ROMANIAN JUJUBE (*ZIZIPHUS JUJUBA* MILL.) GENOTYPES: AN INTEGRATIVE ANALYSIS FOR ROOTSTOCK SELECTION AND ENVIRONMENTAL INSIGHTS

GENOTIPURI ROMÂNEȘTI DE JUJUBE (*ZIZIPHUS JUJUBA* MILL.): O ANALIZĂ INTEGRATIVĂ PENTRU SELECȚIA PORTALTOILOR ȘI PERSPECTIVE DE MEDIU

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Abstract.
Knowledge of valuable Romanian jujube (Ziziphus jujuba Mill.) genotypes is fragmented across separate morphological and biochemical studies. This integrative analysis uses Pearson correlations and PCA on twelve genotypes to link their physical, chemical, and mineral traits. A strong negative correlation was found between fruit size and bioactive compound concentration. The difference between genotypes was clear. 'Mahmudia 2' produced small fruits packed with polyphenols, while the large fruits from 'Ostrov' had much lower levels. The fruit`s location also mattered, as higher lead and cadmium were found in genotypes originating from Danube sites. The integrated data defined chemo-morphological rootstock "ideotypes": 'Jurilovca III 1' for quality (sugars, calcium) and 'Mahmudia 2' for resilience (polyphenols).
Key words: chinese jujube; local populations; fruit traits; bioactive compounds; ideotypes.

Rezumat.
Cunoașterea genotipurilor valoroase de jujube românești (Ziziphus jujuba Mill.) este fragmentată, provenind din studii morfologice și biochimice separate. Această analiză integrativă folosește corelațiile Pearson și analiza componentelor principale (PCA) pe douăsprezece genotipuri pentru a lega trăsăturile lor fizice, chimice și minerale. Analiza a relevat o corelație negativă puternică între mărimea fructului și concentrația de compuși bioactivi. Diferența dintre genotipuri a fost clară. Genotipul 'Mahmudia 2' a produs fructe mici, bogate în polifenoli, în timp ce fructele mari de la 'Ostrov' au avut niveluri mult mai scăzute. Proveniența fructelor a fost de asemenea importantă. Genotipurile din zonele dunărene au prezentat concentrații mai mari de plumb și cadmiu. Datele integrate au definit „ideotipuri" chemo-morfologice pentru portaltoi: 'Jurilovca III 1' pentru calitate (zaharuri, calciu) și 'Mahmudia 2' pentru reziliență (polifenoli).

[1] Research Station for Fruit Growing, Constanța

Cuvinte cheie: curmale chinezești; populații locale; trăsăturile fructelor; compuși bioactivi; ideotipuri.

INTRODUCTION

Ziziphus jujuba Mill., known as jujube or Chinese jujube, is one of the oldest cultivated fruit tree species, with a history spanning thousands of years [Liu *et. al*., 2020]. Its fruits are valued not only for fresh or processed consumption but also for their role as a traditional and functional food, owing to a remarkable nutritional profile [Stoli and Stănică, 2023]. They contain a wide range of bioactive compounds, including polysaccharides, polyphenols, triterpenic acids, amino acids, and vitamins, which give them antioxidant, anti-inflammatory, and immunomodulatory properties [Lu *et. al.*, 2021**]**. A distinctive feature of the jujube is the presence of 23 amino acids, a diversity rarely found in other fruits, which reinforces its "superfruit" status. Furthermore, the species exhibits high natural resistance to diseases and pests, allowing for cultivation with a reduced number of phytosanitary treatments, a considerable advantage in the context of sustainable agriculture [Shahrajabian *et. al*., 2019]. These attributes have spurred a growing global interest in leveraging jujube in the functional food and nutraceutical industries [Ding *et. al*., 2016].

The Dobrogea region of Romania holds a particularly valuable genetic heritage for *Ziziphus jujuba*. The species was introduced to this area approximately two millennia ago by Greek and Roman colonists near ancient fortresses such as Argamum (Jurilovca), Salsovia (Mahmudia), and Vicina (Ostrov) [Stănică, 2019]. Over time, these populations adapted and naturalized, evolving under semi-spontaneous conditions and giving rise to distinct local biotypes. These genotypes, including 'Ostrov', 'Jurilovca', 'Mahmudia', and 'Bugeac', represent a unique genetic reservoir specifically adapted to the region's pedoclimatic conditions [Stoli and Stănică, 2025]. The conservation and in-depth characterization of this germplasm are essential not only for preserving biodiversity but also for identifying valuable traits, such as stress adaptability, superior biochemical profiles, or compatibility as rootstocks, which can be integrated into modern breeding programs.

