental factors, soil type and fertility, application method, dosage, and plant-microorganism interactions. Evaluating comprehensive efficiency and sustainability in lettuce production is challenging when considering these parameters separately. Beyond biofertilizer effects, cultivar and season significantly influence the selection of an appropriate lettuce production model, complicating the final solution. Progress in different agricultural areas requires technology and better tools to evaluate data skillfully to transform them into better decisions and actions (Zavadskas et al. 2016). In this context, MCDM methods can be a useful approach to making the final decision.

In agriculture, there are various examples of the application of different MCDM methods. AHP method, for instance, has been used to select optimal areas for sustainable grape production (D'Antonio et al. 2025). Other applications include evaluating the efficiency of agricultural enterprises with the WASPAS method (Lukić et al. 2021) and recommending paddy fertilizer using the SMART (Simple Multi-Attribute Rating Technique) and AHP method (Sumaryanti et al. 2019). Additionally, researchers have applied Entropy and TOPSIS to assess the contribution of medicinal and aromatic plants to the Turkish economy (Ersen 2024), and used AHP and TOPSIS to define alternative plants based on a region's characteristics by anticipating risk factors in advance (Işık 2023). Finally, the Fuzzy-SWARA (Stepwise Weight Assessment Ratio Analysis) method has been used to determine the soil erodibility factor (Dengiz et al. 2025). Also, MCDM methods were usually employed to solve different problems in fruit production, such as apple and pear (Hao et al. 2022; Nedeljković et al. 2022).

3.1. Ranking alternatives using the MARCOS method

According to the expert's opinion, several different criteria were highlighted as important to individual growers, the processing industry for ready-to-eat products and consumers. Morphological parameters, such as rosette fresh weight, stem length, and number of leaves, are crucial traits for farmers, producers, and breeders. Besides rosette fresh weight and yield, which are important for the individual farmers and whole head sale market, other traits are crucial for the processing industry. The presence of old, damaged and yellowish leaves, a higher number of old leaves, and long stems can significantly increase the amount of waste for disposal and contribute to material and economic losses. Quality parameters study revealed differences in flavonoids, vitamin C, and antioxidant activity among lettuce groups, where red lettuce cultivars stood out with higher levels of bioactive compounds (Mampholo et al. 2016). Chicoric acid and different quercetin compounds were found as the main phenolic compounds in lettuce samples (Santander et al. 2022). Green lettuce cultivars showed higher rosette fresh weight, whereas red cultivars showed higher antioxidant capacity and total phenolic content (Liu et al. 2007; Barickman et al. 2018). For that purpose, we chose 12 different production models and 12 different criteria for the decision to be complete (Table 1 and Table 2). Therefore, taking into account all the suggested criteria, in the process of ranking various production alternatives, the problem of multi-criteria decision-making is formulated. We used the MARCOS method as the starting point for selecting the optimal combination of planting date and biofertilizer due to its stability, even with numerous criteria and alternatives. Stević et al. (2020) confirmed the stability and precision of the MARCOS method, providing evidence that the method is not sensitive to the change of different measurement scales. Even though it is a new method that has been used to address multiple questions in different areas, such as supplier selection in the iron and steel industry (Chakraborty et al. 2020), evaluation of insurance during the COVID-19 pandemic (Ecer & Pamučar 2021), transport efficiency (Stević et al. 2022), and resource selection in mobile crowd computing (Pramanik et al. 2021).

The ranking methodology according to the MARCOS method is presented in detail using the results for the red cultivar 'Murai', while for the green 'Aleppo' are presented initial decision matrix and the final ranking results. The initial decision matrix formed in the first step, which consists of 12 criteria and 12 alternatives, is expanded by adding *AI* and *AAI* (Table 4).

