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Comprehensive agrobiological and biochemical study of sweet pepper (*Capsicum annuum* L.) varieties

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ABSTRACT

Background: Sweet pepper (*Capsicum annuum* L.) fruits are characterized by a high content of vitamin C, carotenoids, and other biologically active compounds that contribute to their nutritional value. Under protected cultivation conditions, this crop ensures stable production of high-quality fruits regardless of seasonal variability. The identification and selection of cultivars capable of accumulating elevated levels of these compounds are of considerable interest for the agricultural sector and the development of functional food products.

Objective: The aim of this study is to conduct a comparative agronomic and biochemical evaluation of Armenian sweet pepper varieties grown under protected cultivation conditions.

Methods: The study was conducted from 2022 to 2024 under greenhouse conditions at the Scientific Centre of Vegetable and Industrial Crops. Nine promising sweet pepper (*Capsicum annuum* L.) varieties- Sate, Manana, Yana, Loshtak, Jermatnayin Hska, Narinj, Araqsi-23, Teghakan-7, and Nizak - were evaluated. Phenological observations, morphological characterization, yield assessment, and fruit quality evaluation were performed throughout the growing season. Biochemical parameters of the fruits were determined using spectrophotometric methods, while dry matter content was measured with a refractometer. Statistical analysis included ANOVA ($p \leq 0.05$), LSD test, and Pearson correlation.

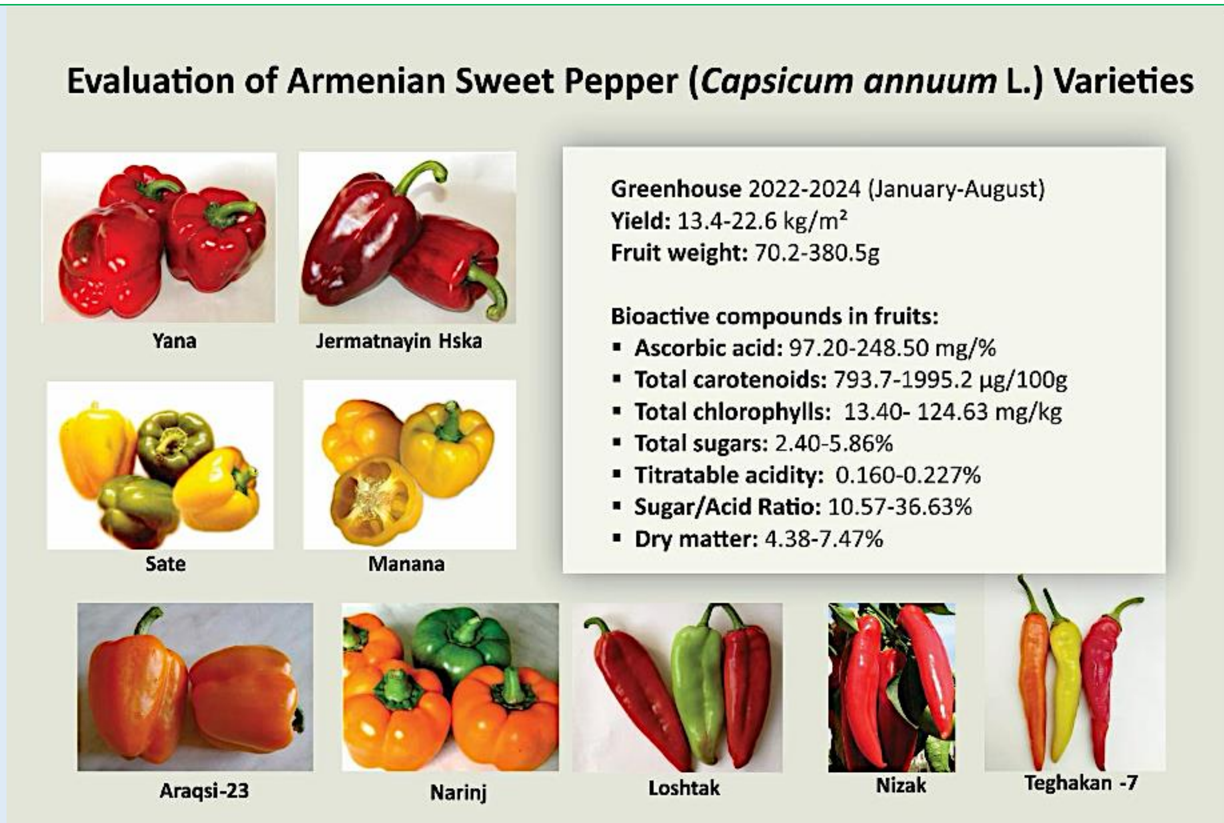
Results: The varieties showed significant differences in developmental timing, fruit shape and color, yield, and nutrient content. The period from emergence to flowering ranged from 80 to 97 days; technical maturity was reached in 107–121 days, and biological maturity in 135–145 days. Fruit morphology varied (cuboid, prismatic, conical), and color transitioned from green at the unripe stage to red, orange, or yellow at full maturity. Yields ranged from 13.4 to 22.6 kg/m², depending on the variety.

The highest levels of vitamin C and total sugars at both ripening stages were recorded in Araqsi-23, Jermatnayin Hska, and Manana. These varieties also demonstrated the highest sweetness index due to their elevated sugar and low acid content. The varieties Sate, Yana, and Narinj exhibited balanced biochemical profiles, making them suitable for both fresh consumption and processing. Loshtak, Teghakan-7, and Nizak had lower values, indicating their suitability for industrial processing. Chlorophyll content in unripe fruits was higher in dark-green-fruited varieties. The highest carotenoid levels were found in red-fruited varieties (Yana, Loshtak, Jermatnayin Hska, Nizak, and Teghakan-7), ranging from 1112.0 to 1995.2 µg/100 g fresh weight. Orange-fruited varieties (Narinj, Araqsi-23) and yellow-fruited ones (Sate, Manana) showed moderate and relatively lower carotenoid content. Importantly, all varieties contained vitamin C levels that exceed the recommended daily intake, emphasizing their high nutritional value.

Novelty: A comprehensive agrobiological and biochemical evaluation of nine Armenian sweet pepper varieties grown under protected cultivation was conducted for the first time. A correlation between morphological and biochemical traits of the fruits was established, which has not been previously reported in the scientific literature. Varieties with high levels of bioactive compounds were identified, highlighting their value for functional food production and breeding within the framework of sustainable agriculture.

