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Evaluation of Criteria in Fruit Production Using the Interval Fuzzy Rough PIPRECIA Method

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Abstract: This study investigates the application of Multi-Criteria Decision-Making (MCDM) techniques in fruit production, specifically focusing on the use of the interval fuzzy rough pivot pairwise relative criteria importance assessment (PIPRECIA) method for criteria evaluation. A total of 11 criteria were evaluated to rank various combinations of plum varieties and rootstocks. The criteria selected represent key aspects of plum production, including phenology, yield, physical fruit characteristics, and the chemical composition and quality of the fruit. Data for the study were collected through surveys of 17 experts and plum producers. The results indicated that the criteria related to overall yield and fruit weight were deemed the most significant, while those concerning the chemical composition and fruit quality were considered of lesser importance. The findings highlight the potential of the interval fuzzy rough PIPRECIA method in addressing both research and managerial challenges in fruit production. It is suggested that future research expand the application of this method to other geographical regions and agricultural sectors. Additionally, the development of accessible software tools featuring user-friendly interfaces could facilitate broader adoption of MCDM techniques in agricultural decision-making.

Keywords: Fruit production; Interval fuzzy rough PIPRECIA; Criteria weights; MCDM; Criteria evaluation

1 Introduction

Among fruit species, plums rank ninth globally in terms of production and fourth among temperate fruits, following apples, pears, and peaches. China is the leading producer of plums worldwide, with a production of 6.8 million tons in 2023, followed by Romania (645,090 tons) and Serbia (362,713 tons). The average global plum production between 2021 and 2023 was 12.5 million tons [1]. The widespread cultivation of plums can be attributed to the versatile use of its fruits, modest growth requirements, high yields, and excellent fruit quality. The variety and rootstock are crucial factors for successful fruit cultivation, including plum production. However, the choice of rootstock is equally significant, as it affects not only vigor and yield [2, 3] but also fruit quality [4, 5]. Greater attention must be paid to rootstock selection compared to the variety, as no universal rootstock exists that is suitable for varying agroecological conditions, cultivation systems, and intensive production [6]. Successful plum production in high-density orchards with high yields and quality fruit depends on both the variety and the rootstock [7].

A well-balanced ratio between generative and vegetative buds is essential for balancing yield and fruit quality. Research over the past two decades highlights the influence of vegetative rootstocks in reducing tree vigor and increasing plum yield per unit area [8, 9]. Through interaction with the grafted rootstock, the variety can significantly influence rootstock performance regarding tree vigor [10]. Fertility is one of the most important breeding goals for European plum varieties [11].

In fruit research, comparisons of varieties and/or variety/rootstock combinations, as well as rootstocks, often involve numerous alternatives—sometimes exceeding ten. Additionally, numerous characteristics (criteria) have been used, which in some studies exceed 20. Ali et al. [12] conducted research on 13 apple varieties with 21 traits each. Some alternatives excel in certain traits, while others perform better in different ones. Objective ranking of these varieties is not feasible without using MCDM techniques. Comparative research with five plum varieties and ten traits was conducted by Milošević et al. [13]. The study found that varieties exhibited different values across various criteria. For instance, the "Katinka" variety had the highest yield per tree, while the "Boranka" and "Čačanska Rana" varieties had the largest fruit size and weight.

Radović et al. [14] focused on the comparative influence of different rootstocks on the chemical composition of plum fruits. The study involved four varieties and three rootstocks, yielding 12 combinations (alternatives). The content of phenolic compounds, sugars, and mineral composition was assessed using ten individual traits (criteria). Significant variation was observed among different variety/rootstock combinations regarding values across individual criteria. These examples illustrate the complexity of ranking and selecting the best alternative (variety or variety/rootstock combination) in fruit production, highlighting the need for MCDM techniques to achieve greater objectivity.

Recently, some studies have incorporated MCDM techniques for ranking alternatives in decision-making processes in fruit production. The fuzzy compromise ranking of alternatives from distance to ideal solution (CRADIS) and Criteria Importance Through Intercriteria Correlation (CRITIC) methods were used for market evaluation of six pear varieties based on ten criteria [15]. In the process of ranking and selecting plum varieties for establishing new orchards, Nedeljković et al. [16] employed several MCDM techniques. They ranked six plum varieties using five criteria and 20 sub-criteria. The weights of the selected criteria were determined using the Full Consistency Method (FUCOM) and the CRITIC, while the fuzzy Measurement Alternatives and Ranking according to Compromise Solution (MARCOS) method was used for ranking alternatives.

2 Methodology

2.1 Preliminaries

An interval fuzzy rough number (IFRN) was marked with "A".

$$A = [A_q^L, A_q^u] = [(a_{1q}^L, a_{1q}^U), (a_{2q}^L, a_{2q}^U), (a_{3q}^L, a_{3q}^U)] \tag{1}$$

where, $a_{jq}^L = \underline{\text{Lim}}\left(I * (a_j)_{lq}\right)$ and $a_{jq}^U = \overline{\text{Lim}}\left(I * (a_j)_{uq}\right)$; $(j = 1, 2, 3; 1 \leq q \leq k)$.