A first study deepened this knowledge by performing a comprehensive biochemical and mineral analysis [Stoli and Stanica, 2023]. This research highlighted genotypes with exceptional chemical profiles: 'Jurilovca III 1' stood out for its very high sugar content, 'Mahmudia 2' for its exceptional concentration of total polyphenols and antioxidant capacity, and 'Jurilovca III 1' also demonstrated a superior mineral content. However, although these two studies offer excellent and detailed characterizations in their specific domains, they remain disjointed analyses. Previous research laid the groundwork for understanding these valuable local genotypes. A second study conducted a detailed morphological characterization of fruits and stones, revealing significant variability among genotypes. That study highlighted the 'Ostrov' genotype for its large-sized fruits, suitable for fresh consumption, and identified the 'Bugeac', 'Jurilovca', and 'Mahmudia' genotypes as having high potential for use as generative rootstocks due to their small fruits and viable seeds [Stoli and Stănică, 2025].

The major knowledge gap lies in the absence of an integrative analysis to explore the relationships and correlations between these datasets. Currently, it is unknown how the physical characteristics of the fruits (mass, diameter) correlate with their biochemical richness (polyphenol content, sugars, antioxidant capacity).

Furthermore, the link between the mineral profile of the fruits and their morphological or qualitative traits has not been investigated, nor has the potential influence of local geochemistry on mineral composition. This lack of an integrated perspective limits the strategic and efficient use of these valuable genotypes in breeding programs, cultivation selection, or the development of value-added products.

MATERIAL AND METHOD

To perform the integrative statistical analysis, quantitative data from both source publications were centralized. This approach allowed for the calculation of correlations between morphological parameters (*e.g.*, fruit weight) and biochemical parameters (*e.g.*, polyphenol content). The statistical analysis of this consolidated data matrix was performed using the following methods:

- descriptive statistics: Mean, standard deviation, and range were calculated for all quantitative variables to provide an overview of the dataset.
- correlation analysis: The Pearson correlation coefficient (r) was applied to quantify the degree of linear association between pairs of variables of interest (*e.g.*, Fruit Mass vs. Total Polyphenols; Calcium Content vs. Soluble Solids).

The statistical significance threshold was set at $p<0.05$.

To evaluate the multivariate relationships, a Principal Component Analysis (PCA) was performed on a focused subset of 10 key morphological and chemical variables discussed in the text.

RESULTS AND DISCUSSIONS

The morphological characteristics of the fruits for the twelve genotypes are detailed in Table 1. Considerable differences were recorded, particularly between the local genotypes and the cultivated varieties. Fruit weight ranged from a minimum of 1.47 g in the local genotype 'Mahmudia 2' to a maximum of 19.97 g in the cultivar 'Taigu Ban'. Among the local genotypes, 'Ostrov' had the largest fruits (4.73 g).

Table 1

Morphological characteristics of jujube fruits

Genotype	Fruits length (mm)	Fruits diameter (mm)	Fruits weight (g)	Pulp weight (g)
Jurilovca I 1	23.29	19.97	3.08	2.79
Jurilovca I 2	23.76	20.33	3.3	3.02

Jurilovca III 1	18.34	16.75	2.18	1.97
Mahmudia 1	21.24	18.62	2.66	2.37
Mahmudia 2	16.48	14.64	1.47	1.33
Ostrov	25.3	22.19	4.73	4.46
Bugeac	19.65	18.78	3.25	2.95
Taigu Ban	44.16	37.61	19.97	18.17
Hu Ping	43.53	35.95	15.64	14.24
Xuan Chen Jiang Zao	41	33.85	13.98	12.53
Jun Zao	43.81	37.03	18.67	17.07
Hongan	33.72	30.04	12.49	11.34

The results of the biochemical analyses are presented in Table 2. The local genotype 'Mahmudia 2' stood out with the highest content of total polyphenols (1020 mg GAE/100g) and the greatest antioxidant capacity (442.5 mg TE/100g). In contrast, the cultivar 'Hu Ping' recorded the lowest values for these parameters. The highest sugar content was identified in the 'Jurilovca III 1' genotype (31.07%).