Table 4- Extended initial decision matrix for cultivar 'Murai'

A	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*	*C8*	*C9*	*C10*	*C11*	*C12*
AAI	27.68	79.42	17.78	132.23	2.60	628.54	4.08	1.02	1.87	7.94	1.80	1.60
A1	27.68	20.77	17.78	237.03	5.43	628.54	7.13	2.02	2.11	10.68	1.35	1.60
A2	31.96	38.88	20.00	174.60	4.30	374.73	6.03	2.07	4.36	18.45	1.43	3.72
A3	32.24	75.87	34.00	138.43	3.47	89.09	6.28	1.05	2.53	8.39	1.33	5.28
A4	29.43	24.19	18.33	213.77	3.77	607.06	6.04	1.35	1.91	8.07	1.40	1.86
A5	29.58	41.53	20.44	351.07	5.20	455.48	4.19	5.50	9.39	41.97	1.48	4.00
A6	31.63	79.42	31.11	156.93	4.30	198.69	4.08	1.14	3.57	12.05	1.38	4.57
A7	29.66	25.28	19.33	204.90	2.60	627.11	5.42	1.30	1.87	7.94	1.70	2.21
A8	31.78	45.08	19.89	458.60	5.47	514.37	4.18	6.54	9.30	37.59	1.78	3.62
A9	31.20	72.84	29.89	136.40	4.40	230.96	5.67	1.03	2.63	9.20	1.68	4.31
A10	32.00	27.08	21.00	191.33	2.70	472.44	6.40	1.33	1.97	8.31	1.72	2.57
A11	33.37	45.01	21.44	303.00	4.73	505.08	5.00	4.71	7.14	30.18	1.80	3.51
A12	29.87	71.71	32.11	132.23	4.77	382.66	5.23	1.02	3.65	12.41	1.71	4.12
AI	33.37	20.77	34.00	458.60	5.47	89.09	7.13	6.54	9.39	41.97	1.33	5.28

Abbreviations: A1: model 1 (autumn - without fertilization-control), A2: model 2 (winter - without fertilization-control), A3: model 3 (spring - without fertilization-control), A4: model 4 (autumn - EM Aktiv), A5: model 5 (winter - EM Aktiv, A6: model 6 (spring - EM Aktiv), A7: model 7 (autumn - Vital Tricho), A8: model 8 (winter - Vital Tricho), A9: model 9 (spring - Vital Tricho), A10: model 10 (autumn - EM Aktiv + Vital Tricho), A11: model 11 (winter - EM Aktiv + Vital Tricho), A12: model 12 (spring - EM Aktiv + Vital Tricho), C1: rosette diameter, C2: stem height, C3: number of leaves, C4: total phenolic content, C5: total carotenoids, C6: nitrate content, C7: vitamin C content, C8: quercetin-3-O-(6″-O-malonyl)-glucoside, C9: luteolin-7-glucoside, C10: chicoric acid, C11: total variable costs, C12: total income, AI: ideal alternatives, AAI: anti-ideal alternatives

In the next step, the data from the extended initial matrix were normalized using the normalization process for the cost criteria (K_2, K_6 and K_{11}) by bringing the most favorable value of the observed criterion into the ratio of the value that should be normalized, and the other criteria by applying the reverse procedure (Table 5).

Table 5- Normalized matrix for cultivar 'Murai'

A	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*	*C8*	*C9*	*C10*	*C11*	*C12*
AAI	0.83	0.26	0.52	0.29	0.48	0.14	0.57	0.16	0.20	0.19	1.35	0.30
A1	0.83	1.00	0.52	0.52	0.99	0.14	1.00	0.31	0.22	0.25	1.01	0.30
A2	0.96	0.53	0.59	0.38	0.79	0.24	0.85	0.32	0.46	0.44	1.07	0.70
A3	0.97	0.27	1.00	0.30	0.63	1.00	0.88	0.16	0.27	0.20	1.00	1.00
A4	0.88	0.86	0.54	0.47	0.69	0.15	0.85	0.21	0.20	0.19	1.05	0.35
A5	0.89	0.50	0.60	0.77	0.95	0.20	0.59	0.84	1.00	1.00	1.11	0.76
A6	0.95	0.26	0.92	0.34	0.79	0.45	0.57	0.17	0.38	0.29	1.04	0.87
A7	0.89	0.82	0.57	0.45	0.48	0.14	0.76	0.20	0.20	0.19	1.28	0.42
A8	0.95	0.46	0.58	1.00	1.00	0.17	0.59	1.00	0.99	0.90	1.34	0.69
A9	0.94	0.29	0.88	0.30	0.80	0.39	0.80	0.16	0.28	0.22	1.26	0.82
A10	0.96	0.77	0.62	0.42	0.49	0.19	0.90	0.20	0.21	0.20	1.30	0.49
A11	1.00	0.46	0.63	0.66	0.87	0.18	0.70	0.72	0.76	0.72	1.35	0.67
A12	0.90	0.29	0.94	0.29	0.87	0.23	0.73	0.16	0.39	0.30	1.28	0.78
AI	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Abbreviations under Table 4