The expressions for addition, subtraction, multiplication and division are as follows:

Addition:

$$\begin{aligned} A + B &= [(a_1^L, a_1^U), (a_2^L, a_2^U), (a_3^L, a_3^U)] + [(b_1^L, b_1^U), (b_2^L, b_2^U), (b_3^L, b_3^U)] \\ &= [(a_1^L + b_1^L, a_1^U + b_1^U), (a_2^L + b_2^L, a_2^U + b_2^U), (a_3^L + b_3^L, a_3^U + b_3^U)] \end{aligned} \tag{2}$$

Subtraction:

$$\begin{aligned} A - B &= [(a_1^L, a_1^U), (a_2^L, a_2^U), (a_3^L, a_3^U)] - [(b_1^L, b_1^U), (b_2^L, b_2^U), (b_3^L, b_3^U)] \\ &= [(a_1^L - b_3^U, a_1^U - b_1^L), (a_2^L - b_2^U, a_2^U - b_2^L), (a_3^L - b_1^U, a_3^U - b_1^L)] \end{aligned} \tag{3}$$

Multiplication:

$$\begin{aligned} A \times B &= [(a_1^L, a_1^U), (a_2^L, a_2^U), (a_3^L, a_3^U)] \times [(b_1^L, b_1^U), (b_2^L, b_2^U), (b_3^L, b_3^U)] \\ &= [(a_1^L \times b_1^L, a_1^U \times b_1^U), (a_2^L \times b_2^L, a_2^U \times b_2^U), (a_3^L \times b_3^L, a_3^U \times b_3^U)] \end{aligned} \tag{4}$$

Division:

$$\begin{aligned} A \div B &= [(a_1^L, a_1^U), (a_2^L, a_2^U), (a_3^L, a_3^U)] \div [(b_1^L, b_1^U), (b_2^L, b_2^U), (b_3^L, b_3^U)] \\ &= [(a_1^L \div b_3^U, a_1^U \div b_1^L), (a_2^L \div b_2^U, a_2^U \div b_2^L), (a_3^L \div b_1^U, a_3^U \div b_1^L)] \end{aligned} \tag{5}$$

2.2 Interval Fuzzy Rough PIPRECIA Method

Fuzzy PIPRECIA method was created by Stević et al. [17] and has been applied many times in various studies [18–20]. IFRN PIPRECIA version was developed in 2024 by Chen et al. [21]. The procedure of the IFR PIPRECIA is shown below.

Step 1: Defining the set of n criteria.

Step 2: Forming the group of t experts who must use two scales shown in Figures 1 and 2.

Step 3: Linguistic scale 1-2 is applied by the experts if the C_j criterion has higher importance compared to C_{j-1}. Abbreviations from Figures 1 and 2 were explained by Chen et al. [21].

A linguistic scale of 0-1 should be applied when C_j has lesser importance compared to C_{j-1}.

Step 4: In this step, Eq. (6) should be applied for each expert.

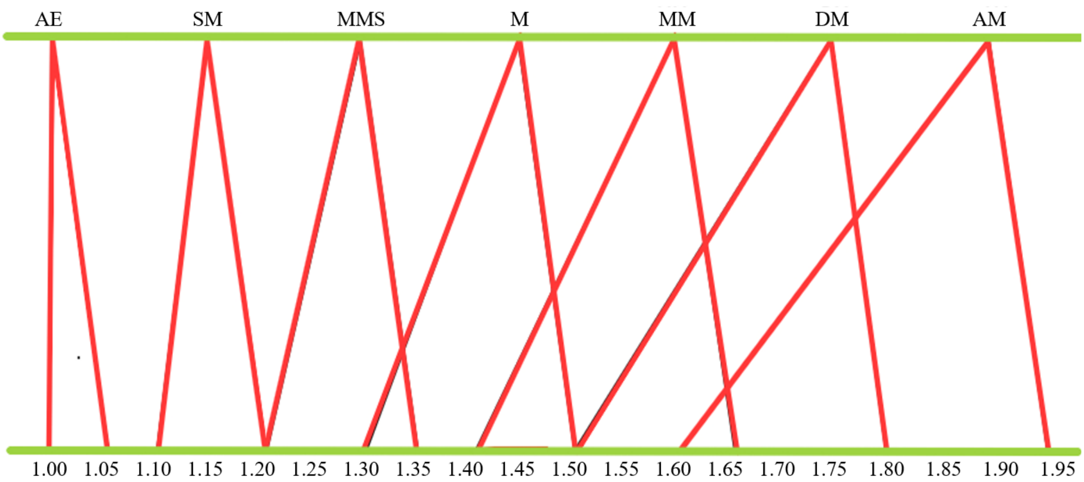

Figure 1. Scale 1-2 [21]