Conclusion: The sweet pepper varieties differed in maturation period, fruit morphology, and levels of bioactive compounds. Several varieties combined high yield potential with notable nutritional value, confirming their suitability for protected cultivation and functional food production. The findings emphasize the importance of an integrated breeding approach focused on enhancing agronomic and nutraceutical traits.

Keywords: sweet pepper, Armenian varieties, greenhouse, phenological characteristics, fruit morphology, ascorbic acid, total carotenoids, total sugars, dry matter chlorophylls, antioxidant properties, yield



INTRODUCTION

Functional foods are attracting increasing attention from researchers due to their significant impact on human health [1-4]. Contemporary nutritional science increasingly emphasizes the role of vegetable crops rich in bioactive compounds in promoting health and preventing chronic diseases [5–16]. Sweet pepper (*Capsicum annuum L. var. annuum*) is among the most widely consumed vegetables, valued for its excellent flavor, appealing appearance, and rich biochemical composition, which has a positive impact on human health [17-19]. Its fruits are a notable source of diverse biologically active compounds, including vitamins, carotenoids, flavonoids, and antioxidants [20-21]. The synergistic action of these bioactive substances positions sweet pepper as an important dietary component that contributes to the prevention of various diseases [22].

An essential component of sweet pepper is vitamin C, a potent antioxidant that protects cells from damage caused by free radicals [23-24]. This vitamin plays a crucial role in human nutrition and physiological functions, including enhancing iron absorption, promoting wound healing, and contributing to skin defense against viral and bacterial infections by stimulating collagen synthesis [25].

The green coloration of immature sweet pepper fruits primarily results from the presence of chlorophylls and carotenoids, whereas the red pigmentation arises from carotenoid pigments such as β-carotene (provitamin A) and oxygenated carotenoids including capsanthin, capsorubin, and their 5,6-epoxide derivatives [26-27]. Carotenoids such as β-carotene are critical antioxidants that protect cellular structures from oxidative stress. They effectively quench singlet oxygen, one of the most reactive and damaging forms of oxygen, with each β-carotene molecule capable of neutralizing up to 300 singlet oxygen molecules. This property makes β-carotene a key factor in the prevention of oxidative damage to cells and tissues.

In addition, carotenoids such as lutein and zeaxanthin, which are predominantly found in orange and yellow pepper cultivars, may reduce the risk of age-related ocular diseases such as macular degeneration by protecting retinal tissues from ultraviolet radiation and oxidative stress [28]. These pigments also contribute to immune function [29] and are associated with reduced risk of oxidative stress-related conditions, including neurodegenerative and cardiovascular diseases, as well as various forms of cancer [30-31]. Remarkably, certain colored pepper varieties have demonstrated the ability to inhibit enzymes implicated in the progression of Alzheimer's disease [32].

In the context of modern agriculture, greenhouse cultivars of sweet pepper have gained particular importance due to their capacity to ensure stable production of high-quality vegetables [33]. In Armenia, sweet pepper (*Capsicum annuum* L.) holds traditional and economic significance, being a staple of the national cuisine and an essential crop in the agri-food sector. The advancement of greenhouse vegetable cultivation under changing climatic conditions extends the growing season, mitigates weather-related risks, and improves yield stability.

Genetic resources and varietal diversity play a crucial role in this context, enabling the development and selection of cultivars with improved consumer and biochemical traits. This, in turn, contributes not only to economic development but also to enhanced food security and nutritional quality [34-35].

The objective of the present study is to conduct an agronomic and biochemical evaluation of Armenian sweet pepper cultivars grown under protected conditions. The findings aim to identify genotypes with elevated levels of functional compounds, assess their productivity, and evaluate their potential suitability for agriculture and the food industry. This research is relevant to both the scientific community and producers focused on delivering high-value functional vegetable products.

MATERIAL AND METHODS

The study was conducted at the Scientific Centre of Vegetable and Industrial Crops of the Ministry of Economy of the Republic of Armenia (SCVIC, MEofRA) over a three-year period from 2022 to 2024.

Research material: The study material included nine promising Armenian greenhouse varieties of sweet pepper, maintained in the germplasm database of the SCVIC gene bank. Table 1 presents the passport data for these varieties, including institutional codes, accession numbers, DOI, accession names, registration certificate and years, as well as breeder information.

Table 1. Passport data of the studied pepper varieties [36].

N	Institutional code	Accession number	Accession DOI	Accession name	Certificate number, organization and year of issue	Authors
1	ARM008	1CAG1029 2CAG1029	10.18730/ZV01M 10.18730/ZV02N	Sate	N 52, Ministry Economy of the Republic of Armenia, Center for Agricultural Research and Certification (MEofRA CARC), 2009	Vardanian I.V., Sargsyan G.Zh.
2	ARM008	1CAG1032 2CAG1032	10.18730/ZV07T 10.18730/ZV08V	Manana	N 176, MEofRA CARC, 2017	Sargsyan G.Zh., Vardanian I.V.
3	ARM008	2CAG1042	In process	Yana	N178, MEofRA CARC, 2017	Sargsyan G.Zh., Vardanian I.V.

N	Institutional code	Accession number	Accession DOI	Accession name	Certificate number, organization and year of issue	Authors
4	ARM008	1CAG1034 1CAG1035 2CAG1035	10.18730/ZV0BY 10.18730/ZV0CZ 10.18730/ZV0D*	Loshtak	N 99, MEofRA CARC, 2013	Sargsyan G.Zh., Vardanian I.V., Abgaryan G.V., Martirosyan G.S., Lin Sh.V.
5	ARM008	1CAG1028 2CAG1028	10.18730/ZTZZJ 10.18730/ZV00K	Jermatnayin Hska	N189, MEofRA CARC, 2018	Sargsyan G.Zh.
6	ARM008	1CAG1027 2CAG1027	10.18730/ZTZXG 10.18730/ZTZYH	Narinj	N123, MEofRA CARC, 2014	Sargsyan G.Zh., Vardanian I.V., Vardanyan N.S., Lin Sh.V.
7	ARM008	1CAG1046 2CAG1046	In process	Araqsi-23	In process, MEofRA CARC, 2023	Sargsyan G.Zh., Vardanian I.V., Kirakosyan G.
8	ARM008	1CAG1047 2CAG1047	In process	Teghakan-7	In process, MEofRA CARC, 2023	Sargsyan G.Zh., Vardanian I.V., Harutyunyan Z.E.
9	ARM008	1CAG1031 2CAG1031	10.18730/ZV05R 10.18730/ZV06S	Nizak	N177, MEofRA CARC, 2017	Sargsyan G.Zh., Vardanian I.V., Abgaryan G.V.