The weighted matrix was determined by multiplying the values of the normalized matrix with the weighting coefficients shown in Figure 3. The AHP method is selected due to its ability to balance qualitative criteria and easily fit in a detailed simulation mode (Meng et al. 2014).

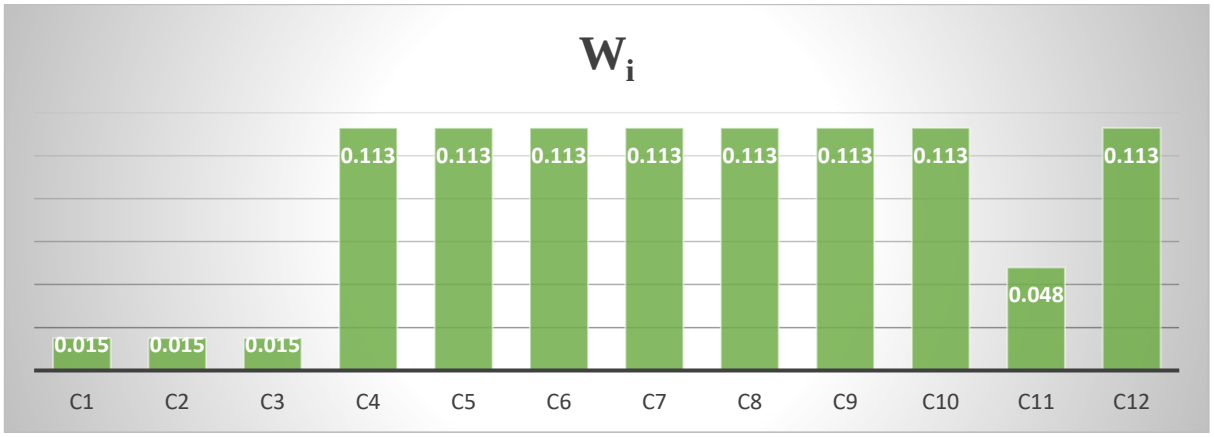


Figure 3- Weighting coefficients (w_i) according to the AHP method for cultivar 'Murai'. Abbreviations under Table 4

In the next three steps, the degree of usefulness of alternatives *K*, the utility function of alternatives f(K_i) was calculated, and the alternatives ranking was performed, and presented in Table 6.

Table 6- Degree, utility function and ranking list of alternatives for cultivar 'Murai'

A	*Si*	*K-*	*K+*	*f(K-)*	*f(K+)*	*f(Ki)*	*Rank*
AAI	0.35	1.00	0.35	0.26	0.74	0.38	----
A1	0.51	1.44	0.51	0.26	0.74	0.54	9
A2	0.56	1.57	0.56	0.26	0.74	0.59	5
A3	0.59	1.66	0.59	0.26	0.74	0.62	4
A4	0.44	1.24	0.44	0.26	0.74	0.46	11
A5	0.77	2.19	0.77	0.26	0.74	0.82	2
A6	0.52	1.47	0.52	0.26	0.74	0.55	6
A7	0.42	1.18	0.42	0.26	0.74	0.44	12
A8	0.81	2.30	0.81	0.26	0.74	0.86	1
A9	0.52	1.47	0.52	0.26	0.74	0.55	8
A10	0.45	1.27	0.45	0.26	0.74	0.48	10
A11	0.69	1.96	0.69	0.26	0.74	0.74	3
A12	0.52	1.47	0.52	0.26	0.74	0.55	7
AI	1.00	2.83	1.00	0.26	0.74	1.06	----

Abbreviations under Table 4

According to the results presented in Table 6, the best-ranked alternative for the red cultivar 'Murai' was A8, which included growing lettuce in the winter season with the application of Vital Tricho biofertilizer, followed by winter season growing with

EM Aktiv biofertilizer (A5), while the worst-ranked alternative was growing in autumn season with Vital Tricho biofertilizer (A7).

