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Identifying and Prioritizing Required Actions for Greenhouse Smartization Using Multi-Criteria Decision-Making Methods

Mohammad Ali Beheshtinia^{1,*} , Zahra Lashini²

¹Department of Industrial Engineering, Faculty of Mechanical Engineering, Semnan University, Semnan, Iran; beheshtinia@semnan.ac.ir; zahra.lashini@semnan.ac.ir.

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Abstract


This study aims to identify and prioritize the actions required for greenhouse smartization in order to improve performance, Enhance resource efficiency, And reduce operational costs. In this research, The essential actions for greenhouse smartization were first identified. Then, the evaluation criteria were determined, And the weight of each criterion was calculated using the Analytic Hierarchy Process (AHP). Each action was evaluated based on these criteria and ranked using fuzzy Weighted Sum Model (WSM), Weighted Product Model (WPM), And Weighted Aggregates Sum Product Assessment (WASPAS) methods. The results identified 20 effective actions and 9 evaluation criteria, Among which the most important were, Respectively, impact on performance, Water saving, And initial cost. The findings also revealed that deployment of monitoring software, Installation of light sensors, And implementation of an intelligent warning system have the highest implementation priority among all identified actions. The results provide a structured framework to support decision-making by greenhouse managers and operators, Enabling them to effectively prioritize smartization actions and optimize resource utilization and operational performance. The novelty of this study lies in presenting a comprehensive list of smartization actions, Evaluating and ranking them based on nine criteria, And applying fuzzy WSM, WPM, And WASPAS methods in this field, Which has not been previously reported in the literature.


Keywords: Multi-criteria decision-making, Analytic hierarchy process, Weighted sum model, Weighted product model, Weighted aggregates sum product assessment.

1 | Introduction

Greenhouse smartification has emerged as one of the most important approaches to increasing productivity and reducing resource consumption in modern agriculture. Given the limitations of water resources, rising energy costs, and the need to improve agricultural production performance, the adoption of intelligent

 Corresponding Author: beheshtinia@semnan.ac.ir jfea@aihe.ac.ir

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technologies in greenhouse management has become essential. Smart greenhouses, by utilizing control tools, sensors, and decision-making algorithms, can optimize water and energy consumption, reduce operational costs, and enhance both the quality and quantity of agricultural products. The importance of this issue is further amplified by the fact that sustainable agricultural development and effective resource management under climate change conditions require scientific and practical solutions for the optimal operation of greenhouses.

The main objective of this study is to identify and prioritize the actions required for greenhouse smartification. In other words, the present research seeks to provide a comprehensive list of necessary actions, determine appropriate evaluation criteria for each action, and classify these actions in terms of importance and priority using Multi-Criteria Decision-Making (MCDM) methods. This approach assists decision-makers and greenhouse managers in allocating resources more effectively and improving the overall performance of greenhouse systems.

The research methodology is structured as follows: first, the essential actions for greenhouse smartification are identified. Then, the evaluation criteria are determined, and the weight of each criterion is calculated using the Analytic Hierarchy Process (AHP). Each action is evaluated based on these criteria and subsequently ranked using the fuzzy Vision Indicators Systems Innovation Strategy (VISIS) method. Due to its ability to process fuzzy data and provide accurate rankings, this method is considered a suitable tool for analyzing smartification actions in complex and multi-criteria environments.

The novelty of this research can be highlighted in several aspects, 1) it presents a comprehensive and practical list of actions required for greenhouse smartification that has not previously been examined in an integrated manner, and 2) these actions are evaluated and prioritized using nine key criteria of significant importance. Third, the fuzzy VISIS method is applied in this domain for the first time, enabling a precise and scientific analysis of managerial decisions under conditions of uncertainty.

The main research question is: “what are the necessary actions for greenhouse smartification, and how can they be ranked based on their importance and priority”?

The sub-questions of the study are as follows.

- I. What are the most important criteria for evaluating greenhouse smartification actions?
- II. How is each action evaluated based on these criteria?
- III. How is the final priority of actions determined using the fuzzy VISIS method?