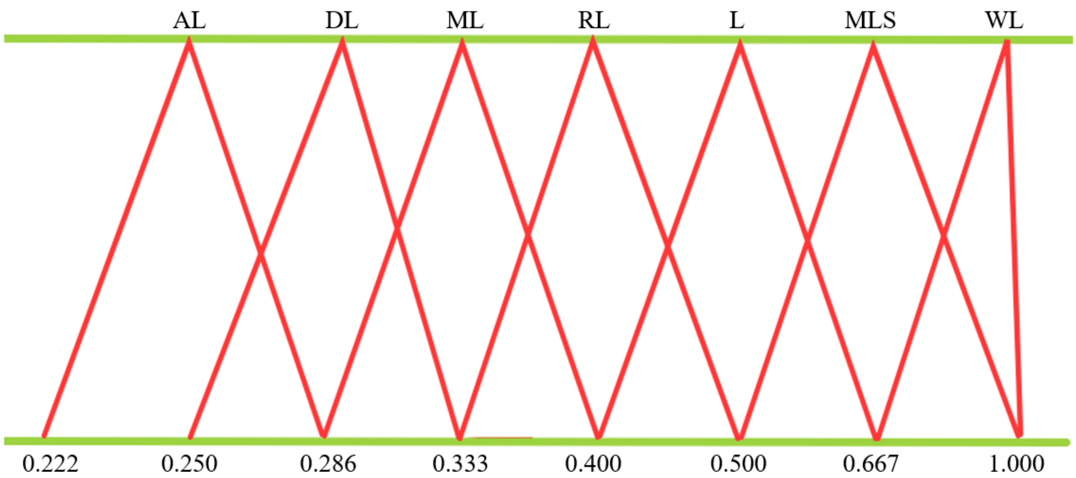

Figure 2. Scale 0-1 [21]

$$\text{Fuzzy } \left[s_j^r\right] = \begin{cases} > [(1,1,1)], [(1,1,1)] & \text{if} \quad C_j > C_{j-1} \\ = [(1,1,1)], [(1,1,1)] & \text{if} \quad C_j = C_{j-1} \\ < [(1,1,1)], [(1,1,1)] & \text{if} \quad C_j < C_{j-1} \end{cases} \tag{6}$$

where, Fuzzy$\left[s_j^r\right]$ is the assessment of criteria by each expert r.
Step 5: Defining the group IFRN matrix x_j.

$$\text{IFRN}\left(\text{X}_j\right) = \left[\left(x_j^{L1}, x_j^{U1}\right), \left(x_j^{L2}, x_j^{U2}\right), \left(x_j^{L3}, x_j^{U3}\right)\right]_{1\times m} \tag{7}$$

Step 6: Computation of the coefficient IFRN $[k_j]$.

$$\text{IFRN}\left[k_j\right] = \begin{cases} [(1,1),(1,1),(1,1)] & \text{if } j = 1 \\ \left[\left(2 - x_j^{U3}\right), \left(2 - x_j^{L3}\right), \left(2 - x_j^{U2}\right), \left(2 - x_j^{L2}\right), \left(2 - x_j^{U1}\right), \left(2 - x_j^{L1}\right)\right] & \text{if } j > 1 \end{cases} \tag{8}$$

Step 7: Computation of IFRN $[q_j]$.

$$\text{IFRN}\left[q_j\right] = \begin{cases} [(1,1),(1,1),(1,1)] & \text{if} \quad j = 1 \\ \frac{[q_{j-1}]}{[k_j]} = \left[\left(\frac{q_{j-1}^{L1}}{k_j^{U3}}\right), \left(\frac{q_{j-1}^{U1}}{k_j^{L3}}\right), \left(\frac{q_{j-1}^{L2}}{k_j^{U2}}\right), \left(\frac{q_{j-1}^{U2}}{k_j^{L2}}\right), \left(\frac{q_{j-1}^{L3}}{k_j^{U1}}\right), \left(\frac{q_{j-1}^{U3}}{k_j^{L1}}\right)\right] & \text{if } j > 1 \end{cases} \tag{9}$$

Step 8: Computation of IFRN $[w_j]$.

$$\text{IFRN}\,[w_j] = \frac{[q_j]}{[\delta_j]}\text{where}\,[\delta_j] = \sum_{j=1}^{n}[q_j] \tag{10}$$

$$\text{then IFRN}\,[w_j] = \left[\left(\frac{q_j^{L1}}{\delta_j^{U3}}\right), \left(\frac{q_1^{U1}}{\delta_j^{L3}}\right), \left(\frac{q_1^{L2}}{\delta_j^{U2}}\right), \left(\frac{q_1^{U2}}{\delta_j^{L2}}\right), \left(\frac{q_1^{L3}}{\delta_j^{U1}}\right), \left(\frac{q_1^{U3}}{\delta_j^{L1}}\right)\right]$$

Step 9: In this step, the experts evaluate the criteria again, starting from the penultimate one.

$$\text{Fuzzy}\ \left[s_j^{r'}\right] = \begin{cases} > [(1,1,1)], [(1,1,1)] & \text{if} \quad C_j > C_{j+1} \\ = [(1,1,1)], [(1,1,1)] & \text{if} \quad C_j = C_{j+1} \\ < [(1,1,1)], [(1,1,1)] & \text{if} \quad C_j < C_{j+1} \end{cases} \tag{11}$$

where, Fuzzy$\left[s_j^{r'}\right]$ is the assessment of criteria by each expert r'.