The same procedure was applied to the green cultivar 'Aleppo' to determine whether the selection of the cultivar, as well as leaf color, had an impact on the obtained ranking results. The initial decision matrix for cultivar 'Aleppo' is presented in Table 7.

Table 7- Initial decision matrix for cultivar 'Aleppo'

A	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*	*C8*	*C9*	*C10*	*C11*	*C12*
A1	25.80	22.82	15.00	372.70	3.60	530.18	10.64	1.07	1.06	3.90	1.35	1.65
A2	28.30	29.52	24.00	116.90	3.17	784.06	5.05	1.19	2.17	11.30	1.43	4.33
A3	30.80	80.66	33.00	92.47	4.20	85.52	5.39	1.00	1.30	5.15	1.33	6.69
A4	28.50	22.29	17.00	313.00	2.47	658.47	6.00	0.83	0.68	9.59	1.40	2.17
A5	29.60	35.74	28.00	123.37	3.83	791.02	3.18	1.14	3.28	17.85	1.48	4.69
A6	30.30	66.91	32.00	112.40	3.90	213.91	8.31	0.87	1.17	5.39	1.38	5.22
A7	28.50	14.37	18.00	226.60	2.13	677.78	5.23	0.92	0.81	7.34	1.70	2.62
A8	30.40	37.75	29.00	131.10	4.83	561.46	6.58	1.34	2.93	13.08	1.78	5.45
A9	27.40	66.74	32.00	102.60	3.73	63.85	6.40	1.00	2.00	8.15	1.68	4.87
A10	28.10	20.61	19.00	358.47	2.77	722.34	4.91	0.80	0.81	12.80	1.72	2.86
A11	32.30	44.77	29.00	18.33	4.60	709.59	3.76	1.21	2.25	13.69	1.80	5.94
A12	28.80	69.37	35.00	115.83	3.93	76.32	6.31	1.13	4.68	17.08	1.71	4.90

Abbreviations under Table 4

Taking into account the previously explained ranking procedure, a ranking list of alternatives for the cultivar 'Aleppo' was determined (Table 8).

Table 8- Ranking list of alternatives for cultivar 'Aleppo'

A	*A1*	*A2*	*A3*	*A4*	*A5*	*A6*	*A7*	*A8*	*A9*	*A10*	*A11*	*A12*
Rank	7	9	5	11	4	8	12	2	3	10	6	1

Abbreviations under Table 4

Based on the results from Table 8, the second hypothesis can be confirmed, indicating that the lettuce cultivar influenced the choice of the most favorable alternative. Results for cultivar 'Aleppo' showed that the best-ranked alternative was A12 (Spring - EM Aktiv + Vital Tricho), followed by the A8 alternative, which was the best-ranked for the cultivar 'Murai'. The worst-ranked alternative was A7, which was also the case with the cultivar 'Murai'. Similarly, the impact of the season on quantitative parameters, as a result of increased chlorophyll content and photosynthetic activity, showed that lettuce grown in autumn produces lower biomass and yield compared to spring (Rouphael et al. 2019). Also, there was a cultivar effect, where for each cultivar different production model was the most adequate. Based on the results presented in Table 9, it can be concluded that cultivating lettuce during the winter using the fertilizer Vital Tricho (A8) achieved the most favorable overall results for both cultivars, with the 'Murai' cultivar ranked first and the 'Aleppo' cultivar ranked second.

