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Revealing the Physicochemical Diversity of Plum Cultivars: A Comprehensive Analysis of Physical and Chemical Attributes

Yahya Selahvarzi[1]*, Pegah Sayyad-Amin[1], Atiyeh Oraee[1], Fatemeh Nadalizadeh[1], Shirin Shahkoomahally[2], Somayeh Rastegar[3]

1 Department of Horticultural Science and Landscape, Ferdowsi University of Mashhad, Iran
2 Department of Horticultural Science, University of Florida, Gainesville, FL 32611, USA
3 Department of Horticultural Sciences, Faculty of Agriculture and Natural Resources, University of Hormozgan, Bandar Abbas, Iran

*Corresponding author's email: selahvarzi@um.ac.ir

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ABSTRACT

Plums have gained popularity among consumers due to their nutritional benefits. This study aims to evaluate the quality of 17 different plum cultivars to identify new varieties with superior flavor and aroma, thereby rejuvenating the market. Plum fruits were collected at full physiological ripeness between July and October of 2021-2022 in Iran. The fruits were assessed for various physical traits, including fruit length, width, flesh thickness, and weight, as well as chemical attributes such as total soluble solids, titratable acidity, pH, anthocyanin, phenolic compounds, and flavonoids. To differentiate between cultivars, an unsupervised principal component analysis (PCA) was employed. The results revealed significant phenotypic variation among the plum cultivars, an advantage for enhancing fruit quality. Total soluble solids ranged from 9.64% to 16.49%, while titratable acidity (TA) varied between 0.26 and 0.88 mg 100 g^{-1} FW. Total phenol content, ascorbic acid, and flavonoid levels ranged from 129.8 to 738.6 mg, 2.53 to 9.24 mg, and 452.2 to 967 mg 100 g^{-1} FW, respectively. Anthocyanin content was found to range from 2.22 to 43.58 mg 100 g^{-1} FW. In conclusion, cultivars such as 'Beygom', 'Torghabeh Sabz', and 'Jangaly' stood out for their fruit firmness, making them well-suited for drying, storage, and transportation. Furthermore, 'Beygom' and 'Torghabeh Sabz' were also found to be rich in bioactive compounds, making them ideal candidates for breeding programs. Overall, the diverse plum genotypes showed potential for commercial cultivation under growth conditions similar to those of available varieties and may also serve as valuable resources for future breeding projects.

Introduction

Plums belong to the Rosaceae family, Prunoideae subfamily, Prunus genus, and Prunophora subgenus. They have been domesticated early and cultivated for at least 2,000 to 4,000 years (Khadivi-Khub and Barazandeh, 2015). Plums are produced annually worldwide, with Austria, Chile, the Netherlands, and Turkmenistan being the main producers and exporters (FAOSTAT, 2021). Wild plums (*Prunus divaricata*) are widespread in Anatolia, the Caucasus, and parts of Asia, including the Hyrcanian forests of northern Iran (Gharaghani et al., 2017). The most commercially important plum species in Iran are *P. cerasifera* Ehrh., *P. macrocarpa*, and *P. domestica* (Esehaghbeygi et al., 2013; Gharaghani et al., 2017). Native plum cultivars such as 'Ghandy', 'Black', 'Bokhara', 'Shams', and 'Ghatretala' belong to *Prunus domestica* L., while

'Santarosa' (or 'Santa Roza') and 'Dargazy' are cultivars of *Prunus salicina* grown in Iran (Esehaghbeygi et al., 2013).

In terms of nutritional value, plums are rich in bioactive compounds such as anthocyanins, flavonoids, pectin, carotenoids, vitamin A, calcium, magnesium, potassium, boron, fiber, and relatively high amounts of carbohydrates (Ionica et al., 2013; Meena et al., 2021). However, they contain low levels of ascorbic acid (Ionica et al., 2013). Various phenolic acids, including gallic acid, naringin, resveratrol, and caffeic acid, have also been identified in plums (Murathan et al., 2020).