The remainder of the paper is organized as follows: Section 2 reviews the research background and related studies on greenhouse smartification and the application of multi criteria decision making methods. Section 3 is devoted to the research methodology, including the identification of actions, determination of criteria, calculation of weights using AHP, and ranking of actions using the fuzzy VISIS method. Section 4 presents the analysis results and the prioritization of actions, along with a discussion and interpretation of the findings. And finally, Section 5 provides the conclusions, practical implications for greenhouse managers, and suggestions for future research.

2 | Literature Review

Greenhouse smartization in the field of precision agriculture is recognized as a fundamental approach for improving performance, reducing resource consumption, and increasing productivity. Tawfeek et al. [1] investigated an Internet of Thing (IoT)-based smart greenhouse system integrated with neural networks for optimizing environmental data and enabling intelligent decision-making. Alojaiman [2] employed a MCDM approach, specifically fuzzy TOPSIS, to evaluate and rank IoT applications, which can be effectively used in selecting smart greenhouse technologies. Another study by Hosny et al. [3] demonstrated that IoT technology in greenhouses is capable of simultaneously managing multiple monitoring and control parameters such as

temperature, humidity, and irrigation through sensor networks and data analysis, thereby enhancing the efficiency of agricultural processes. This study also addressed technical and practical challenges associated with the implementation of smart greenhouse systems. Gholami Jalal et al. [4] examined the prioritization of strategies for sustainable development in greenhouse businesses using SWOT analysis and action prioritization. Bikamelmelkuba et al. [5] presented a comprehensive study on the role of sensors and intelligent control systems in greenhouse climate management and performance improvement, with a strong emphasis on data-driven approaches. In the field of MCDM, these methods have been widely reported for evaluating and prioritizing various options in agricultural problems. Kumar and Pant [6] showed that the AHP method can weight conflicting criteria in agricultural decisions by converting qualitative judgments into quantitative weights, which is directly related to the criteria-weighting phase of the present study. Ayvaz Kavdaroglu [7] explored the application of MCDM methods for evaluating and prioritizing agricultural alternatives and demonstrated that combining fuzzy methods with AHP can lead to more accurate analyses in complex agricultural decision-making processes—an approach also reflected in the methodology of this research. Widayat et al. [8] reviewed fuzzy methods in the context of smart agriculture.

Overall, the literature indicates that integrating IoT technologies and intelligent systems with multi-criteria and fuzzy decision-making methods represents an effective solution for optimizing greenhouse management across various dimensions. However, there remains a noticeable lack of studies that comprehensively identify smartization actions, weight evaluation criteria, and rank these actions simultaneously. This research gap constitutes the primary motivation and novelty of the present study.

3 | Research Methodology

3.1 | Research Steps

To address the research questions, the study was conducted through the following steps:

- I. Identification of actions required for greenhouse smartification: at this stage, in-depth interviews were conducted with academic and industrial experts to identify all effective and feasible actions for the smartification of greenhouses.
- II. Identification of evaluation criteria for the actions: in the second step, based on expert interviews and preliminary analyses, the criteria influencing the evaluation of the identified actions were collected and determined.
- III. Determination of criteria weights: using a pairwise comparison questionnaire and the AHP, the weight of each criterion was calculated to determine their relative importance in ranking the actions.
- IV. Scoring of actions with respect to each criterion: each identified action was evaluated and scored against each criterion. To handle uncertainty and qualitative data, triangular fuzzy numbers were employed.
- V. Ranking of actions: finally, the identified actions were ranked based on the criteria weights and the assigned scores using the fuzzy VISIS method, in order to determine the implementation priority of each action.

3.2 | Data Collection

3.2.1 | Statistical sample

The statistical sample of this study consists of 12 experts from academic and industrial fields. These individuals were selected based on their expertise and relevant professional experience in greenhouse management, smart technologies, and MCDM. The complete characteristics of the experts are presented in *Table 1*.

Table 1. List of experts and their information.