Table 9- Summary table of the best-ranked alternatives for cultivars 'Aleppo' and 'Murai'

Cultivar	***Rank and label of the alternative***		
	Rank 1	**Rank 2**	**Rank 3**
Aleppo	A12	A8	A9
Murai	A8	A5	A11

Abbreviations under Table 4

Literature data demonstrated that *Trichoderma* treatment alleviated the detrimental effects of cold stress on tomato plants, leading to increased photosynthetic and growth rates (Ghorbanpour et al. 2018). Treatments with *Trichoderma harzianum*, even when combined with reduced nutrient solutions, resulted in the highest fresh weight of shoots and nutrient concentrations, demonstrating its potential to enhance biomass production while reducing the reliance on chemical fertilizers (Shabani et al. 2024). Given that each MCDM method has certain particularities compared to others, a comparison of the results obtained using the MARCOS method was made with the results of the four previously mentioned MCDM methods. This procedure does not intend to question the accuracy of the method used, yet confirms the obtained results. The ranking of alternatives using other MCDM methods is given in Figure 4.

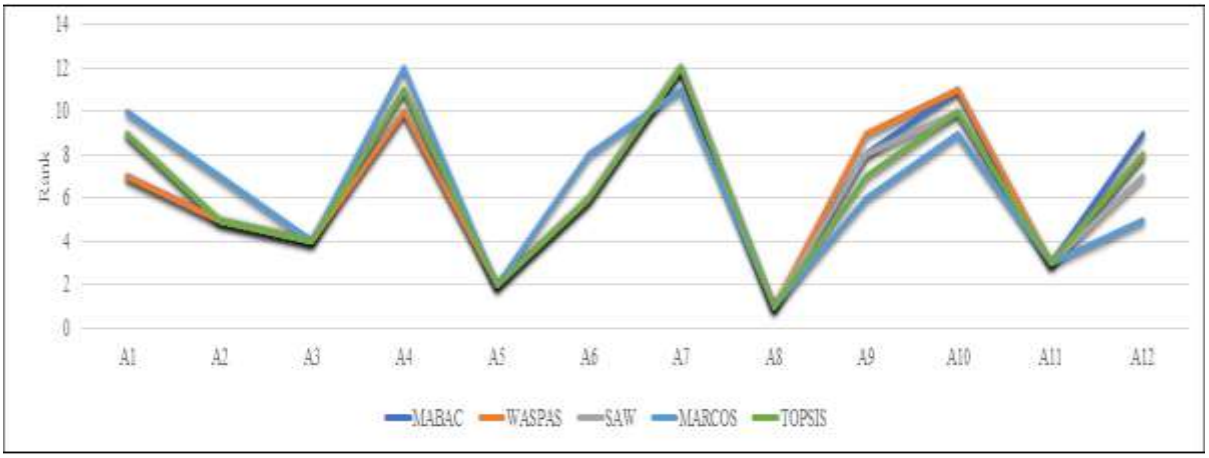


Figure 4- Ranking of alternatives using other MCDM methods ('Murai'). Abbreviations under Table 4

Results from the ranking alternatives showed that all methods used in this study ranked the first six alternatives in the same way, as well as the last one on the ranking list. In other ranking positions, there were minor deviations, which can be expected when there are several alternatives that do not differ significantly in the observed criteria. Furthermore, by using Spearman's rank correlation coefficient, the connection between the ranking lists gathered by using individual methods was additionally analyzed (Table 10).

Table 10- Spearman's rank correlation coefficient for cultivar 'Murai'

Method	MABAC	WASPAS	SAW	MARCOS	TOPSIS
MABAC	1.00	0.99	0.97	0.97	0.97
WASPAS	0.99	1.00	0.97	0.97	0.97
SAW	0.97	0.97	1.00	1.00	0.99
MARCOS	0.97	0.97	1.00	1.00	0.99
TOPSIS	0.97	0.97	0.99	0.99	1.00

The connection between the ranking lists obtained using different MCDM methods was found to be very strong. This was confirmed by the high correlation coefficient values, which ranged from 0.97 to 1.00, thus validating the results of the MARCOS method for the 'Murai' cultivar (Table 10).