Plums are highly sought after by consumers for their appealing appearance, distinct taste, juiciness, wide range of flavor profiles, color, aroma, size, texture, and, more recently, their nutritional qualities and high antioxidant content (Sottile et al., 2022). These fruits have been linked to numerous health benefits, including cancer prevention, decreased risk of disease and heart attacks, allergy prevention, and anti-mutagenic properties. Red plums, in particular, are known for their strong antioxidant properties, which can help reduce the risk of cancer and heart disease (Kim et al., 2022). Recent studies have further highlighted the therapeutic potential and health benefits of various plum cultivars due to their abundance of bioactive compounds that function as natural antioxidants.

The great diversity of plums has also resulted in variations in their chemical composition. The polyphenolic content of plums depends on factors such as variety, genetics, growing location, climate, and ripeness at harvest. Based on fruit color and ripeness index, Forough et al. (2014) showed that the phenolic content in different plum cultivars ranged from 282 to 332 mg 100 g^{-1}. The quality of plums is also influenced by external characteristics, such as the size and color of the pulp and skin, which are linked to their chemical composition (Kitzberger et al., 2017). The internal quality of the fruit is primarily determined by firmness and flavor (Reig et al., 2013). Additionally, Kitzberger et al. (2017) found that total titratable acidity and soluble solids content serve as key taste indicators for assessing quality and predicting consumer acceptance. Fruits that are either too soft or excessively firm negatively impact quality attributes (Reig et al., 2013). High firmness, often due to harvesting immature fruit, leads to decreased flavor, aroma, texture, and juiciness (Reig et al., 2013).

Determining the physical and biochemical characteristics of fruits is crucial for their use in both the fresh and processed food industries. Additionally, developing appropriate machinery for mechanically processing plums requires a thorough understanding of fruit physical properties. It is also important to have comprehensive knowledge of the morphological characteristics of different cultivars to select the most suitable ones for breeding purposes (Yilmaz et al., 2012). Observing both morphological and biochemical traits is essential for traditional cultivar identification methods, as these traits allow for a quick and easy assessment of variability and serve as an effective way to evaluate genetic diversity among accessions based on their morphology (Colic et al., 2012). The official method for registering and protecting new cultivars relies on morphological and biochemical characterization (Farahani et al., 2019).

Consumer demand for safe and high-quality fruits in local markets is increasing due to the unique taste and nutritional benefits they offer. Research on the nutritional content and flavor profiles of traditional plum varieties has been conducted to meet this demand. While progress in plum breeding has been made in regions like Iran over the past two decades, the taste and quality of plum fruit can vary significantly depending on factors such as location, climate, and specific variety (Lin et al., 2023). Given the high yield, popularity among consumers, and potential for export, this study was conducted to compare the physicochemical properties of various plum varieties in Iran. Utilizing supervised modeling based on multivariate orthogonal projection to latent structures discriminant analysis, the primary goal is to investigate the similarities and differences among the various variables. We hypothesize that the chemical and pomological characteristics will be significantly influenced by the different cultivars, regardless of their genetic similarities or differences. This study is believed to be the first to specifically analyze key distinctions among the 17 cultivars grown in Neyshabour City.

Materials and Methods

Fruit from 17 different plum cultivars (Table 1 and Fig. 1) grafted onto Myrobalan rootstock were selected from a commercial orchard located in the Kharv region (36°6' N, 59°3' E) near Neyshabour City, Khorasan Razavi Province, Iran, during the 2021-2022 growing seasons. After collecting data for two consecutive years, no significant differences were found between the years, so the average data were calculated. The average annual temperature in this region ranges from 0 to 10 °C, with rainfall between 100 and 800 mm. To ensure optimal fruit quality, thinning was manually performed on each tree at the beginning of spring to achieve a moderate fruit load per trunk cross-sectional area (approximately 3 fruits cm^{-2} TCSA).

Between July and October, a total of 150 plums were harvested from different parts of 5 to 6 trees per cultivar, with 125 plums collected for each sample. Only mature plums of similar size, free from visible external imperfections, were selected based on color, texture, aroma, and input from local farmers. After harvesting, all plums were promptly cleaned and brought to the testing area. The plums were randomly divided into three groups: 40 plums from each cultivar were set aside for analysis of pomological characteristics, while the remaining plums were frozen and stored at -80 °C for further biochemical analysis.