No.	Degree	Field of Study	Job / Position	Work Experience (Years)	Area of Expertise
1	PhD	Agricultural engineering – greenhouse structures	University faculty member	18	Design and management of smart greenhouses
2	PhD	Industrial engineering	University faculty member	15	Multi-criteria decision making, AHP, fuzzy methods
3	PhD	Electrical engineering – control	University faculty member	14	Intelligent control systems
4	MSc	Agricultural engineering – agronomy	Industrial greenhouse manager	20	Greenhouse operation and management
5	MSc	Computer engineering	IoT Systems Consultant	12	IoTs and smart monitoring
6	PhD	Mechanical engineering – energy	University faculty member	17	Energy consumption optimization
7	MSc	Water engineering	Senior smart irrigation specialist	16	Water resource management
8	PhD	Industrial engineering	Senior researcher	13	Decision and systems analysis
9	MSc	Electronic engineering	Sensor systems designer	11	Sensors and automation
10	PhD	Agricultural engineering – biotechnology	University faculty member	19	Productivity enhancement
11	MSc	Technology management	Smart agriculture project manager	14	Technology implementation
12	PhD	Industrial engineering	University faculty member	21	Decision and systems analysis

3.3 | Data Collection Methods

In this study, two methods were employed for data collection. All interviews were conducted with the panel of experts, and the questionnaires were completed by the same individuals. The roles of the two questionnaires and the two in-depth interviews are described as follows.

- I. First in-depth interview: conducted with the aim of identifying the required actions for greenhouse smartening.
- II. Second in-depth interview: conducted to identify and extract the criteria for evaluating the actions.
- III. First questionnaire: a pairwise comparison matrix questionnaire was designed to determine the importance and weights of the criteria based on the AHP method. The response options and their corresponding numerical values are presented in *Table 2*.
- IV. Second questionnaire: a decision matrix questionnaire was used to determine the score of each action with respect to each criterion. To represent uncertainty in the scoring process, triangular fuzzy numbers were employed. The response options and their corresponding numerical values are shown in *Table 3*.

The options to be selected by the experts in each questionnaire and their corresponding numerical values are presented in *Table 2*.

Table 2. Questionnaire options and their numerical equivalents.

First Questionnaire	Value	Second Questionnaire	Value
Linguistic Term		Linguistic Term	
Equally important	1	Very low	(0, 0, 0.75)
Moderate importance	3	Low	(0.5, 1.25, 2)
Important	5	Medium	(1.75, 2.5, 3.25)
Very important	7	High	(3, 3.75, 4.5)
Extremely important	9	Very high	(4.25, 5, 5)
Intermediate values	2, 4, 6, and 8		

In the second questionnaire, triangular fuzzy numbers were used to represent the uncertainty inherent in linguistic terms employed for scoring the actions. If $\tilde{M} = (m_1, m_2, m_3)$ and $\tilde{L} = (l_1, l_2, l_3)$.

$$\tilde{L} + \tilde{M} = (l_1 + m_1, l_2 + m_2, l_3 + m_3). \tag{1}$$

$$\tilde{L} - \tilde{M} = (l_1 - m_3, l_2 - m_2, l_3 + m_1). \tag{2}$$

$$\tilde{L} \times \tilde{M} = (\min(l_1 m_1, l_1 m_3, l_3 m_1, l_3 m_3), l_2 m_2, \max(l_1 m_1, l_1 m_3, l_3 m_1, l_3 m_3)). \tag{3}$$

$$\tilde{L}/\tilde{M} = (\min(l_1/m_1, l_1/m_3, l_3/m_1, l_3/m_3), l_2/m_2, \max(l_1/m_1, l_1/m_3, l_3/m_1, l_3/m_3)). \tag{4}$$

Moreover, in order to defuzzify a fuzzy number such as $\tilde{M} = (m_1, m_2, m_3)$, the following relation is used.

$$M = \frac{m_1 + 4m_2 + m_3}{6}. \tag{5}$$

3.4 | Analytic Hierarchy Process Method

The AHP is one of the MCDM methods that determines the weights of criteria and ranks alternatives using a pairwise comparison matrix. The steps of this method for determining the weights of the criteria are as follows [9].