Greenhouse conditions: The studies were conducted from January to August (2022-2024) in a glass greenhouse of the SCVIC located in the Darakert village, Ararat Marz, Armenia (40.115018° N, 44.417768° E). The soil composition in the root zone included: total nitrogen 4.2-4.5 mg, phosphorus 6.0-7.3 mg, and potassium 10.5-15.2 mg per 100g of soil. Soil electrical conductivity (EC) ranged from 1.5-2.2 dS·m−1, with a pH level of 7.2-7.5. Plant nutrition is carried out based on soil analysis results and plant development stages. The temperature regime in the greenhouse is maintained at 25–28°C during the day and 16–20°C at night.

Pepper seeds were sown between January 19 and 22. Between March 11 and 14, 50-day-old pepper seedlings were transplanted into the soil using the seedling method, with a planting scheme of (90+60) x 45cm, for four pepper plants per square meter. The experiment followed a block-randomized design with three replications.

Phenological observations and yield: Observations conducted throughout the entire growing season, with the recording of key phenological development stages of the plants: from mass germination to the onset of flowering (50%); from mass germination to the achievement of fruit stages of technical (TR) and biological ripeness (BR) (50%). Total yield recorded at all stages of ripening.

Morphological assessment of pepper fruits: The evaluation was conducted according to the international descriptor "Descriptors for Capsicum (Capsicum spp.)" [37].

Quality indicators of fruits: The biochemical analysis of pepper fruits was conducted in the laboratory of plant biotechnology, phytopathology, and biochemistry at the Scientific Center. Key quality indicators of the fruits were analyzed at the stages of technical (TR) and biological ripeness (BR) in three replications.

Ascorbic acid: The content of ascorbic acid was measured using a spectrophotometric method with the UV spectrophotometer Carry 60 UV-Vis (Agilent Technologies, USA), according to the standard procedure involving 2,4-dinitrophenylhydrazine and measuring absorption at λ = 520 nm. Calibration solutions were prepared based on L-ascorbic acid [15].

Total carotenoids: Only fruits that had reached the biological ripeness stage were used for the analysis. For carotenoid extraction, 10 ml of ethanol was used per 1 g of ground sample. Extraction carried out at room temperature for 30 minutes. The quantitative determination of total carotenoid content was performed spectrophotometrically at a wavelength of 450 nm, and the results were expressed in micrograms of beta-carotene equivalents per 100 g of fresh weight (FW) of the sample [38].

Chlorophyll: To assess the total chlorophyll concentration (a+b), green fruits were subjected to maceration for 24 hours, with 30 ml of methanol as the organic solvent. Light absorption at wavelengths of 666 nm and 653 nm was measured using a spectrophotometer [39]. The measurement results were used to calculate the chlorophyll content using the formula provided below. All values are expressed in mg/kg of fresh weight (FW).

$$Chlorophyll a = 15.65 * A_{666nm} - 7.34 * A_{653nm}$$

$$Chlorophyll\ b = 27.05 * A_{653nm} - 11.21 * A_{666nm}$$

Total sugars: The amount of total sugars was determined spectrophotometrically. The optical density of the solution was measured at λ = 490 nm. Calibration solutions were prepared based on glucose [15].

Titratable acidity (TA): TA was determined by acid-base titration using 0.1 N NaOH and phenolphthalein as an indicator. The titration endpoint was considered to be the appearance of a persistent pink color [40]. The results were expressed as a percentage of citric acid equivalents using a conversion factor of 0.0064 according to the following formula:

$$TA = \frac{V_{\text{NaOH}} \times N_{\text{NaOH}} \times 0.0064}{V_{\text{sample}}} \times 100$$

Sugar/Acid Ratio: This was calculated as the ratio of total sugar content to titratable acidity, which allows for the assessment of the flavor balance of the fruits [40]:

$$S/A = \frac{S}{TA}$$

Dry matter: The dry matter content was measured using a refractometer.

Correlation analysis: A Pearson correlation analysis was conducted using Python software and visualized as a heatmap to identify relationships between traits. This allowed for a clear assessment of the degree and direction of correlation between variables [41].

Data processing: Analysis of variance (ANOVA) was used for statistical analysis of experimental data, with a significance level of $p \leq 0.05$. The least significant difference (LSD) test was applied to compare mean values. The results are presented as mean values ± standard deviation (SD).

RESULTS

Phenological observations: The studies revealed that the varieties Narinj, Teghakan-7, and Nizak have the shortest duration from mass germination to flowering (80 days), to technical ripening (110 days), and to biological ripening (135 days). These varieties exhibit early development both in terms of the onset of flowering and the achievement of fruit ripeness. In contrast, the varieties Araqsi-23 and Jermatnayin Hska demonstrated the longest duration of phenological phases: 90 and 97 days to flowering, 120-121 days to technical ripening, and 141-145 days to biological ripening. This indicates a later fruit maturation compared to the other varieties. For the remaining varieties, the duration from mass germination to flowering ranged from 82 to 94 days to technical ripening from 110 to 120 days, and to biological ripening from 135 to 140 days, which classifies them as varieties with medium maturation times (Table 2).

Table 2. Duration of phenophases of the studied varieties

N	Variety	* Number of days from germination to		
		flowering	TR	BR
1	Sate	83	113	136
2	Manana	94	113	140
3	Yana	94	112	136
4	Loshtak	82	111	136
5	Jermatnayin Hska	97	121	145
6	Narinj	80	107	135
7	Araqsi-23	95	120	141
8	Teghakan-7	80	110	134
9	Nizak	80	110	135

*The average data is rounded to the nearest whole number.

Morphological characteristics of fruits: The greenhouse sweet pepper varieties studied exhibited significant variation in morphological traits, including color, shape, and fruit weight, which are essential criteria for selecting varieties for both fresh consumption and processing. At the technical ripening stage, fruit color ranged from light green (Loshtak, Nizak) and yellow green (Teghakan-7, Nizak) to dark green (Sate, Manana, Yana, Jermatnayin Hska, Narinj, Araqsi-23). At biological ripening, the color changed from red (Yana, Loshtak, Jermatnayin Hska, Teghakan-7, Nizak) to orange (Narinj, Araqsi-23) and yellow (Sate, Manana). Fruit shape also varied: from cubic (Manana, Narinj) and prismatic (Sate, Yana, Jermatnayin Hska, Araqsi-23) to conical (Loshtak) and elongated-conical (Teghakan-7, Nizak). This diversity in shape and color enhances consumer appeal and provides flexibility in choosing varieties for different market segments. Fruit weight ranged from 70.2 g to 380.5 g, accompanied by variations in diameter, length, and wall thickness (Table 3).