Table 1. Phenological traits (species, origin, blooming day, and harvest date) of some plum cultivars (2021-2022).

Cultivar	Species	Origin	Blooming date	Harvest date
Santarosa	*Prunus salicana*	Italy	1-11 March	1-11 July
Ghatretala	*Prunus domestica*	Iran	11-20 March	1-11 July
Pivehzhan	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Sabz	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Rotaby	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Ghandy	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Jangaly	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Beygom	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Pakutah	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Torghabeh Sabz	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Kobrayi	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Torghabeh Zard	*Prunus domestica*	Iran	30 March-9 April	11 September-22 September
Shoghany(Dargazy)	*Prunus salicana*	Iran	30 March-9 April	11 September-22 September
Bokhara	*Prunus domestica*	Iran	30 March-9 April	23 September-1 October
California	*Prunus domestica*	USA	30 March-9 April	Beginning of September
President	*Prunus domestica*	Italy	21 April	8-14 September
Shams	*Prunus domestica*	Iran	30 March-9 April	11-21 August

Fruit physical properties
Fruit size measurements

The length, width, and flesh thickness of fruits were measured with a digital caliper. The geometric mean diameter (Dg) and surface area (S) were calculated using equations.

$Dg = (LWT)^{1/3}$

$S = \pi (D_g)^2$

Aspect ratio is the width-to-length ratio (Ra), indicating how oblong something is, and is calculated as follows:

$$R_a = \frac{W}{L}$$

The sphericity index (Sp) was calculated using the following equations and was defined as a comparison of the solid shape with a sphere of equal volume.

$$S_p = \frac{Dg}{L}$$

Static friction coefficient (μs) was determined by a galvanized iron sloppy plate device and glassy sheet. The fruit was placed on an adjustable slope plate. The angle of the slope plate (Φ) increased by the slope plate angle was measured when the fruit started moving, which was used according to the methods of Ertekin et al. (2006) to calculate its static friction coefficient via the below formula:

$$\mu s = \tan \Phi$$

Weight and volume of fruit

The weight of the fruits was measured using a balanced technical scale (Kern FCB). Plum volume and density were determined using the toluene displacement method (Ertekin et al., 2006).

Fruit color

Peel and pulp color were assessed using an image processing system that measured color in the L*, a*, and b* color spaces. ImageJ software, equipped with a color space converter, was used to convert RGB color space to the L*, a*, and b* spaces. In this system, L* represents a perfectly reflective diffuser with a value of 100, while a value of 0 represents black. Positive a* values indicate red, while negative a* values represent green. Similarly, positive b* values indicate yellow, and negative b* values represent blue (Laribi et al., 2013).