Results of all methods used, as well as the MARCOS method, for the cultivar 'Aleppo', ranked the alternative A12 as the best, followed by the alternative A8, while the worst-ranked alternative was A7. The values of Spearman's rank correlation coefficient for cultivar 'Aleppo' are presented in Table 11.

Table 11- Spearman's rank correlation coefficient for cultivar 'Aleppo'

Method	MABAC	WASPAS	SAW	MARCOS	TOPSIS
MABAC	1.00	0.94	0.97	0.97	0.80
WASPAS	0.94	1.00	0.94	0.94	0.83
SAW	0.97	0.94	1.00	1.00	0.85
MARCOS	0.97	0.94	1.00	1.00	0.85
TOPSIS	0.80	0.83	0.85	0.85	1.00

In a mutual comparison, the MARCOS, WASPAS, SAW, and MABAC methods have a very strong to perfect relationship with correlation coefficient values of 0.94-1.00, while the ranking list obtained by the TOPSIS method indicates a strong relationship compared to other methods (Table 11).

To assess the impact of changes in the weighting coefficients on the ranking of alternatives, a sensitivity analysis was conducted (Božanić et al. 2019). A sensitivity analysis was conducted through four scenarios. In the first scenario, all criteria are given the same importance (Figure 5, S1). Through the other three scenarios, in each of them, criteria from one group, qualitative (S2), quantitative (S3), and economic (S4) were individually given two times greater importance compared to criteria from other groups that had equal importance (Figure 5).

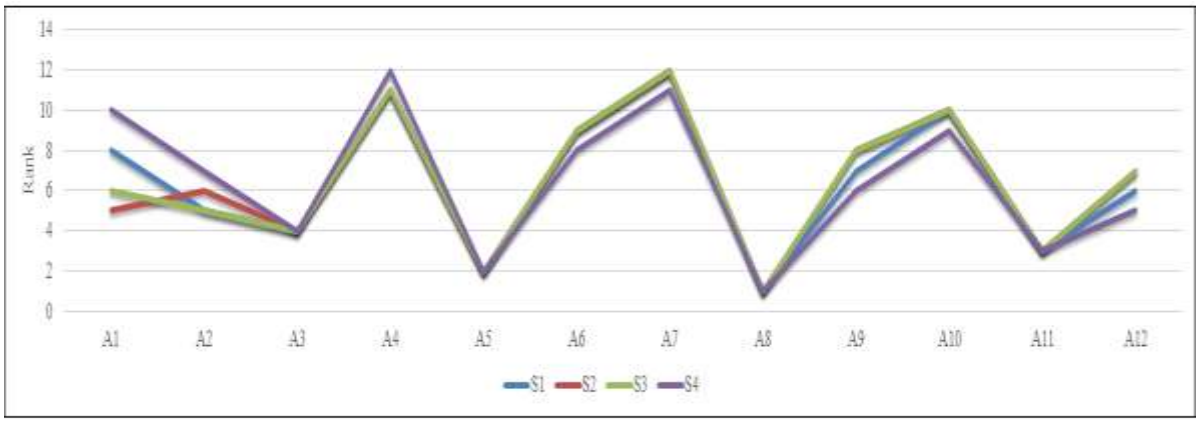


Figure 5- Sensitivity analysis for cultivar 'Murai'. Abbreviations under Table 4

Sensitivity analysis results for cultivar 'Murai' showed that there were no significant changes in the ranking list. The best-ranked alternatives as well as the worst-ranked ones in most scenarios kept the same positions in the ranking list. Thus, in all scenarios, alternative A8 was ranked the best, alternative A5 ranked second, and alternative A11 ranked third. In 75% of the scenarios, the A7 alternative was the last on the ranking list, while in the remaining 25% of the scenarios, such as in a situation where a two-fold value is assigned to economic criteria, this alternative took the 11th position. In the same way, the sensitivity analysis procedure was carried out for the cultivar 'Aleppo' (Figure 6).