Step 10: Computation of the coefficient IFRN $[k_j']$.

$$\text{IFRN}\ \left[k_j'\right] = \begin{cases} [(1,1),(1,1),(1,1)] & \text{if} \quad j=1 \\ \left[\left(2-x_j^{U3'}\right), \left(2-x_j^{L3'}\right), \left(2-x_j^{U2'}\right), \left(2-x_j^{L2'}\right), \left(2-x_j^{U1'}\right), \left(2-x_j^{L1'}\right)\right] & \text{if}\ j>1 \end{cases} \tag{12}$$

Step 11: Computation of IFRN $[q_j']$.

$$\text{IFRN}\,[q_j'] = \begin{cases} [(1,1),(1,1),(1,1)] & \text{if} \quad j=n \\ \frac{[q_{j-1}']}{[k_j']} = \left[\left(\frac{q_{j-1}^{L1'}}{k_j^{U3'}}\right), \left(\frac{q_{j-1}^{U1'}}{k_j^{L3'}}\right), \left(\frac{q_{j-1}^{L2'}}{k_j^{U2'}}\right), \left(\frac{q_{j-1}^{U2'}}{k_j^{L2'}}\right), \left(\frac{q_{j-1}^{L3'}}{k_j^{U1'}}\right), \left(\frac{q_{j-1}^{U3'}}{k_j^{LL'}}\right)\right] & \text{if}\ j<n \end{cases} \tag{13}$$

Step 12: Computation of IFRN $\left[w_j'\right]$.

$$\text{IFRN}\,[w_j'] = \frac{[q_j']}{[\delta_j']}\ \text{where}\ [\delta_j'] = \sum_{j=1}^{n}[q_j'] \tag{14}$$

$$\text{then IFRN}\ [w_j'] = \left[\left(\frac{q_j^{L1'}}{\delta_j^{U3'}}\right), \left(\frac{q_1^{U1'}}{\delta_j^{L3'}}\right), \left(\frac{q_1^{L2'}}{\delta_j^{U2'}}\right), \left(\frac{q_1^{U2'}}{\delta_j^{L2'}}\right), \left(\frac{q_1^{L3'}}{\delta_j^{U1'}}\right), \left(\frac{q_1^{U3'}}{\delta_j^{L1'}}\right)\right]$$

Step 13: Final weights can be obtained:

$$[w_j''] = \frac{1}{2}\left(\text{IFR}\,[w_j] + \text{IFR}\,[w_j']\right) \tag{15}$$

3 Case Study

This study is part of the project related to determining criteria weights and creating a web application in fruit production to support producers and decision-makers. Totally, 17 experts were involved in this project from various structures. For the purpose of this study, independent producers were selected and the calculation process of criteria weights based on the preference of three experts from this field was shown.

3.1 Computation of Criteria Weights Using the IFRN PIPRECIA Method

The IFRN PIPRECIA method was used for calculating criteria weights. The following 11 criteria integrating plum cultivars/rootstocks were observed: C1 - the number of flower buds per 1 m of fruiting twig; C2 - the number of flower buds per 1 m of 2-year-old twig; C3 - germination of pollen; C4 - final fruit set; C5 - trunk cross-sectional area; C6 - cumulative yield efficiency; C7 - fruit weight; C8 - flesh ratio; C9 - soluble solids; C10 - total phenolic content in skin of fruit; C11 - radical-scavenging activity. The first activity in applying this method was assessing the mutual significance of criteria by experts using the linguistic scales, as shown in Table 1.

The next step was transforming linguistic values into Triangular Fuzzy Numbers (TFNs), as shown in Table 2.

The procedure of converting TFNs into interval fuzzy rough is as follows:

A rough matrix for C5 is shown below.

Based on the expert assessment, as shown in Table 2, three classes of objects l, m and u were selected: $l = (0.29; 0.40; 0.33), m = (0.33; 0.50; 0.40)$ and $u = (0.40; 0.67; 0.50)$.

$$\begin{aligned} l: \quad & \underline{\text{Lim}}(0.29) = 0.29, \overline{\text{Lim}}(0.29) = \frac{1}{3}(0.29+0.40+0.33) = 0.34 \\ & \underline{\text{Lim}}(0.40) = \frac{1}{3}(0.29+0.40+0.33) = 0.34, \overline{\text{Lim}}(0.40) = 0.40 \\ & \underline{\text{Lim}}(0.33) = \frac{1}{2}(0.29+0.33) = 0.31, \overline{\text{Lim}}(0.33) = \frac{1}{2}(0.40+0.33) = 0.37 \end{aligned}$$

$$m: \quad \underline{\mathrm{Lim}}(0.33) = 0.33, \overline{\mathrm{Lim}}(0.33) = \frac{1}{3}(0.33 + 0.50 + 0.40) = 0.41$$
$$\underline{\mathrm{Lim}}(0.50) = \frac{1}{3}(0.33 + 0.50 + 0.40) = 0.41, \overline{\mathrm{Lim}}(0.50) = 0.50$$
$$\underline{\mathrm{Lim}}(0.40) = \frac{1}{2}(0.33 + 0.40) = 0.37, \overline{\mathrm{Lim}}(0.40) = \frac{1}{2}(0.50 + 0.40) = 0.45$$
$$u: \quad \underline{\mathrm{Lim}}(0.40) = 0.40, \overline{\mathrm{Lim}}(0.40) = \frac{1}{3}(0.40 + 0.67 + 0.50) = 0.52$$
$$\underline{\mathrm{Lim}}(0.67) = \frac{1}{3}(0.40 + 0.67 + 0.50) = 0.52, \overline{\mathrm{Lim}}(0.67) = 0.67$$
$$\underline{\mathrm{Lim}}(0.50) = \frac{1}{2}(0.40 + 0.50) = 0.45, \overline{\mathrm{Lim}}(0.50) = \frac{1}{2}(0.67 + 0.50) = 0.58$$