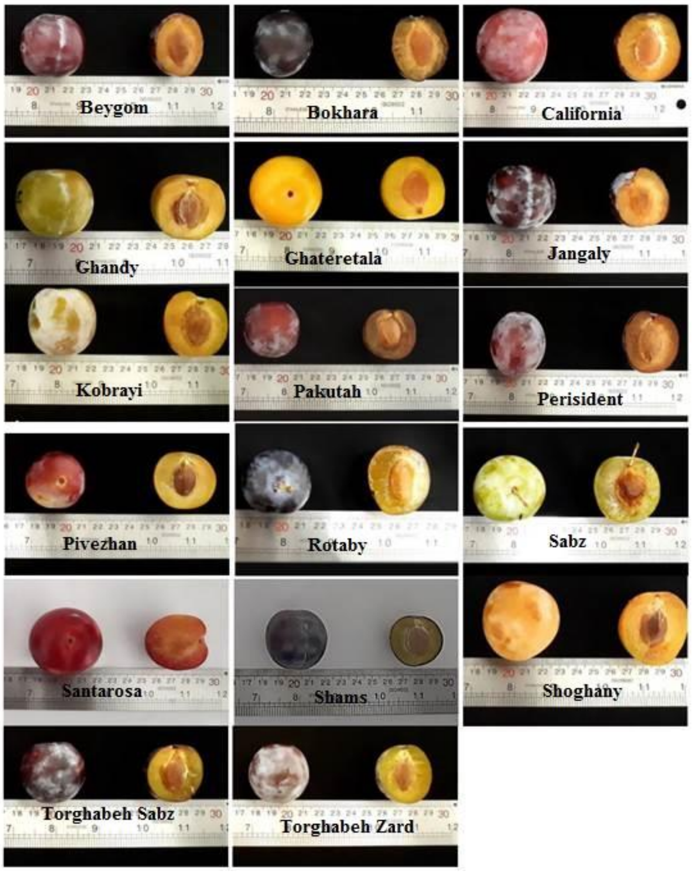

Fig. 1. The fruit pictures of the 17 plum cultivars studied in Iran.

Fruit firmness

Fruit firmness was measured according to the method described by Ertekin et al. (2006) using a penetrometer model from STEP Systems GmbH. To measure firmness, two points were marked on the fruit equator with circles of 1 cm in diameter, and firmness was measured for 3 fruits.

Fruit chemical properties

Total soluble solids (TSS), titratable acidity (TA), TSS/TA ratio, and pH

TSS was measured using a digital refractometer model DR-101-61 and expressed in Brix. TA was determined by the titration method with pH 8.2 using 0.1 N NaOH). The pH of the juice was measured at room temperature using a digital pH meter. The ratio TSS/TA was used as the maturity index or ripening index (RI) (Reig, 2013).

Total soluble sugar contents

The total soluble sugar content in the juice was determined by the anthrone reagent method. A mixture of 5 mL of plum juice, diluted with 20 mL of distilled water, was added to 4 mL of anthrone solution (150 mg of pure anthrone in 100 mL of H_2SO_4 72%). Measurements were taken using a spectrophotometer (Cecil Bio Quest, CE 2502) at 625 nm after heating the sample in boiling water at 90 °C for 10 min (Davarpanah et al., 2016).

Total anthocyanin content (TAC)

Two buffer systems were used to determine the total anthocyanin content of plum juice: 0.40 M sodium acetate (pH 4.50) and 0.025 M potassium chloride (pH 1.00). The fruit extract was left overnight in a mixture of formic acid and methanol (Davarpanah et al., 2018). Absorbance readings were taken at 510 nm and 700 nm after centrifuging the supernatant. All measurements were performed at room temperature (22 °C) for each sample in triplicate (n = 3). The total anthocyanin content was calculated as the equivalent of cyanidin-3-glucoside using the following equation:

$$TAC\ (mg\ 100\ g^{-1}\ FW) = \frac{(AxMWxDFx1000)}{L^{*}\varepsilon}$$

Where TAC = total anthocyanin content (mg 100 g-1 FW); MW = molecular weight; DF = dilution factor; l = path length; ε = molar extinction coefficient; 1,000 = gram-to-milligram conversion factor.

A = absorbance calculated according to equation:

$$A = (ApH\ 1.0 - ApH\ 4.5)\ 525\ nm - (ApH\ 1.0 - ApH\ 4.5)\ 700\ nm$$

Total flavonoid content

The total flavonoid content was assessed using the colorimetric aluminum chloride method. The juice extract was diluted 1:1 with 80% methanol, and 75 µL $NaNO_2$ (5%) was added to 250 µL of the juice extract. Then, after 6 min, 150 µL of 10% aluminum chloride was added followed by 500 µL of 1 M NaOH 5 min later. The mixture was then mixed with 2.5 mL of distilled water. The absorbance was measured at 510 nm using a spectrophotometer (Cecil Bio Quest, CE 2502, Cambridge, UK). The total flavonoid content of the samples was expressed as mg of catechin equivalents (CE) 100 g-1 fresh weight (Grilo et al., 2017).