Table 3. Morphological characteristics of the fruits of the studied varieties

N	Variety	Shape	Color		Diameter, cm (±SD)	Length, cm(±SD)	Pericarp thickness, mm (±SD)	Weight, g (±SD)
			technical ripeness	biological ripeness				
1	Sate	Prismatic	Dark green	Yellow	6.2 ± 1.0	8.5 ±0.8	8.1±1.0	175.4±2.7
2	Manana	Cube	Dark green	Yellow	9.9 ± 1.0	10.6 ±1.2	10.1±1.2	210.3±3.6
3	Yana	Prismatic	Dark green	Red	8.5 ± 0.8	10.3 ±1.0	9.1±1.4	200.6±3.4
4	Loshtak	Conical	Light green	Red	5.8 ± 0.8	17.2 ±1.5	5.2±0.7	140.1±3.8
5	Jermatnayin Hska	Prismatic	Dark green	Red	9.2 ± 1.4	16.2 ±1.6	10.2±0,8	380.5±4.6
6	Narinj	Cube	Dark green	Orange	5.4 ± 0.7	5.5± 0.6	6.7±0.7	116.0±2.5
7	Araqsi-23	Prismatic	Dark green	Orange	7.5 ± 0.7	7.8± 1.0	8.5±0.6	224.5±3.5
8	Teghakan-7	Elongated-conical	Light green-yellow	Red	3.8 ± 0.6	18.1± 3.4	5.5±0.8	70.2±2.8
9	Nizak	Elongated-conical	Light green-yellow	Red	4.1 ± 0.5	17.4± 2.0	6.5±1.1	97.6±2.5

Productivity: The productivity analysis revealed significant differences between the varieties in terms of average yield per square meter. The highest yield was demonstrated by the variety Jermatnayin Hska, with a yield of 22.6 kg/m². This high result is attributed to the large fruit size (380.5 ± 4.6 g) and the number of fruits per plant (14.5 ± 1.6 pcs.). These characteristics make this variety one of the most promising for intensive greenhouse cultivation.

The variety Araqsi-23 also showed high productivity, with a yield of 21.5 kg/m², an average fruit weight of 224.5 ± 3.5 g, and 23.4 ± 2.2 fruits per plant. The combination of fruit weight and quantity makes it suitable for both fresh consumption and commercial production.

The average yield levels were recorded for the varieties Loshtak (15.3 kg/m²), Narinj (15.2 kg/m²), Manana (15.1 kg/m²), Sate (14.7 kg/m²), and Yana (13.4 kg/m²). These varieties are characterized by attractive external qualities and excellent taste, making them particularly in demand in the fresh produce market. Comparatively lower productivity was observed in the varieties Teghakan-7 (14.8 kg/m²) and Nizak (14.3 kg/m²). Despite having a larger number of fruits per plant (50.6 ± 5.4 and 36.7 ± 4.3, respectively), their average fruit weight was lower (70.2 g and 97.6 g), which determined their overall yield. However, due to their compact size and uniform fruit shape, these varieties are well-suited for processing and canning, expanding their commercial use.

All yield differences were statistically confirmed. $LSD_{0.5}$ values ranged from 0.56 to 1.65 kg/m², indicating the reliability of the observed differences between the varieties (Table 4).

Table 4. Productivity of the studied pepper varieties

N	Variety	Number of fruits per plant, pcs (±SD)	Average total yield, kg/m²	LSD_{05}, kg/m²
1	Sate	21.3 ± 1.5	14.7	0.56
2	Manana	17.3 ± 1.4	15.1	0.99
3	Yana	16.2 ± 1.6	13.4	0.55
4	Loshtak	27.0 ± 2.4	15.3	1.04
5	Jermatnayin Hska	14.5 ± 1.6	22.6	1.65
6	Narinj	32.5 ± 2.0	15.2	1.38
7	Araqsi-23	23.4 ± 2.2	21.5	1.24
8	Teghakan-7	50.6 ± 5.4	14.8	0.82
9	Nizak	36.7 ± 4.3	14.3	1.10

Fruit Quality Indicators

Ascorbic Acid: The results of the study revealed significant differences in the ascorbic acid content depending on the pepper varieties and fruit ripeness stages. The highest concentrations of vitamin C were observed in the varieties Araqsi-23 (188.44 ± 3.04 mg/% at the technical ripening stage and 248.50 ± 3.23 mg/% at the biological ripening stage), Jermatnayin Hska (155.45 ± 3.12 mg/% and 234.50 ± 3.78 mg/%) and Yana (144.63 ± 4.14 mg/% and 218.62 ± 3.65 mg/%), indicating their high biological value. In the other varieties, the ascorbic acid content ranged from 97.20 to 143.50 mg/% at the technical ripening stage and from 119.71 to 212.91 mg/% at the biological ripening stage (Table 5).

According to the World Health Organization (WHO) recommendations, an adult's daily intake of vitamin C is at least 60 mg/100 g [42]. All the studied varieties exceeded this norm by 62.00–313.17%, fully covering the physiological need for vitamin C (Table 5).

Table 5. Ascorbic acid content in sweet pepper fruits ($p \le 0.05$) and percentage exceeding the recommended daily allowance- RDA = 60 mg [42].