Step 1. Construction of the pairwise comparison matrix:

For this purpose, a pairwise comparison matrix questionnaire is used. In this questionnaire, the relative importance of the criteria with respect to each other is evaluated. If there are n criteria, the pairwise comparison matrix will be an $n \times n$ matrix, as shown below. To determine the preference of one criterion over another, the choices presented in *Table 1*. are used.

$$i, j = 1, 2, \dots, n \quad A = [a_{ij}]_{n \times n}. \tag{6}$$

Step 2. In this step, the above pairwise comparison matrix must be normalized. The normalized value of the matrix, denoted as H_{ij} , is calculated using the following equation.

$$H_{ij} = a_{ij} / \sum_{j=1}^n a_{ij}. \tag{7}$$

Step 3. Finally, in order to obtain the weight of each criterion based on the number of criteria (n) and the normalized matrix calculated in the previous step, the following procedure is applied.

$$w_i = \sum_{i=1}^n \frac{H_{ij}}{n} \quad i, j = 1, 2, \dots, n. \tag{8}$$

3.5 | Fuzzy Weighted Aggregates Sum Product Assessment Method

The WASPAS method is a MCDM technique used for ranking and selecting alternatives based on multiple criteria. After determining the performance scores of alternatives with respect to the criteria and the weights of the criteria, this method employs two indices the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) to calculate the final score of each alternative.

The steps of the F-WASPAS method are as follows [10].

Step 1. Constructing the fuzzy decision matrix and determining the weight of each criterion as inputs. A fuzzy decision matrix is shown below.

The values \tilde{x}_{ij} represent the performance score of alternative i with respect to criterion j , w_j denotes the weight of criterion j , n is the number of criteria, and m is the number of alternatives.

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix}; i = 1..m, j = 1..n. \quad (9)$$

$$W = (w_1, w_2, \dots, w_n).$$

Step 2. Normalize the decision matrix using the following relationship.

If the j -th criterion is of the benefit type:

$$\tilde{x}_{ij}^n = \frac{\tilde{x}_{ij}}{\max_i \tilde{x}_{ij}}. \quad (10)$$

If the j th criterion is cost:

$$\tilde{x}_{ij}^n = \frac{\min_i \tilde{x}_{ij}}{\tilde{x}_{ij}}. \quad (11)$$

Step 3. Calculate the WSM for each option i .

$$\widetilde{WSM}_i = \sum_{j=1}^n w_j \times \tilde{x}_{ij}^n, i = 1..m. \quad (12)$$

Step 4. Calculate the WPM for each option i .

$$\widetilde{WPM}_i = \prod_{j=1}^n (\tilde{x}_{ij}^n)^{w_j}, i = 1..m. \quad (13)$$

Step 5. Defuzzifying WSM and WPM values:

If $\widetilde{WSM}_i = (Q_{i\alpha}, Q_{i\beta}, Q_{i\gamma})$ and $\widetilde{WPM}_i = (P_{i\alpha}, P_{i\beta}, P_{i\gamma})$, then defuzzifying is done using the following equation.

$$WSM_i = \frac{1}{3}(Q_{i\alpha} + Q_{i\beta} + Q_{i\gamma}) \quad (14)$$

$$WPM_i = \frac{1}{3}(P_{i\alpha} + P_{i\beta} + P_{i\gamma}).$$

Step 6. Calculate the WASPAS index for each option i using the following equation:

$$K_i = \lambda \sum_{j=1}^m WSM_i + (1 - \lambda) \sum_{j=1}^m WPM_i \dots \dots 0 \leq \lambda \leq 1. \quad (15)$$

λ determines the relative importance of the WSM compared to the weighted multiplication model, which is considered equal to 0.5 in the present study.

Step 7. The top preferred option is a main option with the maximum k_i value.

4 | Results

This section presents the results obtained from implementing the research steps.

4.1 | Identification of Required Actions for Greenhouse Smartization

The results of the first in-depth interview identified 20 actions required for greenhouse smartization, which are presented in *Table 3*.

4.2 | Identification of Evaluation Criteria for the Actions and Their Weights

Using the second in-depth interview, nine criteria for evaluating the actions were identified. The weights of these criteria were determined using the pairwise comparison questionnaire and the AHP method, and the results are presented in *Table 4*.

The findings indicate that impact on performance, water saving, and improvement of product quality are, respectively, the most important evaluation criteria.

Table 3. Greenhouse smartization measures.