Table 2

Biochemical profile of jujube fruits

Genotype	Sugar content (%)	Total polyphenols (mg galic acid/100)	Antioxidant capacity (mg Trolox/100g)
Jurilovca I 1	26.4	690	375
Jurilovca I 2	19.04	750	382.5
Jurilovca III 1	31.07	780	405
Mahmudia 1	19.71	720	397.5
Mahmudia 2	22.49	1020	442.5
Ostrov	29.9	510	232.5
Bugeac	26.17	690	315
Taigu Ban	19.03	420	142.5
Hu Ping	15.91	390	120
Xuan Chen Jiang Zao	19.48	540	270
Jun Zao	16.35	480	202.5
Hongan	17.45	450	240

The content of macroelements and heavy metals is summarized in Table 3. Lead and Cadmium levels were highest in the 'Mahmudia 1' and 'Ostrov' genotypes but remained within the permissible legal limits. The local genotypes generally showed a superior content of Calcium and Potassium compared to the cultivated varieties. The highest Calcium content was measured in 'Jurilovca III 1' (47.95 mg/100g), while the highest value for Potassium was found in 'Mahmudia 1' (55.16 mg/100g).

Table 3

Mineral composition of jujube fruits

Genotype	Pb (μg/kg)	Cd (μg/kg)	K (mg/100g)	Ca (mg/100g)
Jurilovca I 1	7.88	<1	42.09	38.95
Jurilovca I 2	13.53	<1	51.99	37.51
Jurilovca III 1	16.8	<1	53.61	47.95
Mahmudia 1	49.86	3.87	55.16	34.66
Mahmudia 2	9.21	<1	51.06	36.3
Ostrov	45.43	3.66	52.54	14.44
Bugeac	8.9	<1	47.87	25.09
Taigu Ban	26.73	2.17	53.6	9.44
Hu Ping	17.68	1.89	49.43	6.29
Xuan Chen Jiang Zao	20.77	2.58	54.07	9.57
Jun Zao	17.37	2.3	51.88	8.33
Hongan	40	2.2	49.79	9.97

The integrative statistical analysis of the chemo-morphological and mineral data revealed several key findings.

A strong, statistically significant negative correlation was identified between the physical parameters of the fruits and the concentration of bioactive compounds. Specifically, fruit mass, fruit diameter, and pulp mass were inversely correlated with total polyphenol content (Table 4 and Figure 1) and antioxidant capacity (Table 5 and Figure 2). This is most evident when comparing the genotypes at the extremes: the 'Ostrov' genotype, which produces the largest fruits (average mass 4.73 g), shows a modest polyphenol content (510 mg gallic acid/100 g), whereas the 'Mahmudia 2' genotype, with some of the smallest fruits (average mass 1.47 g), has an exceptional polyphenol content (1020 mg gallic acid/100 g) and the highest antioxidant capacity (442.5 mg Trolox/100 g) of all genotypes studied.

Table 4

Pearson Correlation Matrix between fruit weight and total polyphenol content

		Fruit weight (g)	Total Polyphenols
Fruit weight (g)	Pearson Correlation	1	-.818**

	Sig. (2-tailed)		1
	N	12	12
**. Correlation is significant at the 0.01 level (2-tailed).			

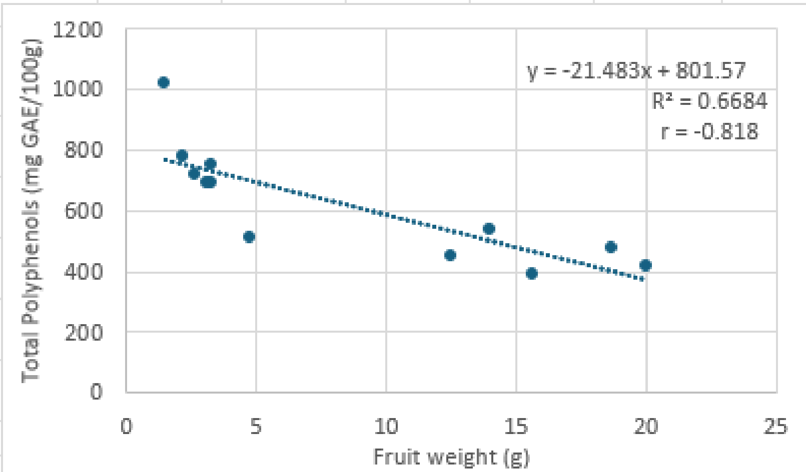

Fig. 1. Correlation between fruit weight and total polyphenol content

Table 5

Pearson Correlation Matrix between fruit weight and antioxidant capacity

		Fruit weight (g)	**Antioxidant Capacity**
Fruit weight (g)	Pearson Correlation	1	-.875**
	Sig. (2-tailed)		0
	N	12	12
**. Correlation is significant at the 0.01 level (2-tailed).			