N	Variety	Ascorbic acid, mg/% (FW) (±SD)		Exceeding the RDA, % (TR – BR)
		TR	BR	
1	Sate	118.91 ± 3.12	195.90 ± 3.73	98.18 - 226.50
2	Manana	125.42 ± 4.03	203.41 ± 4.11	109.03 - 238.35
3	Yana	144.63 ± 4.14	218.62 ± 3.65	141.05 - 263.37
4	Loshtak	130.54 ± 3.25	207.04 ± 3.51	117.57 - 245.07
5	Jermatnayin Hska	155.45 ± 3.12	234.5 ± 3.78	159.08 - 290.83
6	Narinj	115.12 ± 2.56	212.91 ± 2.80	91.87 - 254.85
7	Araqsi-23	188.44 ± 3.04	248.50 ± 3.23	214.07 - 313.17
8	Teghakan-7	97.64 ± 2.68	120.32 ± 3.10	62.73 - 100.53
9	Nizak	97.20 ± 3.20	119.71 ± 3.32	62.00 - 99.52

Total sugars, Titratable acidity, Sugar-acid balance: The content of total sugars in the fruits of the studied sweet pepper varieties ranged from 2.40% to 4.52% at the stage of technical ripening and from 3.42% to 5.86% at the stage of biological ripening. The highest sugar content was recorded in Manana, Jermatnayin Hska, and Araqsi-23 varieties. At the stage of technical ripening, their values were 4.52 ± 0.35%, 4.05 ± 0.25%, and 3.78 ± 0.26%, respectively, while at biological ripening, the values were 5.86 ± 0.32%, 5.45 ± 0.40%, and 5.12 ± 0.38%, respectively.

Titratable acidity in the studied varieties ranged from 0.171 ± 0.06 to 0.227 ± 0.03% at technical ripening and from 0.160 ± 0.05 to 0.196 ± 0.04% at biological ripening.

The sugar-acid ratio is an essential criterion for the comprehensive evaluation of organoleptic qualities and the potential usage of varieties (Table 6). The highest index values observed in the varieties Manana (28.84-36.63), Jermatnayin Hska (23.27-33.43), and Araqsi-23 (22.11-31.60), which can be attributed to the combination of high sugar content and low acidity, especially at the biological ripeness stage. These varieties are characterized by a pronounced sweetness and high sensory appeal. The average values were shown by the varieties Sate (16.43-27.75), Yana (21.75-30.43), Narinj (19.34-21.55), and Loshtak (14.50-20.35), demonstrating a balanced taste, suitable both for fresh consumption and culinary processing. The lowest values were observed in the varieties Teghakan-7 (12.44-17.91) and Nizak (10.57-17.81), which are related to moderate sugar levels and relatively high acidity, making them more suitable for processing into preserved products.

Table 6. Total sugar content, titratable acidity, and their ratio in sweet pepper fruits ($p \le 0.05$).

N	Variety	Total sugars, % (FW) ±SD		Titratable acidity, % (FW) ±SD		Sugar/Acid Ratio, % ±SD	
		TR	BR	TR	BR	TR	BR
1	Sate	3.45 ± 0.51	5.05 ± 0.46	0.210±0.05	0.182±0.04	16.43	27.75
2	Manana	4.52 ± 0.35	5.86 ± 0.32	0.182±0.05	0.160±0.05	28.84	36.63
3	Yana	3.72 ± 0.54	4.93 ± 0.43	0.177±0.04	0.162±0.04	21.75	30.43
4	Loshtak	2.61 ± 0.22	3.50 ± 0.24	0.180±0.05	0.172±0.05	14.50	20.35
5	Jermatnayin Hska	4.05 ± 0.25	5.45 ± 0.40	0.174±0.06	0.163±0.05	23.27	33.43
6	Narinj	3.52 ± 0.25	4.16 ± 0.35	0.182±0.04	0.193±0.04	19.34	21.55
7	Araqsi-23	3.78 ± 0.26	5.12 ± 0.38	0.171±0.06	0.162±0.05	22.11	31.60
8	Teghakan-7	2.55 ± 0.34	3.51 ± 0.35	0.205±0.04	0.196±0.04	12.44	17.91
9	Nizak	2.40 ± 0.41	3.42 ± 0.44	0.227±0.03	0.192±0.05	10.57	17.81

Dry Matter: The dry matter content in sweet pepper fruits varied depending on the variety: from 4.38% to 6.02% at the technical ripening stage and 4.98% to 7.47% at the biological ripening stage. The highest values were recorded in the varieties Teghakan-7, Nizak, and Narinj. At the technical ripening stage, the dry matter content for these varieties was 6.02 ± 0.58%, 5.66 ± 0.45%, and 4.84 ± 0.30%, respectively, and at the biological ripening stage, it was 7.47 ± 0.45%, 6.81 ± 0.45%, and 6.01 ± 0.50%, respectively (Table 7).

Table 7. Dry matter content in fruits of the studied varieties ($p \leq 0.05$).

N	Variety	Dry matter, % ±SD	
		TR	BR
1	Sate	4.58 ± 0.30	5.20 ± 0.44
2	Manana	4.74 ± 0.25	5.72 ± 0.31
3	Yana	4.66 ± 0.38	5.81 ± 0.45
4	Loshtak	4.38 ± 0.22	4.98 ± 0.18
5	Jermatnayin Hska	4.50 ± 0.42	5.58 ± 0.45
6	Narinj	4.84 ± 0.30	6.01 ± 0.50
7	Araqsi-23	4.74 ± 0.45	5.54 ± 0.52
8	Teghakan-7	6.02 ± 0.58	7.47 ± 0.45
9	Nizak	5.66 ± 0.45	6.81 ± 0.45

Chlorophyll: Chlorophylls play a crucial role in determining the color and quality of pepper fruits. In immature fruits, the content of chlorophyll a and b is the highest, which gives them an intense green color. The study revealed that the total chlorophyll content among the examined varieties ranged from 13.40 to 124.63 mg/kg FW. The highest total chlorophyll levels were observed in the cultivars Jermatnayin Hska, Araqsi-23, Yana, and Narinj, which are associated with their dark green fruit color at the technical ripening stage. In contrast, cultivars such as Loshtak, Teghakan-7, and Nizak demonstrated comparatively lower chlorophyll content (Table 8).

Table 8. Chlorophyll a and b content in sweet pepper fruits ($p \leq 0.05$).