Ascorbic acid content

Ascorbic acid was determined following the method of Nweze et al. (2015). In each 100 mL conical flask, 25 mL of juice was added and titrated with 2 mL of starch as an indicator. Ten milliliters of 1 M H2SO4 was titrated with a standard iodine solution until a blue color appeared. The amount of ascorbic acid was calculated as follows:

$$Ascorbic\ acid\ (mg\ 100g^{-1}) = [\frac{the\ used\ iodine\ solution \times 0.1 \times 0.773 \times 88.1 \times 100}{fruit\ juice\ (mL)}] \times 100$$

Total phenolic content

The Folin-Ciocalteu reaction method (FC) helped to determine the total phenolic content in fruit juice. In this method, 250 µL of the mixed alcoholic extract was combined with distilled water, 10% Folin-Ciocalteu reagent, and 7.5% sodium carbonate. The absorbance of the solution was measured after 1 h using a spectrophotometer at 675 nm (Davapanah et al., 2016).

Total antioxidant activity

The antioxidant activity was determined using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) method (Alothman et al., 2010). A mixture of 10 mL of methanol and 100 mL of fruit juice was distilled together in a ratio of 6:4 (v/v). After diluting the solution, 2 mL of 0.1 mM DPPH in methanol was added, shaken, and allowed to stand for 15 min at room temperature. The absorbance of the solution was measured at 515 nm using a spectrophotometer (Cecil Bio Quest, CE 2502, Cambridge, UK). The reaction mixture without DPPH was used for background correction. The antioxidant activity was calculated as follows:

$$Antioxidant\ activity\ (\%) = [1 - (\frac{Absample}{Abs - control})] \times 100$$

Total dry matter

The total dry matter percentage was determined by transferring the sample to an oven at 105 °C (Elena, 2013).

Statistical analysis

To determine the differences between cultivars in terms of physical and chemical fruit traits, a one-way analysis of variance (ANOVA) was performed with SAS version 11, with the cultivar as the main effect while replicated as a random effect. The data were presented as mean values with standard deviation. Variations among the samples were analyzed using ANOVA, with Duncan's post-hoc test in SPSS that identified significant differences (P<0.05). Pearson's correlation matrix method examined the correlations between all characteristics. Principal component analysis (PCA) was performed to assess the correlations between the varieties. While using multivariate analysis, biplots were generated based on similarities among the varieties and the variables.

Results

Physical properties

Fruit length, width, flesh thickness and weight

According to the results in Table 2, fruit length varied from 30.28 mm ('Shams') to 40.38 mm

('California') among the cultivars. Cultivars such as 'President,' 'Pakutah,' and 'Ghandy' were grouped as having the lowest lengths. Fruit width ranged from 29.30 mm to 38.41 mm, with the highest width attributed to the 'Sabz' cultivar and the lowest to 'Beygom.' In terms of fruit width, 'Beygom,' 'Shams,' 'President,' 'Bokhara,' and 'Torghabeh Zard' were categorized as having the least width. The 'President' cultivar had the thinnest flesh (29.33 mm), while 'Sabz' had the thickest (40.05 mm). 'Sabz' and 'Santarosa' exhibited the highest fruit diameter, while the lowest was found in 'Pakutah,' followed by 'Torghabeh Zard,' 'Bokhara,' 'President,' and 'Shams.' Considering the geometric mean diameter and area of the plum cultivars, the highest values were observed in 'Sabz,' with differences in these traits ranging from 30.43 mm to 38.8 mm and from 2910 mm^2 to 472.2 mm^2 among the cultivars, respectively. As demonstrated in Table 1, fruit weight varied among cultivars from 18.88 g ('Shams') to 36.64 g ('Sabz'). Table 2 also showed that the Static Friction Coefficient (SFC) varied from 0.11 ('Torghabeh Sabz') to 0.21 ('Beygom').

Table 2. Some physical properties (length, width, thickness, weight, volume, density, and firmness) of 17 plum cultivars.