Fig. 2. Correlation between fruit weight and antioxidant capacity

The mineral analysis identified distinct geochemical patterns linked to geographical origin. The 'Mahmudia 1' (Pb: 49.86 µg/kg; Cd: 3.87 µg/kg) and 'Ostrov' (Pb: 45.43 µg/kg; Cd: 3.66 µg/kg) genotypes showed significantly higher concentrations of heavy metals, specifically lead (Pb) and cadmium (Cd), compared to other local genotypes. It is noted that all values are below the maximum limits permitted by European legislation. Furthermore, the analysis of essential minerals showed that the 'Jurilovca III 1' genotype contains the highest concentration of calcium (Ca) at 47.95 mg/100 g, while the 'Mahmudia 1' genotype has the highest level of potassium (K) at 55.16 mg/100 g.

The results of this study provide a deeper understanding of the relationships between the physical, chemical, and environmental traits of Romanian jujube genotypes, with significant implications for breeding and cultivation.

The inverse correlation between fruit size and bioactive content reflects a physiological principle known as the "dilution effect." The biosynthesis of secondary metabolites like polyphenols occurs early in fruit development [Sulusoglu, 2014]. As the fruit later expands by accumulating water and sugars, these pre-existing compounds are diluted, leading to lower concentrations in larger fruits [Wang *et. al.*, 2024]. This finding highlights a critical trade-off for breeding programs: selecting for large fruit size, often desired for fresh consumption, may unintentionally reduce the nutraceutical value. Consequently, small-fruited but biochemically rich genotypes like 'Mahmudia 2' are identified as elite genetic resources, not for the fresh market, but for developing high-value ingredients for functional foods and nutraceuticals.

The distinct heavy metal profiles suggest possible environmental signatures (Figure 3). The higher Pb and Cd levels in the 'Mahmudia 1' and 'Ostrov' genotypes are likely linked to their collection sites near the Danube River. The river's floodplain and delta are known to accumulate sediments and associated pollutants from its basin, suggesting a higher bioavailability of these elements in the local soil

[Gati *et. al.*, 2016]. This underscores the importance of site selection for commercial orchards and suggests jujube genotypes could serve as bio-indicators of soil geochemistry.

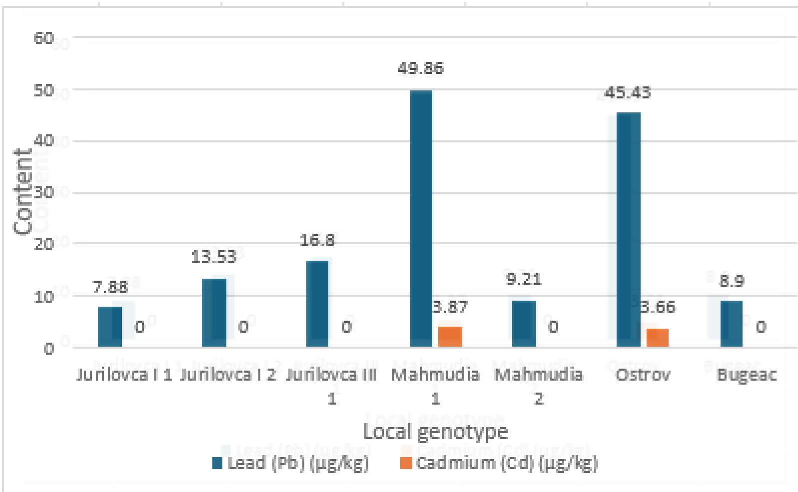

Fig. 3. Geographic variation in mineral and heavy metal levels

A significant finding regarding food safety is the non-detectable Cadmium level in the 'Mahmudia 2' genotype (Figure 4). This result is particularly noteworthy when contrasted with the 'Mahmudia 1' genotype which, despite growing in close proximity, showed quantifiable levels of this heavy metal. This stark difference suggests that 'Mahmudia 2' may possess a valuable genetic trait that limits its uptake or accumulation of Cadmium from the soil.