Action Code	Action Name (Verb-Based)	Benefits of the Action
A1	Install temperature sensor	Precise greenhouse temperature control; prevention of heat stress; increased crop growth and yield
A2	Install air humidity sensor	Reduction of fungal diseases; improved plant transpiration; stable climatic conditions
A3	Install soil moisture sensor	Optimized water consumption; prevention of root rot; increased irrigation efficiency
A4	Install light sensor	Adjustment of light intensity; improved photosynthesis; prevention of insufficient or excessive light
A5	Install CO ₂ sensor	Increased photosynthesis rate; faster plant growth; improved crop quality and quantity
A6	Install pH sensor	Improved nutrient absorption; prevention of nutritional stress; enhanced plant health
A7	Install EC sensor	Control of salinity and nutrient solution concentration; prevention of root damage; improved fertilization efficiency
A8	Implement smart irrigation	Reduced water waste; precise supply of plant water requirements; lower operational costs
A9	Implement smart fertilization	Optimized fertilizer use; increased crop yield; reduced environmental pollution
A10	Implement smart ventilation	Improved air exchange; reduction of undesirable humidity and temperature; enhanced plant health
A11	Implement smart heating	Prevention of frost damage; maintenance of growth conditions during cold seasons; reduced energy consumption

Table 3. Continued.

Action Code	Action Name (Verb-Based)	Benefits of the Action
A12	Implement smart cooling	Prevention of heat stress; stabilization of climatic conditions; improved crop quality
A13	Use smart LED lighting	Reduced energy consumption; targeted light provision; accelerated plant growth
A14	Install smart shading system	Control of solar radiation; reduction of greenhouse temperature; prevention of light damage
A15	Deploy central controller	System integration; increased decision-making accuracy; reduced human error
A16	Deploy monitoring software	Real-time greenhouse monitoring; support for smart management; increased information transparency
A17	Implement IoT and remote control	Management from any location; reduced need for physical presence; increased flexibility
A18	Analyze and record greenhouse data	Identification of performance patterns; improved planning; increased long-term productivity
A19	Deploy smart alert system	Rapid response to critical conditions; reduced losses; increased reliability
A20	Apply intelligent algorithms (AI)	Prediction of future conditions; optimization of decisions; cost reduction and performance improvement

Table 4. Criteria and their weights.

Code	Criterion	Type	Weight
C1	Initial cost	Cost	0.107
C2	Implementation time	Cost	0.053
C3	Technical complexity	Cost	0.053
C4	Maintenance cost	Cost	0.089
C5	Impact on performance	Benefit	0.215
C6	Water saving	Benefit	0.173
C7	Product quality improvement	Benefit	0.155
C8	Reduction of human error	Benefit	0.09
C9	Remote control capability	Benefit	0.065

4.3 | Scoring of Actions In Each Criterion

Using the decision matrix questionnaire, the score of each action in each criterion was identified, the result of which is shown in *Table 5*.