N	Variety	Chlorophyll a, mg/kg (FW) ±SD	Chlorophyll b, mg/kg (FW) ±SD	Total chlorophyll, mg/kg (FW) ±SD
1	Sate	21.92 ± 1.83	11.45 ± 0.91	33.37 ± 2.04
2	Manana	46.51 ± 2.97	25.13 ± 2.17	71.64 ± 3.68
3	Yana	48.98 ± 3.12	26.96 ± 2.31	75.94± 3.88
4	Loshtak	14.99 ± 1.21	8.89 ± 0.77	23.88 ± 1.43
5	Jermatnayin Hska	73.85 ± 4.53	50.78 ± 3.53	124.63 ± 5.74
6	Narinj	28.61 ± 1.79	14.14 ± 1.12	42.75 ± 2.11
7	Araqsi-23	64.66 ± 3.93	37.02 ± 2.57	101.68 ± 4.70
8	Teghakan-7	9.89 ± 0.73	3.51 ± 0.32	13.40 ± 0.80
9	Nizak	12.76 ± 1.03	10.38 ± 0.87	23.14 ± 1.35

Figure 1A illustrates the extraction and the characteristic absorption peak for chlorophylls at a wavelength of 666 nm. The prominent peak values observed in the cultivars Jermatnayin Hska, Araqsi-23, Yana, and Narinj confirm their high chlorophyll content, which correlates with the intense dark green coloration of their fruits at the technical ripening stage. In contrast, cultivars with lighter-colored fruits, such as Loshtak, Teghakan-7, and Nizak, exhibited less pronounced peaks at this wavelength, indicating lower chlorophyll content.

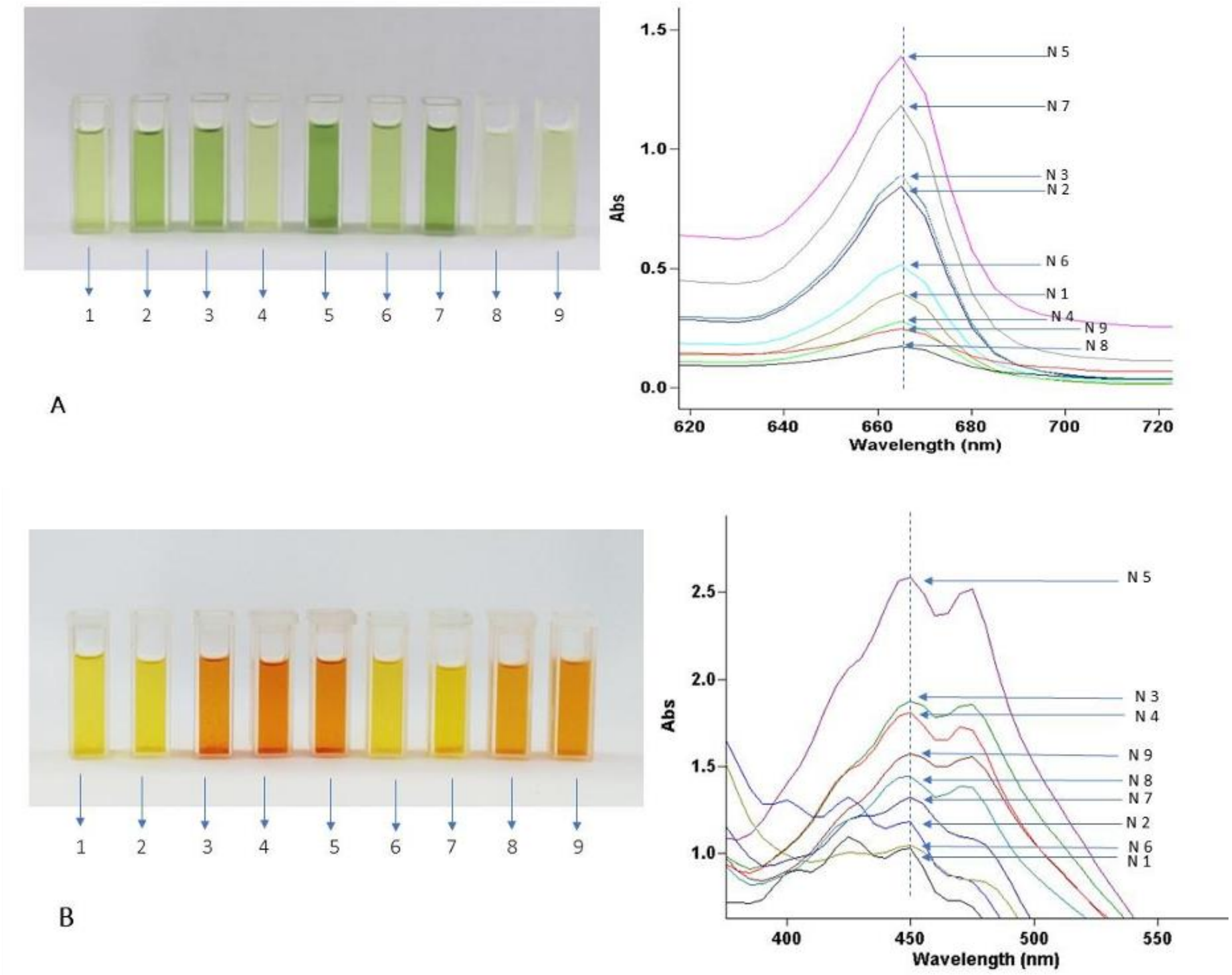


Figure 1. Extraction and spectrophotometric absorption peaks for chlorophyll (A) and carotenoids (B): N1- Sate, N2- Manana, N3- Yana, N4- Loshtak, N5- Jermatnayin Hska, N6- Narinj, N7- Araqsi-23, N8- Teghakan-7, N9- Nizak.

Total Carotenoids: As pepper fruits ripen, chlorophyll content decreases, leading to a change in color from green to yellow, orange, or red, depending on the variety. This shift is associated with chlorophyll degradation and the accumulation of other pigments, primarily carotenoids, as well as the cessation of photosynthetic activity in mature fruits.

According to the obtained data, the highest carotenoid content recorded in varieties with red-colored fruits, where the concentration ranged from 1112.0 to 1995.2 µg/100 g. In orange-colored varieties, this value ranged from 804.5 to 1018.6 µg/100 g, while in yellow-fruited varieties it was lower, within the range of 793.7 to 908.3 µg/100 g (Figure 2).

The spectrogram (Figure 1B) shows the characteristic absorption peak of carotenoids at 450 nm, corresponding to the maximum absorption of β-carotene. The most pronounced peaks in this spectral region were observed in red-fruited varieties such as Jermatnayin Hska, Yana, Loshtak, and Nivak, indicating a high carotenoid concentration. In contrast, the lowest amplitude was recorded in the yellow variety Sate and the orange variety Narinj, which is consistent with their relatively low total carotenoid content.