Cultivar	L (mm)	W (mm)	T (mm)	We (g)	V (cm^3)	D (g cm^{-3})	F(N)
Santarosa	36.76 ± 0.5^{bc}	36.52 ± 0.4^{b}	38.65 ± 0.5^{a}	33.61 ± 1.4^{ab}	28.12 ± 1.5^{b}	1.21 ± 0.02^{cde}	1.08 ± 0.03^{f}
Ghatretala	34.19 ± 0.3^{de}	34.59 ± 0.3^{c}	34.39 ± 0.3^{bc}	24.52 ± 0.6^{ef}	23.57 ± 0.6^{cd}	1.04 ± 0.001^{gh}	1.67 ± 0.06^{b}
Pivehzhan	36.55 ± 0.2^{bc}	34.71 ± 0.3^{bc}	34.06 ± 0.2^{bcd}	26.24 ± 0.4^{de}	22.85 ± 0.7^{cde}	1.16 ± 0.02^{d-g}	1.30 ± 0.1^{def}
Sabz	37.92 ± 0.3^{b}	38.41 ± 0.3^{a}	40.05 ± 0.5^{a}	36.64 ± 0.7^{a}	32.56 ± 0.8^{a}	1.13 ± 0.02^{d-g}	1.58 ± 0.02^{bc}
Rotaby	35.08 ± 0.3^{cd}	30.36 ± 0.2^{fgh}	31.88 ± 0.2^{ef}	21.27 ± 0.4^{fgh}	18.77 ± 0.4^{fgh}	1.13 ± 0.01^{d-g}	1.40 ± 0.02^{cd}
Ghandy	30.78 ± 0.2^{gh}	34.24 ± 0.2^{c}	34.99 ± 0.1^{b}	25.86 ± 0.3^{de}	19.14 ± 0.6^{e-h}	1.37 ± 0.03^{ab}	1.24 ± 0.04^{def}
Jangaly	32.95 ± 0.2^{ef}	31.14 ± 0.2^{efg}	34.71 ± 0.3^{b}	23.12 ± 0.5^{efg}	21.37 ± 0.5^{def}	1.08 ± 0.005^{efg}	1.97 ± 0.05^{a}
Beygom	34.11 ± 0.2^{de}	29.30 ± 0.2^{h}	33.13 ± 0.3^{b-e}	21.37 ± 0.3^{fgh}	17.32 ± 0.4^{ghi}	1.24 ± 0.02^{bcd}	2.19 ± 0.04^{a}
Pakutah	31.52 ± 0.2^{fgh}	30.74 ± 0.3^{e-h}	33.19 ± 0.2^{b-e}	21.73 ± 0.5^{fgh}	14.98 ± 0.6^{i}	1.52 ± 0.07^{a}	0.27 ± 0.02^{g}
Torghabeh Sabz	32.68 ± 0.4^{efg}	32.25 ± 0.4^{de}	33.30 ± 0.4^{b-e}	22.70 ± 0.8^{efg}	19.35 ± 0.8^{e-h}	1.19 ± 0.04^{def}	2.02 ± 0.04^{a}
Kobrayi	33.66 ± 0.4^{de}	31.99 ± 0.5^{ef}	32.68 ± 0.5^{c-f}	24.03 ± 0.9^{efg}	22.81 ± 0.5^{cde}	1.05 ± 0.03^{fgh}	1.15 ± 0.04^{ef}
Torghabeh Zard	32.99 ± 0.3^{ef}	29.92 ± 0.2^{gh}	32.67 ± 0.3^{c-f}	21.85 ± 0.6^{fgh}	16.27 ± 0.4^{hi}	1.34 ± 0.02^{bc}	1.24 ± 0.05^{def}
Shoghany(Dargazy)	37.79 ± 0.6^{b}	33.92 ± 0.5^{cd}	33.80 ± 0.6^{b-e}	28.40 ± 1.2^{cd}	26.22 ± 1.04^{bc}	1.07 ± 1.04^{efg}	1.34 ± 0.04^{cde}
Bokhara	34.02 ± 0.3^{de}	30.03 ± 0.4^{gh}	32.14 ± 0.5^{def}	21.25 ± 0.8^{fgh}	19.71 ± 0.7^{e-h}	1.09 ± 0.03^{efg}	1.21 ± 0.03^{def}
California	40.38 ± 0.4^{a}	34.94 ± 0.3^{bc}	34.07 ± 0.4^{bcd}	30.48 ± 0.8^{bc}	27.88 ± 0.9^{b}	1.10 ± 0.01^{d-g}	1.38 ± 0.04^{cde}
President	34.93 ± 0.3^{cd}	30.05 ± 0.2^{gh}	29.33 ± 0.1^{g}	20.33 ± 0.3^{gh}	19.47 ± 0.2^{e-h}	1.04 ± 0.01^{gh}	1.42 ± 0.04^{cd}
Shams	30.28 ± 0.4^{h}	29.96 ± 0.4^{gh}	31.04 ± 0.3^{fg}	18.88 ± 0.6^{h}	20.66 ± 0.3^{d-g}	0.9 ± 0.02^{h}	1.18 ± 0.02^{def}