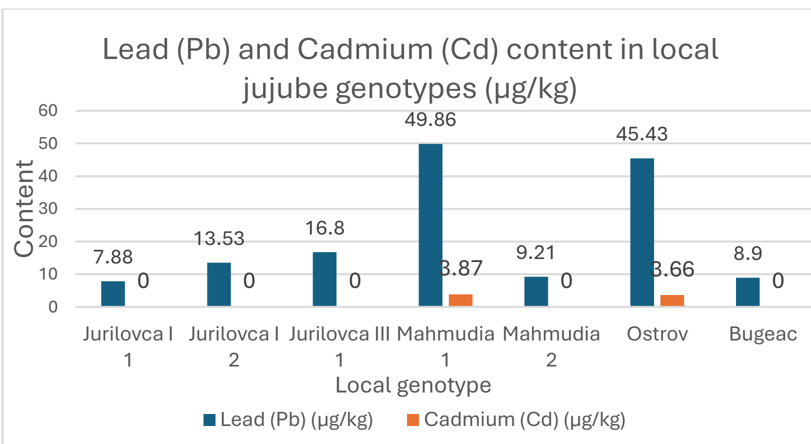

Fig. 4. Lead (Pb) and Cadmium (Cd) content in the fruits of local jujube genotypes (µg/kg)

Furthermore, the mineral content appears to influence fruit quality. The high calcium content in 'Jurilovca III 1' may contribute to improved fruit firmness and shelf-life, as Ca is essential for cell wall integrity [Roper, 2016]. Potassium's role in sugar transport suggests a link between its high levels and the fruit's soluble solids content.

These integrated findings allow for the definition of data-driven "rootstock ideotypes." A rootstock can significantly influence scion performance, including fruit quality. Based on this analysis, 'Jurilovca III 1' emerges as an ideotype for quality and productivity. Its high sugar and calcium content indicate a superior capacity for mineral uptake and assimilation, potential traits for enhancing fruit quality in the scion. 'Mahmudia 2' represents an ideotype for resilience and adaptability; its exceptionally high polyphenol and acidity levels indicate a robust defense metabolism, which could confer enhanced tolerance to biotic and abiotic stress upon the scion [Jayswal and Lal, 2020; Vijayalaxmi, 2023].

Finally, 'Bugeac', with its balanced profile, could serve as a general-purpose rootstock. This strategic approach, which moves beyond simple morphological selection, is supported by recent trials that have begun to test these local genotypes as rootstocks [Stoli *et. al.*, 2022].

The Principal Component Analysis (PCA) of the 10 key variables revealed a clear separation between local genotypes and cultivated varieties (Table 6). The first principal component (PC1), explaining 58.6% of the total variance, separated genotypes primarily based on fruit size (to the right) and the content of bioactive compounds and key minerals (to the left). The second principal component (PC2), explaining 19.7% of the variance, further differentiated genotypes based on heavy metal content (upwards) (Figure 5.)

Table 6

Coordinates of the jujube genotypes on the first two principal components (PC1, PC2)

Genotype	Type	PC1	PC2
Jurilovca I 1	Local	-1.54	-0.32
Jurilovca I 2	Local	-1.74	-0.8
Jurilovca III 1	Local	-2.71	0.81
Mahmudia 1	Local	-0.81	2.5
Mahmudia 2	Local	-3.42	0.3
Ostrov	Local	-0.52	-2.31
Bugeac	Local	-1.45	-1.18
Taigu Ban	Cultivar	4.31	0.58
Hu Ping	Cultivar	2.56	-1.33
Xuan Chen Jiang Zao	Cultivar	1.83	0.69
Jun Zao	Cultivar	3.12	0.28
Hongan	Cultivar	2.4	0.77