Table 1. Assessment of criteria using linguistic scales

	DM1		DM2		DM3	
	IFRNP	IIFRNP	IFRNP	IIFRNP	IFRNP	IIFRNP
C1	-	-	-	-	-	-
C2	AE	WL	SM	MLS	AE	WL
C3	AE	WL	AE	WL	SM	MLS
C4	MMS	L	SM	WL	SM	MLS
C5	ML	MMS	L	MMS	RL	M
C6	M	AL	MMS	RL	M	RL
C7	AE	WL	WL	AE	AE	WL
C8	ML	M	WL	AE	AE	WL
C9	AE	MLS	MLS	SM	L	MMS
C10	DL	M	WL	AE	WL	AE
C11	WL	AE	WL	AE	WL	AE

Table 2. Expert assessment of criteria

	DM1		DM2		DM3	
	IFRNP	IIFRNP	IFRNP	IIFRNP	IFRNP	IIFRNP
C1	-	-	-	-	-	-
C2	(1,1,1.05)	(0.67,1,1)	(1.1,1.15,1.2)	(0.5,0.67,1)	(1,1,1.05)	(0.67,1,1)
C3	(1,1,1.05)	(0.67,1,1)	(1,1,1.05)	(0.67,1,1)	(1.1,1.15,1.2)	(0.5,0.67,1)
C4	(1.2,1.3,1.35)	(0.4,0.5,0.67)	(1.1,1.15,1.2)	(0.67,1,1)	(1.1,1.15,1.2)	(0.5,0.67,1)
C5	(0.29,0.33,0.4)	(1.2,1.3,1.35)	(0.4,0.5,0.67)	(1.2,1.3,1.35)	(0.33,0.4,0.5)	(1.3,1.45,1.5)
C6	(1.3,1.45,1.5)	(0.22,0.25,0.29)	(1.2,1.3,1.35)	(0.33,0.4,0.5)	(1.3,1.45,1.5)	(0.33,0.4,0.5)
C7	(1,1,1.05)	(0.67,1,1)	(0.67,1,1)	(1,1,1.05)	(1,1,1.05)	(0.67,1,1)
C8	(0.29,0.33,0.4)	(1.3,1.45,1.5)	(0.67,1,1)	(1,1,1.05)	(1,1,1.05)	(0.67,1,1)
C9	(1,1,1.05)	(0.5,0.67,1)	(0.5,0.67,1)	(1.1,1.15,1.2)	(0.4,0.5,0.67)	(1.2,1.3,1.35)
C10	(0.25,0.29,0.33)	(1.3,1.45,1.5)	(0.67,1,1)	(1,1,1.05)	(0.67,1,1)	(1,1,1.05)
C11	(0.67,1,1)	(1,1,1.05)	(0.67,1,1)	(1,1,1.05)	(0.67,1,1)	(1,1,1.05)
C12	(1,1,1.05)	(0.67,1,1)	(1.1,1.15,1.2)	(0.5,0.67,1)	(1,1,1.05)	(0.67,1,1)

In this way, IFRNs were computed as follows:

$$\text{IFRN}\,(E_1) = [(0.29, 0.34), (0.33, 0.41), (0.40, 0.52)]$$
$$\text{IFRN}\,(E_2) = [(0.34, 0.40), (0.41, 0.50), (0.52, 0.67)]$$
$$\text{IFRN}\,(E_3) = [(0.31, 0.37), (0.37, 0.45), (0.45, 0.58)]$$

Using the averaging equation, the final IFRN for C5 was calculated as follows:

$$\text{IFRN}\,(C_5) = [(0.31, 0.37), (0.37, 0.45), (0.46, 0.59)]$$

Then IFRN (X_j) was calculated (Table 3). For the inverse IFRN PIPRECIA method, the same methodology was applied.

Table 3. Initial IFRN PIPRECIA matrix

	IFRN PIPRECIA	Inverse IFRN PIPRECIA
	IFRN (X_j)	
C1	$[(0,0),(0,0),(0,0)]$	$[(0.573,0.648),(0.816,0.963),(1,1)]$
C2	$[(1.01,1.017),(1.017,1.067),(1.067,1.133)]$	$[(0.573,0.648),(0.816,0.963),(1,1)]$
C3	$[(1.01,1.017),(1.017,1.067),(1.067,1.133)]$	$[(0.457,0.582),(0.6,0.796),(0.816,0.963)]$
C4	$[(1.11,1.153),(1.167,1.217),(1.217,1.283)]$	$[(1.21,1.253),(1.317,1.367),(1.367,1.433)]$
C5	$[(0.312,0.368),(0.371,0.45),(0.457,0.589)]$	$[(0.274,0.306),(0.317,0.362),(0.382,0.477)]$
C6	$[(1.247,1.29),(1.367,1.417),(1.417,1.483)]$	$[(0.704,0.853),(1,1),(1.007,1.03)]$
C7	$[(0.816,0.963),(1,1),(1.02,1.043)]$	$[(0.829,1.047),(1.05,1.07),(1.07,1.32)]$
C8	$[(0.472,0.604),(0.604,0.64),(0.64,0.967)]$	$[(0.743,0.872),(0.872,1.093),(1.093,1.27)]$
C9	$[(0.493,0.6),(0.6,0.802),(0.802,0.997)]$	$[(1.033,1.05),(1.05,1.1),(1.1,1.3)]$
C10	$[(0.437,0.54),(0.602,0.63),(0.631,0.927)]$	$[(1,1),(1,1),(1.05,1.05)]$
C11	$[(0.667,0.667),(1,1),(1,1)]$	$[(0,0),(0,0),(0,0)]$

In the next step, IFRN (k_j) was calculated.