Data (means ± SD) followed by different small letters indicate a significant difference at $P \leq 0.05$ based on Duncan's test. (L, Length; W, Width; T, Thickness; We, Weight; V, Volume; D, Density; F, Firmness).

Fruit volume, density, and firmness

According to the volume and density, there were differences in the mean values for all plum varieties. The range of volumes was 14.98 cm^3 ('Pakutah', 'Torghabeh Zard', and 'Beygom') to 32.56 cm^3 ('Sabz') and the range of densities was from 0.9 g cm^{-3} ('Shams') to 1.52 g cm^{-3} ('Pakutah'). 'Beygom' (2.19 N), 'Torghabeh Sabz' (2.02 N), and 'Jangaly' (1.97 N) had the highest firmness, respectively, while 'Pakutah' (0.27 N) had the lowest (Table 2).

Aspect ratio and sphericity index

Regarding the aspect ratio and sphericity index, 'Ghandy' had the highest values. The sphericity index ranged from 89.78% and 108.87%. In this study, the aspect ratio (height-to-length) was valued between 0.85-0.11 (Table 3).

Fruit color

There were differences in skin and flesh color among the cultivars (Fig. 2A-C). According to the results, fruit pulp color ranged in L* (Fig. 2A), a* (Fig. 2B), and b* (Fig. 2C) values from 44 ('Shams') to 81.8 ('Ghatretala') for L*, -18.4 ('Sabz') to 14.6 ('Santarosa') for a*, 21 ('Shams'), and 65.4 ('Ghatretala') for b* values. The range of fruit skin varied from 18 ('Jangaly' and 'Torghabeh Sabz'') to 84 ('Ghatretala' and 'Shoghany'), -25 ('Sabz') to 34 ('Santarosa' and

'California'), and from -17.8 ('President', 'Shams', and 'Rotaby') to 63.2 ('Ghatretala') for L*, a* and b* indices, respectively (Fig. 2). Phenolic compounds, which are often present in plums, are responsible for their color and potential health benefits.

Table 3. Fruit diameter indices (geometric mean diameter, sphericity percent, surface area, and aspect ratio) of 17 plum cultivars.