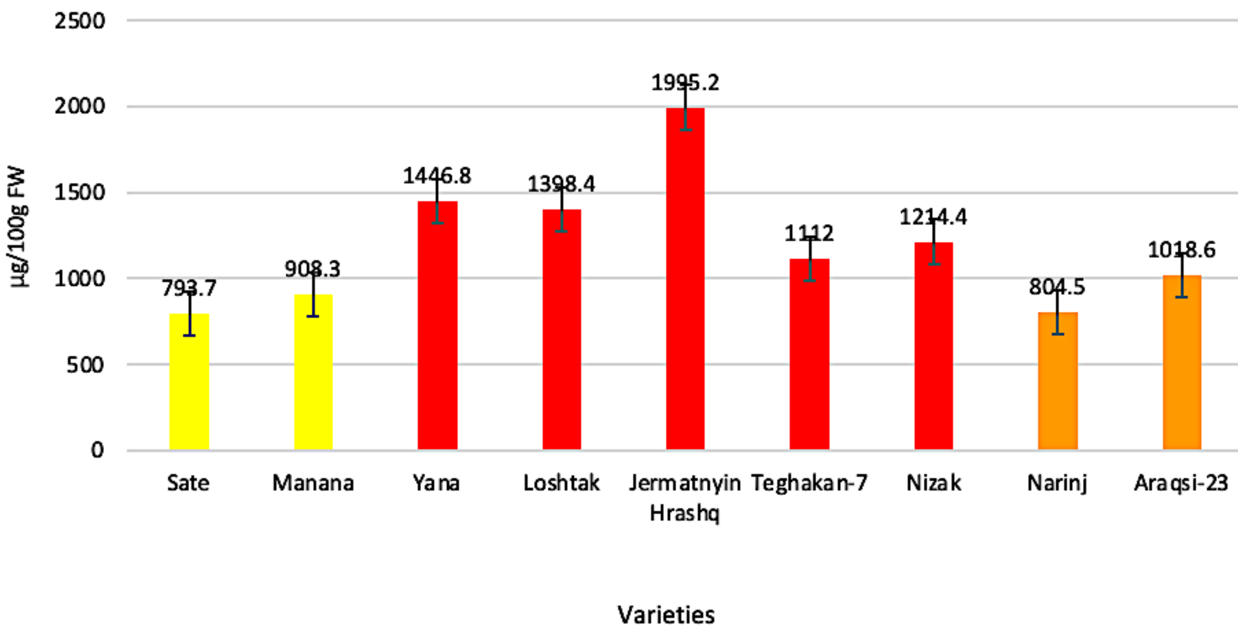


Figure 2. Total carotenoid content (µg/100 g FW) in pepper fruits ($p \leq 0.05$).

DISCUSSION

At present, *Capsicum annuum* L. is one of the most important and widely cultivated vegetable crops across various agro-climatic zones worldwide [43]. Its total cultivation area exceeds 1.5 million hectares, underscoring the crop's strategic relevance in global agriculture [44].

The development of marketable qualities in sweet pepper is determined by a combination of fruit morphological traits (such as shape, weight, and color), ripening stage, and edaphoclimatic conditions [25, 45]. Color transition during ripening is associated with chlorophyll degradation and the accumulation of carotenoids, the biosynthesis of which is regulated by genes such as PSY, CCS, and CHY2 [46-47]. Elucidating these genetic mechanisms represents a promising direction for breeding programs aimed at enhancing the nutritional value of pepper fruits.

The results of the present study confirmed a pronounced varietal diversity in fruit mass, shape, and color, all of which significantly influence marketability. At the stage of biological ripening, fruits exhibited intense pigmentation (red, orange, yellow), enhancing both their visual appeal and commercial value.

Correlation analysis of quantitative traits (Figure 3) revealed notable differences in the relationships between morphological and biochemical characteristics at the stages of technical and biological ripening. In both stages, fruit mass showed a strong positive correlation with fruit diameter, length, and pericarp thickness, reflecting the synchronized development of these morphological parameters. A consistent positive association was also established between fruit mass and total yield. In contrast, the number of fruits per plant exhibited a marked negative correlation with individual fruit mass, indicating the presence of a compensatory mechanism between fruit number and size. These relationships are in agreement with the findings of González-López et al. (2021) and align with data reported for other crops, such as tomato [48-50].

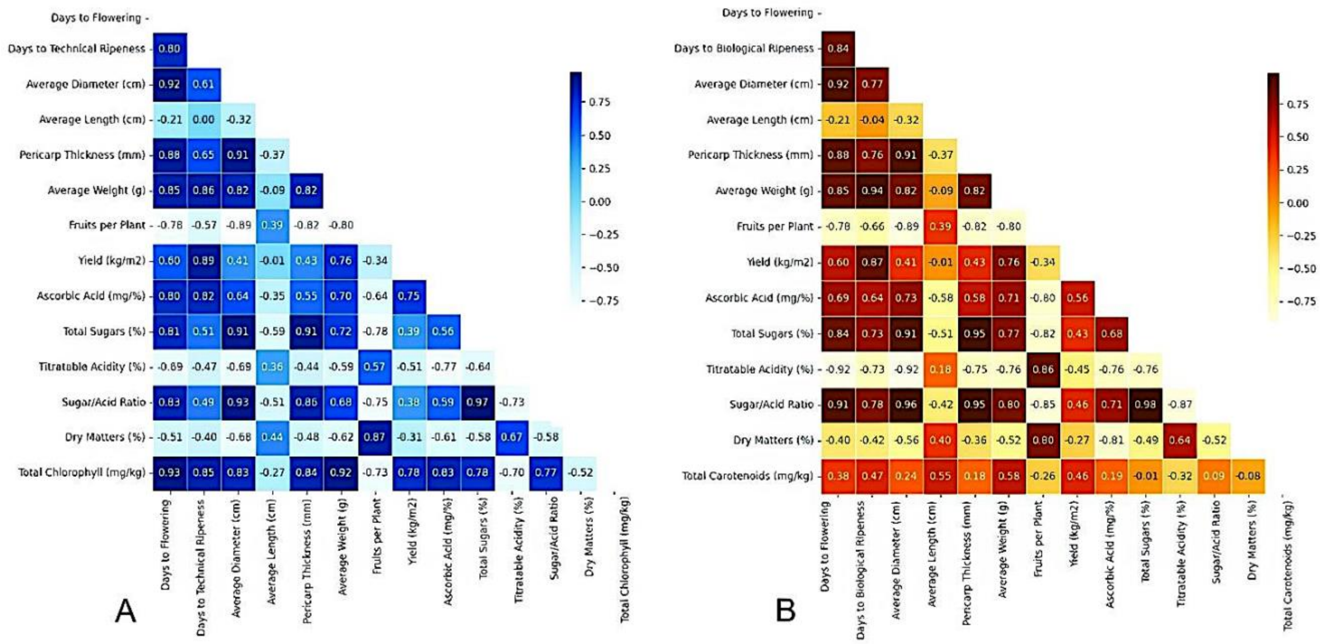


Figure 3. Heatmap of correlation analysis of traits at the technical (A) and biological (B) ripening stages

The content of dry matter in both ripening phases showed a positive correlation with the levels of sugars and ascorbic acid, indicating the interconnection between carbohydrate and vitamin accumulation processes. In the technical ripening phase, a negative correlation found between chlorophyll content and dry matter levels, while in the biological ripening phase, a similar negative correlation was observed between carotenoid content and fruit mass, diameter, yield, and the number of fruits per plant.