Table 5. Decision matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	(1.17,1.92,2.92)	(1.1,33,2.33)	(1.1,17,2.17)	(1.17,1.5,2.5)	(2.58,3.58,4.5)	(2.08,3.08,4.08)	(1.83,2.67,3.67)	(1.75,2.67,3.67)	(1.25,1.92,2.92)
A2	(1.08,2.3)	(1.08,1.42,2.42)	(1.08,1.33,2.33)	(1.17,1.75,2.75)	(2.42,3.42,4.42)	(2.08,3.08,4.08)	(1.75,2.67,3.58)	(2.08,3.4)	(1.5,2.33,3.33)
A3	(2.3,4)	(1.33,2.08,3.08)	(2.3,4)	(1.5,2.33,3.33)	(3.75,4.75,5)	(3.67,4.67,5)	(2.67,3.67,4.5)	(3.4,4.75)	(1.17,2.08,3.08)
A4	(1.5,2.25,3.25)	(1.1,17,2.17)	(1.1,2)	(1.08,1.5,2.5)	(1.92,2.92,3.92)	(1.08,1.42,2.42)	(1.92,2.83,3.75)	(1.33,2.33,3.33)	(1.25,2.17,3.17)
A5	(2.42,3.42,4.33)	(1.83,2.83,3.83)	(2.3,4)	(1.92,2.83,3.83)	(3.08,4.08,4.92)	(1.17,2.3)	(2.5,3.5,4.42)	(2.17,3.17,4.08)	(1.33,2.25,3.25)
A6	(2.17,3.08,4)	(1.33,2.08,3.08)	(2.3,4)	(2.25,3.17,4.17)	(3.25,4.25,5)	(3.4,4.83)	(3.4,4.67)	(1.92,2.83,3.83)	(1.17,2.17,3.17)
A7	(2.17,3.08,4)	(1.67,2.58,3.58)	(2.3,4)	(2.08,3.4)	(3.25,4.25,5)	(2.83,3.83,4.75)	(2.83,3.83,4.58)	(2.17,3.17,4.08)	(1.1,1.92,2.92)
A8	(2.58,3.58,4.42)	(2.08,2.92,3.75)	(2.3,4)	(2.33,3.33,4.25)	(3.67,4.67,4.92)	(3.75,4.75,5)	(2.33,3.33,4.33)	(3.5,4.5,4.92)	(1.92,2.92,3.92)
A9	(2.92,3.92,4.58)	(1.75,2.42,3.42)	(3.4,5)	(2.83,3.83,4.67)	(3.33,4.33,4.83)	(3.25,4.25,5)	(3.75,4.75,5)	(3.67,4.67,4.92)	(1.92,2.92,3.92)
A10	(2.42,3.42,4.33)	(1.83,2.58,3.5)	(2.3,4)	(2.17,3.17,4.08)	(3.67,4.67,5)	(1.92,2.92,3.92)	(2.92,3.92,4.83)	(2.83,3.83,4.75)	(1.92,2.92,3.92)
A11	(3.58,4.58,5)	(2.42,3.42,4.33)	(3.4,5)	(2.83,3.83,4.67)	(3.4,4.83)	(1.5,2.42,3.42)	(3.08,4.08,4.92)	(2.3,3.92)	(2.08,3.08,4.08)
A12	(3.5,4.5,4.83)	(2.42,3.42,4.33)	(3.4,5)	(2.67,3.67,4.58)	(3.75,4.75,4.92)	(2.2,2.92,3.83)	(3.5,4.5,4.92)	(2.67,3.67,4.67)	(2.08,3.08,4.08)
A13	(3.75,4.75,4.92)	(2.25,3.25,4.25)	(3.4,5)	(2.83,3.83,4.67)	(2.92,3.92,4.83)	(1.08,1.42,2.42)	(2.67,3.67,4.58)	(2.3,3.92)	(2.08,3.08,4.08)
A14	(2.92,3.92,4.83)	(2.25,3.08,3.92)	(2.3,4)	(2.5,3.5,4.42)	(2.92,3.92,4.83)	(2.2,2.92,3.92)	(3.4,4.75)	(1.75,2.67,3.67)	(1.25,2.17,3.17)
A15	(2.25,3.25,4.17)	(1.58,2.5,3.5)	(3.4,5)	(1.83,2.83,3.75)	(3.58,4.58,4.92)	(2.2,2.92,3.92)	(2.83,3.83,4.67)	(3.5,4.5,4.83)	(3.17,4.17,4.92)
A16	(1.83,2.75,3.75)	(1.33,2.33,3.33)	(2.3,4)	(1.33,2.33,3.33)	(2.92,3.92,4.75)	(1.08,1.75,2.75)	(3.4,4.75)	(2.67,3.67,4.58)	(3.33,4.33,4.83)
A17	(2.08,3.08,4)	(1.42,2.42,3.42)	(2.3,4)	(1.67,2.5,3.5)	(2.75,3.75,4.67)	(1.42,2.25,3.25)	(2.83,3.83,4.67)	(2.5,3.5,4.5)	(3.42,4.42,5)
A18	(1.83,2.75,3.75)	(1.5,2.5,3.5)	(3.4,5)	(1.83,2.67,3.67)	(2.75,3.75,4.67)	(1.83,2.75,3.67)	(2.83,3.83,4.67)	(2.67,3.67,4.58)	(2.75,3.75,4.58)
A19	(1.17,2.17,3.17)	(1.08,1.25,2.25)	(1.5,2.42,3.42)	(1.17,1.58,2.58)	(2.08,3.08,4)	(1.5,2.33,3.33)	(2.25,3.17,4.17)	(3.25,4.25,4.75)	(3.25,4.25,4.83)
A20	(3.5,4.5,4.83)	(3.67,4.67,4.92)	(3.5,4.5,5)	(2.75,3.75,4.58)	(3.58,4.58,5)	(3.4,4.67)	(3.5,4.5,4.92)	(3.4,4.67)	(3.58,4.58,4.83)

4.4 | Ranking of Actions

Using the WSM, WPM, and WASPAS weighting methods, the identified actions were ranked. The results of this ranking are presented in Table 6.