The first part of the matrix IFRN (k_j) is equal to IFRN of one, because that is the rule defined in the applied methodology.

$$\text{IFRN}\,(k_j) = \begin{pmatrix} [(1.000,1.000),(1.000,1.000),(1.000,1.000)] \\ [(0.867,0.933),(0.933,0.983),(0.983,0.990)] \\ [(0.867,0.933),(0.933,0.983),(0.983,0.990)] \\ [(0.717,0.783),(0.783,0.833),(0.847,0.890)] \\ [(1.411,1.543),(1.550,1.629),(1.632,1.688)] \\ [(0.517,0.583),(0.583,0.633),(0.710,0.753)] \\ [(0.957,0.980),(1.000,1.000),(1.037,1.184)] \\ [(1.033,1.360),(1.360,1.396),(1.396,1.528)] \\ [(1.003,1.198),(1.198,1.400),(1.400,1.507)] \\ [(1.073,1.369),(1.369,1.398),(1.460,1.563)] \\ [(1.000,1.000),(1.000,1.000),(1.333,1.333)] \end{pmatrix}$$

An example of calculating the elements of matrix IFRN (k_j) is as follows:

$$\begin{aligned} \text{IFRN}\,[k_2] &= \begin{bmatrix} (2-x_j^{U3}),(2-x_j^{L3}),(2-x_j^{U2}),(2-x_j^{L2}),(2-x_j^{U1}),(2-x_j^{L1}) \\ (2-1.333),(2-1.067),(2-1.067),(2-1.017),(2-1.017),(2-1.010) \end{bmatrix} \\ &= [(0.867,0.933),(0.933,0.983),(0.983,0.990)] \end{aligned}$$

The next activity represents the calculation of IFRN $[q_j]$ as follows:

$$\text{IFRN}\,[q_j] = \begin{pmatrix} [(1.000,1.000),(1.000,1.000),(1.000,1.000)] \\ [(1.010,1.017),(1.017,1.071),(1.071,1.154)] \\ [(1.020,1.034),(1.034,1.148),(1.148,1.331)] \\ [(1.146,1.221),(1.241,1.465),(1.465,1.858)] \\ [(0.679,0.748),(0.762,0.945),(0.950,1.316)] \\ [(0.901,1.054),(1.203,1.621),(1.628,2.548)] \\ [(0.761,1.017),(1.203,1.621),(1.661,2.663)] \\ [(0.498,0.729),(0.862,1.192),(1.221,2.578)] \\ [(0.331,0.520),(0.616,0.995),(1.020,2.569)] \\ [(0.211,0.356),(0.440,0.727),(0.745,2.393)] \\ [(0.159,0.267),(0.440,0.727),(0.745,2.393)] \end{pmatrix}$$

Again, the first element is equal to IRFN of one. In order to calculate the shown matrix, the following procedure should be applied:

$$\begin{aligned} \text{IFRN}\,[q_3] &= \left[\left(\frac{q_2^{L1}}{k_3^{U3}}\right),\left(\frac{q_2^{U1}}{k_3^{L3}}\right),\left(\frac{q_2^{L2}}{k_3^{U2}}\right),\left(\frac{q_2^{U2}}{k_3^{L2}}\right),\left(\frac{q_2^{L3}}{k_2^{U1}}\right),\left(\frac{q_2^{U3}}{k_3^{L1}}\right)\right] \\ \text{IFRN}\,[q_3] &= \left[\left(\frac{1.010}{0.990}\right),\left(\frac{1.017}{0.983}\right),\left(\frac{1.017}{0.983}\right),\left(\frac{1.071}{0.933}\right),\left(\frac{1.017}{0.933}\right),\left(\frac{1.154}{0.867}\right)\right] \\ \text{IFRN}\,[q_3] &= [(1.020,1.034),(1.034,1.148),(1.148,1.331)] \end{aligned}$$

The matrix IFRN $[w_j]$ was obtained after summing the previous matrix and calculating

$$[\delta_j] = [(7.717, 8.964), (9.818, 12.512), (12.654, 21.804)] :$$

$$\text{IFRN}\,[w_j] = \begin{pmatrix} [(0.046, 0.079), (0.080, 0.102), (0.112, 0.130)] \\ [(0.046, 0.080), (0.081, 0.109), (0.120, 0.150)] \\ [(0.047, 0.082), (0.083, 0.117), (0.128, 0.173)] \\ [(0.053, 0.097), (0.099, 0.149), (0.163, 0.241)] \\ [(0.031, 0.059), (0.061, 0.096), (0.106, 0.171)] \\ [(0.041, 0.083), (0.096, 0.165), (0.182, 0.330)] \\ [(0.035, 0.080), (0.096, 0.165), (0.185, 0.345)] \\ [(0.023, 0.058), (0.069, 0.121), (0.136, 0.334)] \\ [(0.015, 0.041), (0.049, 0.101), (0.114, 0.333)] \\ [(0.010, 0.028), (0.035, 0.074), (0.083, 0.310)] \\ [(0.007, 0.021), (0.035, 0.074), (0.083, 0.310)] \end{pmatrix}$$

$$\text{IFRN}\,[w_1] = \left[\left(\frac{1.000}{21.804}\right), \left(\frac{1.000}{12.654}\right), \left(\frac{1.000}{12.512}\right), \left(\frac{1.000}{9.818}\right), \left(\frac{1.000}{8.964}\right), \left(\frac{1.000}{7.717}\right)\right]$$