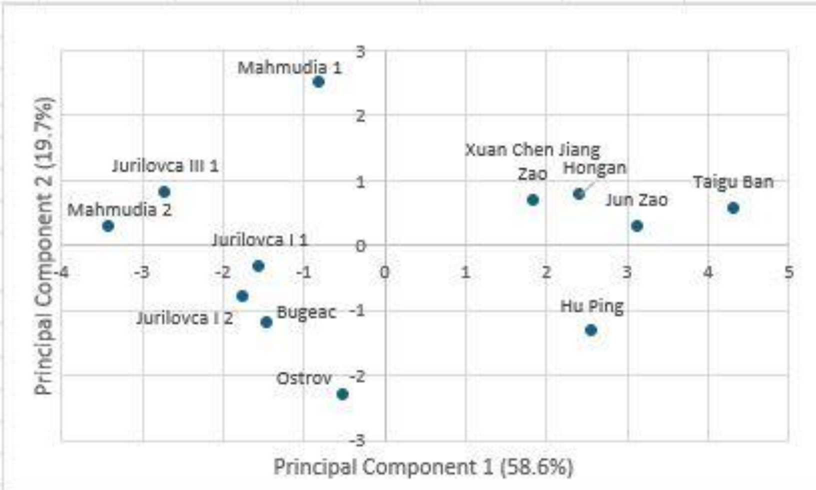

Fig. 5. Principal component analysis (PCA) score plot of jujube genotypes

CONCLUSIONS

This study performed the first integrative analysis of morphological, biochemical, and mineral data for a unique set of local jujube genotypes from Romania, generating new and valuable insights that surpass the conclusions of previous individual studies.

The main original contributions of this work are:

- Quantitative confirmation of the trade-off between size and nutraceutical value. A significant inverse correlation between fruit mass and the concentration of bioactive compounds, particularly polyphenols, was statistically demonstrated. The multivariate analysis (PCA) visually confirmed this distinction, revealing a clear separation between the small, nutritionally dense local genotypes and the large-fruited cultivars.

This discovery provides a solid scientific basis for strategically guiding breeding programs based on the final purpose (fresh consumption versus processing for functional products);

- Identification of environmental signatures in the mineral composition: A possible link between the geographical origin of the genotypes and their mineral profile was highlighted, especially the accumulation of heavy metals (Pb, Cd) in fruits from areas adjacent to the Danube.

This aspect opens a new research direction at the intersection of horticulture and environmental science, emphasizing the importance of local geochemical factors;

- Proposal of data-driven rootstock "ideotypes": The integrated analysis allowed for the definition of distinct chemo-morphological profiles for genotypes with rootstock potential.

Specific ideotypes were proposed for improving the fruit quality of the scion (based on 'Jurilovca III 1') and for increasing stress resilience (based on 'Mahmudia 2'), transforming a general hypothesis into a targeted breeding strategy.

These findings have direct practical implications. Breeders can use this analytical framework to select parental material more efficiently, balancing production traits with nutritional quality.

For the food industry, genotypes like 'Mahmudia 2' prove to be exceptional sources for developing high-value-added extracts for the functional food and nutraceutical market [Ding *et. al*., 2016]. For growers, the study underscores the critical importance of site selection, demonstrating that soil and the surrounding environment can directly influence the chemical composition of the harvest.

To validate and extend the conclusions of this study, the following research directions are recommended:

- Soil analysis and geochemical hypothesis validation: It is essential to perform a detailed soil analysis at the exact GPS coordinates mentioned in the original study for the 'Mahmudia 1' and 'Ostrov' genotypes. This should include determining the total and bioavailable content of heavy metals (Pb, Cd) and the general mineral composition to directly confirm the link between soil and fruit composition;

- Establishment of experimental grafting plots: To directly test the hypotheses regarding rootstock ideotypes, establishing controlled experiments is recommended. These should use the proposed rootstocks ('Jurilovca III 1', 'Mahmudia 2', 'Bugeac') and a common scion (*e.g*., 'Ostrov' or a valuable commercial cultivar). Measurements should target the rootstock's influence on the scion's growth, stress tolerance (*e.g*., controlled water stress), and, most importantly, on the physical, biochemical, and mineral quality of the fruits produced by the scion. This approach would directly validate the potential identified in this analysis and continue the work already started in this field [Stoli *et. al*., 2022].

- In-depth metabolomic analysis: The current study was based on total polyphenol content. A logical next step is to perform a metabolomic analysis (*e.g*., via HPLC-MS) to identify and quantify specific phenolic compounds (*e.g*., phenolic acids, flavonoids like rutin or quercetin) that contribute to the exceptional antioxidant capacity of genotypes like 'Mahmudia 2'. Identifying specific high-value compounds would exponentially increase the commercial and nutraceutical potential of these genotypes [Shao *et. al*., 2024].

- Sensory evaluation: Correlating objective chemical data *(e.g*., sugar/acid ratio, dry matter content) with consumer preferences through sensory evaluation panels would provide a complete picture of fruit quality and guide genotype selection not only based on composition but also on market acceptability.

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