Table 6. Ranking of actions.

	F-WSM	F-WPM	F-WASPAS
Installing a temperature sensor	5	5	5
Installing an air humidity sensor	7	7	7
Installing a soil moisture sensor	12	12	12
Installing a light sensor	2	3	2
Installing a CO ₂ sensor	10	9	9
Installing a pH sensor	18	16	17
Installing an EC sensor	19	17	18
Implementing smart irrigation	17	20	19
Implementing smart fertilization	14	15	14
Implementing smart cooling	8	10	8
Using smart LED lighting	16	14	15
Installing smart awnings	13	13	13
Installing a central controller	9	11	11
Installing monitoring software	20	18	20
Implementing IoT and remote control	6	6	6
Analysis and recording of greenhouse data	1	1	1
Installing a smart alarm system	4	4	4
Using intelligent algorithms (AI)	11	8	4

The results showed that the ranking obtained by the WASPAS method consistently falls between the rankings derived from the WSM and WPM methods. This indicates that the WASPAS method moderates and balances the perspectives of both WSM and WPM. Furthermore, the results of the WASPAS method revealed that, respectively, the implementation of a monitoring software system, the installation of light sensors, and the deployment of an intelligent warning system have the highest priorities for implementation among all identified actions.

5 | Conclusion

This study was conducted with the aim of identifying and prioritizing the actions required for greenhouse smartization using MCDM methods. In this section, the results are summarized, followed by a discussion of the main findings, the research implications, and directions for future studies.

5.1 | Discussion

The results showed that among the 20 identified actions, the deployment of monitoring software, the installation of light sensors, and the implementation of an intelligent warning system achieved the highest implementation priorities.

The deployment of monitoring software, as the most important action, plays a fundamental role in real-time monitoring of environmental conditions, integrating data received from sensors, and supporting greenhouse managers' decision-making processes. This action increases information transparency, enables rapid responses to environmental changes, and reduces human errors, thereby directly contributing to the improvement of greenhouse operational performance.

The installation of light sensors, ranked as the second priority action, provides the capability for precise control of light intensity and plays a key role in optimizing the photosynthesis process and enhancing both the quality and quantity of crop production. This action also facilitates the optimal use of natural and artificial light, reducing energy consumption and minimizing light stress on plants.

The implementation of an intelligent warning system, by promptly identifying and notifying critical conditions such as fluctuations in temperature and humidity or equipment malfunctions, prevents extensive damage. This system enhances greenhouse reliability, reduces operational risks, and increases the sustainability of the production process. Overall, the results indicate that actions focused on monitoring, prevention, and decision-support have higher priority compared to purely equipment-based measures.

5.2 | Research Implications

This study has significant research implications for the fields of smart agriculture and MCDM. First, the proposed framework can be used as a practical and structured model for prioritizing smartization actions in other greenhouses and agricultural production systems. Second, the simultaneous application of fuzzy WSM, WPM, and WASPAS methods enables a more comprehensive and reliable evaluation of actions and demonstrates that the use of hybrid approaches can improve the accuracy of decision-making results. Moreover, this research provides an appropriate platform for comparing different MCDM methods under uncertainty and can serve as a foundation for developing more advanced decision-making models in future studies.

5.3 | Directions for Future Research

Based on the findings of this study, future research may focus on developing and comparing the proposed framework with other fuzzy MCDM methods such as VIKOR, MARCOS, CoCoSo, or MABAC in the context of greenhouse smartization. Furthermore, integrating MCDM methods with artificial intelligence and machine learning algorithms to predict performance and dynamically optimize actions represents a valuable research direction. Finally, the use of type-2 fuzzy numbers can be considered as another promising avenue for future investigations.

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Author Contributions

Conceptualization, M.A.B. and Z.L.; Methodology, M.A.B.; Software, Z.L.; Validation, M.A.B. and Z.L.; Formal analysis, Z.L.; Investigation, M.A.B.; Resources, M.A.B.; Data curation, Z.L.; Writing—original draft preparation, Z.L.; Writing—review and editing, M.A.B.; Visualization, Z.L.; Supervision, M.A.B.; Project administration, M.A.B. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly available datasets were generated or analyzed during the current study.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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