Carotenoid content at biological ripening demonstrated a weak to moderate correlation with morphological traits. However, it showed a positive correlation with sugar and dry matter content, suggesting that metabolic processes, rather than structural changes in fruits, predominantly influence these pigment levels.

The taste characteristics of fruits, which determine consumer preferences, are formed by the balance between sugars and organic acids. In our study, it was also found that at the stage of technical ripening, the taste was characterized by higher acidity, due to elevated levels of organic acids and a moderate sugar content. In contrast, at the stage of biological ripening, an increase in sweetness was observed, which, together with a decrease in acidity, resulted in a harmonious and balanced taste. The most favorable sugar-to-acid ratio was found in varieties with red and orange fruit coloration, highlighting their high organoleptic value. The obtained results are consistent with data from other studies, emphasizing the crucial role of the biochemical profile in shaping flavor quality [51-52]. These results also help inform consumers about the fruits' nutritional quality, further enhancing the study's practical relevance and interdisciplinary impact.

In addition to taste qualities, important indicators of the nutritional value of sweet pepper include bioactive compounds, primarily vitamin C and carotenoids. Their content varies depending on the genotype, agro-climatic conditions, and fruit ripening stage [53-54]. According to Kanabar et al. (2024), the vitamin C content in fresh pepper ranges from 76 to 243 mg/100 g [26], and according to Brezeanu et al. (2022), the level of ascorbic acid varies from 99.29 to 265.82 mg/100 g of raw weight [55]. In our study, the vitamin C content ranged from 97.20 to 188.44 mg/100 g at the technical ripening stage and from 119.71 to 248.50 mg/100 g at the biological ripening stage. All the studied varieties significantly exceeded the recommended daily intake of vitamin C, providing between 62.00% and 313.17% of the daily requirement when consuming 100 g of fresh fruit. These results are consistent with the data from Howard et al. (2000), who reported that sweet pepper contains high levels of L-ascorbic acid, covering 124–338% of the daily vitamin C requirement [56].

Given the growing consumer interest in healthy eating, sensory characteristics of food, such as fruit color, play a crucial role as indicators of ripeness and nutritional value [57]. The color of ripe fruits is closely associated with carotenoid content, pigments known for their antioxidant properties. The biosynthesis of these compounds involves a complex network regulated by multiple genes. One of the main goals in breeding remains enhancing β-carotene content, a provitamin A essential for human health [58]. According to our findings, the highest levels of carotenoids were observed in red-fruited varieties, ranging from 1112.0 to 1995.2 μg/100 g, followed by orange varieties (804.5–1018.6 μg/100 g), and yellow varieties with values ranging from 793.7 to 908.3 μg/100 g. This highlights a direct relationship between the intensity of color and carotenoid accumulation, especially β-carotene, which acts as an indicator of fruit ripeness. Our results align with existing literature, which suggests that ripe red peppers have the highest concentration of β-carotene and total carotenoids, while orange varieties are intermediate, and yellow varieties contain the lowest levels of carotenoids [59]. According to de Azevedo-Meleiro (2009), the β-carotene content in ripe pepper fruits ranges from 5.1 to 6.8 μg/g in red-fruited hybrids and from 1.6 to 3.9 μg/g in yellow-fruited ones, confirming the trend of higher provitamin A levels in red-fruited forms [60]. Rodríguez-Rodríguez (2020) also reported that the β-carotene content in red pepper fruits can reach up to 2167 μg/100 g [61].

CONCLUSION

The conducted research revealed pronounced varietal diversity in sweet pepper regarding maturation times, morphometric characteristics, and fruit color, which determine their market value and suitability for different consumer market segments. The established variability in morphological traits underscores their significance in the breeding process when creating targeted genotypes.

Biochemical analysis showed that the studied varieties are characterized by high levels of ascorbic acid, total sugars, and carotenoids, indicating their high nutritional and antioxidant value. This supports their potential for versatile use, both for fresh consumption and for industrial processing. Agronomic assessment demonstrated stable yields for Armenian varieties under the studied conditions, confirming their potential for practical use in production and inclusion in breeding programs.

Thus, the results highlight the importance of a comprehensive evaluation of varieties, integrating morphological, biochemical, and agronomic indicators. This study fills an important knowledge gap by providing the first comprehensive evaluation of local and introduced *Capsicum annuum* L. genotypes cultivated under greenhouse conditions in Armenia, identifying varieties with high nutritional and functional value for targeted breeding and sustainable protected cultivation. Further research should focus on molecular-genetic studies of the regulatory mechanisms of secondary metabolite synthesis and on analyzing the impact of agro-climatic factors to enhance the effectiveness of selection and the adaptive potential of promising genotypes.

List of abbreviations: Scientific Centre of Vegetable and Industrial Crops - SCVIC, MEofRA – Ministry Economy of the Republic of Armenia**,** CARC –Center for Agricultural Research and Certification, TR - technical ripening, BR- biological ripening, FW- fresh weight, g- gram, mgmilligram, µg- microgram, Recommended daily allowance- RDA.

Competing interests: The authors declare that they have no financial, professional, or personal competing interests that could have appeared to influence the work reported in this manuscript.

Authors' contributions: IV and GS conceived and designed the study. IV, HM, and ZH performed the biochemical analyses. IV and ZH interpreted the biochemical and statistical data. AS, MZ, and MD conducted the literature review and compiled the references. GS and GM provided the data on the varieties. LT and ASh prepared the tables and graphical illustrations. AV provided the passport data of the varieties and, together with AP, edited the manuscript. DS carried out Python-based data processing. All authors read and approved the final version of the manuscript.

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