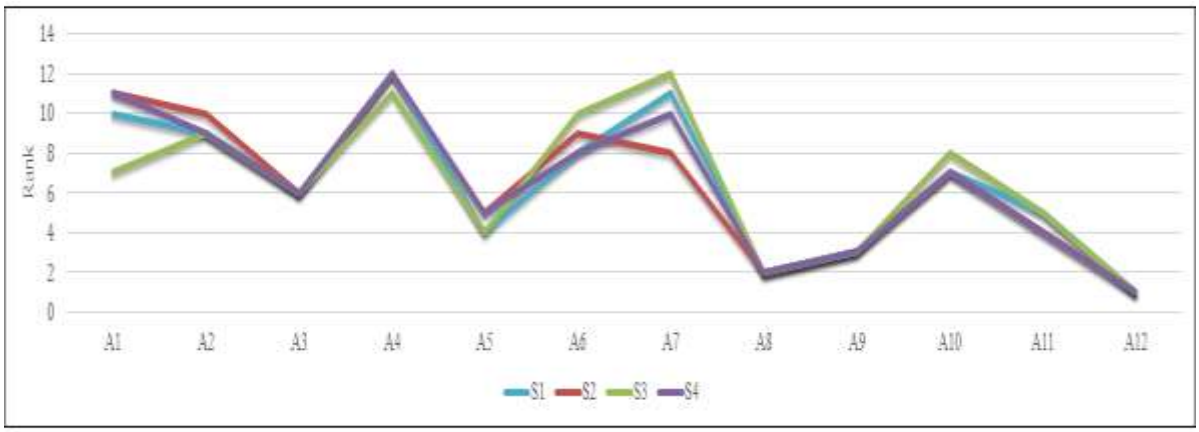


Figure 6- Sensitivity analysis for cultivar 'Aleppo'. Abbreviations under Table 4

Results for the sensitivity analysis for the cultivar 'Aleppo' confirmed no significant changes in the alternative ranking compared to the created ranking list. In all scenarios, alternative A12 was ranked the best, alternative A8 was ranked second, and alternative A9 was third. In 75% of the scenarios, alternative A4 was the last on the ranking list, while in the remaining 25% of the scenarios, such as in the situation where the two-fold value is assigned to qualitative criteria compared to the other observed ones, it took the 11th position. Based on the results of the sensitivity analysis, the first hypothesis can be confirmed, as the highest-ranked alternative retained its position for both cultivars across all four scenarios. Maksimović et al. (2021) validated the fuzzy MARCOS method results using sensitivity analysis in the overall ranking of plum varieties. Despite higher fertilization treatment costs, our study found that models A8 and A12 exhibit the best economic and biotechnical characteristics. They provide the most suitable material for farmers and the processing industry, being rich in bioactive compounds and economically viable. The application of MCDM methods in vegetable production and their inclusion in the decision process has not been extensively used in previous studies.

This study explored various perspectives in the decision-making process. By observing the individual criteria for each analyzed alternative in the initial extended matrix, it is possible to evaluate each of their contributions. In agricultural production, it is rare to consider only one criterion, farmers and the industry prioritize multiple criteria to produce high yields and quality products. MCDM methods are crucial for combining these criteria to find the optimal solution. The results of this study are beneficial to growers from the aspect of defining the structure for all costs leading to the optimization of the production, effect of biofertilizer, and season on different properties, taking into account all criteria before making decisions in short- and long-term periods. In total variable costs, fertilization costs account for 1.70-20.65% (Table 3), which could be a limiting factor in the acceptance of the application of biofertilizers by the farmers, especially when the control variants did not show the worst results. On the other hand, applying the MARCOS method and validating it with other MCDM methods greatly enhances the scientific contribution of this study. Before making a decision, it is necessary to consider the positive effects of the application of biofertilizers regarding

decreasing soil, water, and air pollution, as well as expanding soil diversity and the availability of nutrients, and their contribution to the quantity and quality parameters. Results on tomato in pot and field trials revealed that reduced rates of chemical fertilizer combined with bio-organic fertilizer produced tomato yields equivalent to those achieved with 100% chemical fertilizer (Ye et al. 2020). Also, each cultivar has its pros and cons, and many of the quality and quantity parameters depend on lettuce type and leaf color. Seasonality plays a great role in the way that temperature and photoperiod affect lettuce production parameters and their influence on both plants and microorganisms. Significant genotype × environment interactions were observed when analyzing morphological parameters of lettuce cultivars (Tobar-Tosse et al. 2022). The complex interaction of various production factors, especially in non-controlled agricultural environments, demands a comprehensive methodology for analyzing each factor. That is why the conjoint effect of MCDM methods can provide a completely new insight into decision analysis.