Using equations for the inverse IFRN PIPRECIA, part of the methodology criteria weights is as follows:

$$\text{IFRN}\,[w_j{}'] = \begin{pmatrix} [(0.005, 0.020), (0.036, 0.110), (0.142, 0.547)] \\ [(0.006, 0.027), (0.043, 0.114), (0.142, 0.547)] \\ [(0.009, 0.037), (0.050, 0.118), (0.142, 0.547)] \\ [(0.014, 0.052), (0.071, 0.142), (0.169, 0.567)] \\ [(0.011, 0.039), (0.048, 0.090), (0.107, 0.321)] \\ [(0.019, 0.066), (0.081, 0.147), (0.173, 0.489)] \\ [(0.025, 0.075), (0.081, 0.147), (0.172, 0.475)] \\ [(0.029, 0.072), (0.077, 0.137), (0.160, 0.323)] \\ [(0.037, 0.081), (0.087, 0.124), (0.145, 0.236)] \\ [(0.036, 0.077), (0.083, 0.112), (0.130, 0.165)] \\ [(0.036, 0.077), (0.083, 0.112), (0.124, 0.157)] \end{pmatrix}$$

The final criteria weights are shown in Table 4.

The obtained results show that the order of criteria is as follows: C7>C6>C4>C8>C3>C2>C1>C9>C10>C11.

Table 4. Results of the IFRN PIPRECIA method

	W_j
C1	[(0.025,0.050),(0.058,0.106),(0.127,0.338)]
C2	[(0.026,0.054),(0.062,0.111),(0.131,0.348)]
C3	[(0.028,0.059),(0.067,0.117),(0.135,0.360)]
C4	[(0.033,0.074),(0.085,0.146),(0.166,0.404)]
C5	[(0.021,0.049),(0.055,0.093),(0.106,0.246)]
C6	[(0.030,0.075),(0.089,0.156),(0.177,0.410)]
C7	[(0.030,0.078),(0.089,0.156),(0.178,0.410)]
C8	[(0.026,0.065),(0.073,0.129),(0.148,0.328)]
C9	[(0.026,0.061),(0.068,0.113),(0.129,0.284)]
C10	[(0.023,0.053),(0.059,0.093),(0.107,0.238)]
C11	[(0.022,0.049),(0.059,0.093),(0.103,0.233)]

4 Conclusions

The research was conducted on 11 different criteria relevant to the selection of plum variety/rootstock combinations, involving 17 domain experts and fruit producers. The interval fuzzy rough PIPRECIA method proved to be applicable for addressing complex decision-making problems in fruit production. Based on the independent evaluations of experts and the application of the IFRN PIPRECIA method, the results highlight the prioritization of criteria related to yield and physical fruit characteristics. Specifically, the criteria of fruit weight (C7), cumulative yield efficiency (C6), and final fruit set (C4) were determined as the most important. At the same time, criteria related to the chemical composition and fruit quality were identified as the least important (C9 - soluble solids; C10 - total phenolic content in skin of fruit; and C11 - radical-scavenging activity).

The experience gained from this research demonstrates the significant potential of using the interval fuzzy rough PIPRECIA method in addressing research and managerial problems in fruit production. Future studies should focus on applying this and similar methods to decision-making problems in other agricultural sectors and developing digital tools to facilitate the application of MCDM techniques for a broader range of users.

Author Contributions

Conceptualization, M.R. and R.B.; methodology, Ž.S.; software, Ž.S.; validation, D.M., and A.G.L.; formal analysis, G.V.; investigation, M.R.; resources, M.R.; data curation, G.V.; writing—original draft preparation, Ž.S.; writing—review and editing, G.V.; visualization, Ž.S.; supervision, D.M.; project administration, R.B.; funding acquisition, M.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data supporting our research results are included within the article or supplementary material.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] FAO, "Faostat," https://www.fao.org/faostat/en/#home, 2024.

[2] M. Sitarek, Z. S. Grzyb, and B. Koziński, "Effect of four different rootstocks on the growth, yield and fruit quality of Valor plum trees," *Acta Hortic.*, vol. 734, pp. 413–416, 2007. https://doi.org/10.5555/20073168350

[3] M. Mészáros, J. Kosina, L. Laňar, and J. Náměstek, "Long-term evaluation of growth and yield of Stanley and Cacanska lepotica plum cultivars on selected rootstocks," *Hort. Sci.*, vol. 42, no. 1, pp. 22–28, 2015. https://doi.org/10.17221/192/2014-HORTSCI

[4] A. E. Rato, A. C. Agulheiro, J. M. Barroso, and F. Riquelme, "Soil and rootstock influence on fruit quality of plums (Prunus domestica L.)," *Sci. Hortic.*, vol. 118, no. 3, pp. 218–222, 2008. https://doi.org/10.1016/j.scienta.2008.06.013

[5] V. Usenik, N. Fajt, M. Mikulic-Petkovsek, A. Slatnar, F. Stampar, and R. Veberic, "Sweet cherry pomological and biochemical characteristics influenced by rootstock," *J. Agric. Food Chem.*, vol. 58, no. 8, pp. 4928–4933, 2010. https://doi.org/10.1021/jf903755b

[6] T. Milosevic, B. Zornic, and I. Glisic, "A comparison of low-density and high-density plum plantings for differences in establishment and management costs, and in returns over the first three growing seasons–A mini-review," *J. Hort. Sci. Biotechnol.*, vol. 83, no. 5, pp. 539–542, 2008. https://doi.org/10.1080/14620316.2008.11512419

[7] I. Sosna and M. Licznar-Malańczuk, "Growth, yielding and tree survivability of several apricot cultivars on Myrobalan and Wangenheim Prune seedlings," *Acta Sci. Pol. Hortorum Cultus*, vol. 11, no. 1, pp. 27–37, 2012.