Taking the above into account, this study has certain limitations. It focused on only two cultivars and three biofertilizer types, which may restrict the applicability of the findings. Although the study encompassed three consecutive growing seasons, the complex interactions among biological, environmental, and economic factors may not be fully captured. This underscores the challenge of accounting for seasonal variability and its effects on the outcomes. The decision-making methods employed involve some degree of subjectivity in selecting and weighting criteria, which could influence the results. Furthermore, these models rely on fixed input data and may not completely reflect the dynamic nature of environmental conditions or market demand changes. These considerations point to opportunities for future research to refine and expand upon the current approach.

4. Conclusions

This study demonstrates the significant impact of both the growing season and biofertilizer type on the qualitative, quantitative, and economic outcomes in covered production systems. Using the MARCOS multi-criteria decision-making method, our results highlight that optimal strategies vary by cultivar: the ‘Murai’ cultivar reaches peak performance in winter with Vital Tricho biofertilizer (alternative A8), while for the ‘Aleppo’ cultivar, the optimal choice is spring with a combination of EM Aktiv and Vital Tricho (alternative A12). These findings are supported by four additional decision-making methods and validated through sensitivity analysis, confirming the robustness of the preferred alternatives despite variations in factor weighting.

From a practical point of view, this research supports farmers in selecting the most favorable planting schedules and biofertilizer types tailored to specific cultivars to maximize productivity and economic return. It emphasizes the importance of integrating economic criteria in the decision-making process to ensure sustainability and justify investments in covered systems. The alignment of results across multiple decision-making methods strengthens confidence in these recommendations, making them dependable for guiding effective and sustainable agronomic practices. This study contributes by expanding the application of the MARCOS method to agricultural planning and analysis, demonstrating its suitability not only for farm-level decision-making but also for use by agricultural companies. This broadens the method’s relevance and potential impact across primary production systems.

Further research should broaden the scope to include more lettuce cultivars and varieties, as well as diverse biofertilizer combinations, to develop more comprehensive guidelines. Additionally, investigating the long-term ecological and economic sustainability of these biofertilizers across different seasons and environmental conditions would provide valuable insights. Implementing more advanced fuzzy multi-criteria decision-making methods would allow for the inclusion of organoleptic factors such as taste and texture. This would significantly enhance the robustness and practical applicability of the recommendations, as they would reflect not only economic, morphological, and chemical but also crucial characteristics of the product that are vital for the consumer.

Abbreviations	Full name
MCDM	Multi-criteria decision-making
AHP	Analytic Hierarchy Process
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
MARCOS	Measurement of Alternatives and Ranking according to Compromise Solution
FST	Fuzzy Set Theory
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
GP	Goal programming
MABAC	Multi-Attributive Border Approximation Area Comparison
ARAS	Additive Ratio Assessment
WASPAS	Weighted Aggregates Sum Product Assessment
SAW	Simple Additive Weighting
EDAS	Evaluation based on Distance from Average Solution
AI	Ideal alternative
AAI	Anti-ideal alternative
USD	United States dollar
RSD	Serbian dinar
SMART	Simple Multi-Attribute Rating Technique
SWARA	Stepwise Weight Assessment Ratio Analysis

HPLC	High-Performance Liquid Chromatography
GA	Gallic acid
FW	Fresh weight
DW	Dry weight

Author Declarations

Authors' contributions: Concept: M.S., R.B., Design: M.S., R.B., Data collection: R.B., G.V., Analysis: S.S., V.M., J.D.M., R.B., G.V., Lj.Š., Writing: M.S., R.B., S.S., V.M., J.D.M.

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