[8] M. Meland, "Performance of six European plum cultivars on four plum rootstocks growing in a northern climate," *Acta Agric. Scand. Sect. B–Soil Plant Sci.*, vol. 60, no. 4, pp. 381–387, 2010. https://doi.org/10.1080/09064710903103917

[9] J. Blažek and I. Pištěková, "Final evaluation of nine plum cultivars grafted onto two rootstocks in a trial established in 1998 at Holovousy," *Hort. Sci. (Prague)*, vol. 39, no. 3, pp. 108–115, 2012. https://doi.org/10.17221/150/2011-HORTSCI

[10] B. Gonçalves, J. Moutinho-Pereira, A. Santos, A. P. Silva, E. Bacelar, C. Correia, and E. Rosa, "Scion–rootstock interaction affects the physiology and fruit quality of sweet cherry," *Tree Physiol.*, vol. 26, no. 1, pp. 93–104, 2006. https://doi.org/10.1093/treephys/26.1.93

[11] S. Milenković, D. Ružić, R. Cerović *et al.*, *Sorte Voćaka Stvorene u Institutu za Voćarstvo-Čačak i Nove Sorte Maline i Kupine za Tržište Svežih Plodova i Preradevina.* Institut za Istraživanja u Poljoprivredi Srbija, Beograd, Grafika Jureš, Čačak, 2006.

[12] M. T. Ali, S. Mehraj, M. S. Mir, I. A. Shah, Z. A. Shah, H. A. El-Serehy, S. A. Wanig, U. Fayazf, F. A. Al-Misned, and H. M. Shafik, "Deciphering the response of thirteen apple cultivars for growth, fruit morphology and fruit physico-chemical attributes during different years," *Heliyon*, vol. 9, no. 6, p. e17260, 2023. https://doi.org/10.1016/j.heliyon.2023.e17260

[13] N. Milošević, I. Glišić, M. Dordević, S. Radičević, and S. Marić, "Ispitivanje sorti šljive ranog vremena sazrevanja ploda na području Čačka," in *Zbornik Radova: XXVI Savetovanje o Biotehnologiji sa Medunarodnim Učešćem*, 2021, pp. 151–159. https://doi.org/10.46793/SBT26.151M

[14] M. Radović, D. Milatović, Z. Tešić, T. Tosti, U. Gašić, B. Dojčinović, and D. D. Zagorac, "Influence of rootstocks on the chemical composition of the fruits of plum cultivars," *J. Food Compos. Anal.*, vol. 92, p. 103480, 2020. https://doi.org/10.1016/j.jfca.2020.103480

[15] A. Puška, M. Nedeljković, R. Prodanović, R. Vladisavljević, and R. Suzić, "Market assessment of pear varieties in Serbia using fuzzy CRADIS and CRITIC methods," *Agriculture*, vol. 12, no. 2, p. 139, 2022. https://doi.org/10.3390/agriculture12020139

[16] M. Nedeljković, A. Puška, M. Jeločnik, D. Božanić, J. Subić, A. Štilić, and A. Maksimović, "Enhancing fruit orchard establishment: A multicriteria approach for plum variety selection," *Yugoslav J. Oper. Res.*, vol. 34, no. 2, pp. 355–380, 2023. https://doi.org/10.2298/YJOR230815033N

[17] Z. Stević, Z. Stjepanović, Z. Božičković, D. K. Das, and D. Stanujkić, "Assessment of conditions for implementing information technology in a warehouse system: A novel fuzzy PIPRECIA method," *Symmetry*, vol. 10, no. 11, p. 586, 2018. https://doi.org/10.3390/sym10110586

[18] M. Bakır, S. Akan, and E. Özdemir, "Regional aircraft selection with fuzzy PIPRECIA and fuzzy MARCOS: A case study of the Turkish airline industry," *Facta Univ., Ser. Mech. Eng.*, vol. 19, no. 3, pp. 423–445, 2021. https://doi.org/10.22190/FUME210505053B

[19] A. Mishra, "Evaluation of TPM adoption factors in manufacturing organizations using fuzzy PIPRECIA method," *J. Qual. Maint. Eng.*, vol. 30, no. 1, pp. 101–119, 2023. https://doi.org/10.1108/JQME-11-2020-0115

[20] K. Zorlu and V. Dede, "Analysis of barriers to sustainable tourism development with interpretive structural modelling and fuzzy PIPRECIA," *J. Anatol. Geogr.*, vol. 2, no. 2, pp. 84–96, 2024.

[21] N. Chen, Q. Liu, Z. Stević, M. Andrejić, and V. Pajić, "An integrated cost based approach for warehouse performance evaluation: A new multiphase model," *Alexandria Eng. J.*, vol. 101, pp. 62–77, 2024. https://doi.org/10.1016/j.aej.2024.05.063