Cultivar	D_g (mm)	S (mm^2)	R_a (mm)	S_p (%)	S.F.C
Santarosa	37.29 ± 0.5^{ab}	4387.4 ± 121.6^{ab}	0.99 ± 0.005^{b}	101.49 ± 0.3^{b}	0.17 ± 0.004^{bcd}
Ghatretala	34.39 ± 0.3^{de}	3721.3 ± 67.5^{de}	1.01 ± 0.004^{b}	100.59 ± 0.2^{b}	0.18 ± 0.002^{b}
Pivehzhan	35.09 ± 0.2^{cd}	3871.2 ± 52.9^{cd}	0.94 ± 0.005^{cd}	96.01 ± 0.2^{de}	0.13 ± 0.002^{ghi}
Sabz	38.76 ± 0.3^{a}	4727.2 ± 78.6^{a}	1.01 ± 0.009^{b}	102.33 ± 0.8^{b}	0.15 ± 0.003^{def}
Rotaby	32.37 ± 0.2^{fg}	3296.5 ± 50.5^{fg}	0.86 ± 0.007^{fg}	92.34 ± 0.4^{fg}	0.16 ± 0.002^{cde}
Ghandy	33.28 ± 0.1^{ef}	3480.7 ± 35.6^{ef}	1.11 ± 0.007^{a}	108.17 ± 0.5^{a}	0.13 ± 0.002^{g-j}
Jangaly	32.90 ± 0.2^{efg}	3404.7 ± 55.3^{efg}	0.94 ± 0.004^{de}	99.85 ± 0.2^{bc}	0.17 ± 0.001^{bcd}
Beygom	32.10 ± 0.1^{fgh}	3239.6 ± 39.7^{fgh}	0.85 ± 0.008^{g}	94.16 ± 0.5^{ef}	0.21 ± 0.009^{a}
Pakutah	31.80 ± 0.2^{fgh}	3180.5 ± 50.5^{fgh}	0.97 ± 0.006^{bcd}	100.90 ± 0.3^{b}	0.14 ± 0.001^{f-i}
Torghabeh Sabz	32.73 ± 0.4^{efg}	3377.5 ± 86.7^{efg}	0.98 ± 0.008^{bc}	100.24 ± 0.5^{b}	0.11 ± 0.001^{j}
Kobrayi	32.76 ± 0.4^{efg}	3389.7 ± 97.8^{efg}	0.94 ± 0.008^{cd}	97.29 ± 0.5^{cd}	0.13 ± 0.001^{g-j}
Torghabeh Zard	31.82 ± 0.2^{fgh}	3186.7 ± 56.6^{fgh}	0.90 ± 0.007^{ef}	96.48 ± 0.4^{de}	0.14 ± 0.003^{efg}
Shoghany(Dargazy)	35.09 ± 0.5^{cd}	3890.3 ± 121.7^{cd}	0.90 ± 0.01^{fg}	93.07 ± 1.006^{f}	0.12 ± 0.001^{ij}
Bokhara	32.01 ± 0.4^{fgh}	3232.6 ± 88.0^{fgh}	0.88 ± 0.008^{fg}	94.16 ± 0.6^{ef}	0.13 ± 0.004^{ghi}
California	36.35 ± 0.3^{bc}	4159.3 ± 82.9^{bc}	0.86 ± 0.007^{fg}	90.07 ± 0.4^{g}	0.12 ± 0.001^{hij}
President	31.34 ± 0.2^{gh}	3087.4 ± 40.8^{gh}	0.86 ± 0.006^{g}	89.78 ± 0.4^{g}	0.18 ± 0.005^{bc}
Shams	30.40 ± 0.3^{h}	2910.6 ± 61.4^{h}	0.99 ± 0.01^{bc}	100.53 ± 0.8^{b}	0.14 ± 0.002^{fgh}

Data (means ± SD) followed by different small letters indicate a significant difference at $P \leq 0.05$ based on Duncan's test. (D_g: geometric mean diameter; S_p: sphericity percentage; S: surface area; R_a: aspect ratio).

Chemical properties

TSS, TA, TSS/TA and pH

The TSS ranged from 9.64% ('Pivehzhan') to 16.49% ('Pakutah'), while TA varied from 0.26 mg 100 g^{-1} FW ('Torghabeh Zard') to 0.88 mg 100 g^{-1} FW ('President'). Cultivars such as 'Sabz', 'Kobrayi', and 'Ghatretala' had similar TSS content. In terms of TA, cultivars with the highest content after 'President' were 'Jangaly' and 'Ghatretala', followed by 'Santarosa', 'Pakutah', 'Sabz', and 'Rotbay' cultivars. The maturity index (TSS/TA) ranged from 13.52 to 47.64. 'Pakutah' and 'Shoghany' were in one group with a higher index, while 'Torghabeh Sabz' and 'Ghandy' were in the next group. The pH ranged from 3.25 ('Santarosa') to 4.48 ('Shoghany'). 'Santarosa', 'Sabz', 'Jangaly', and 'Rotaby' were grouped together in one category (Table 4).

Ascorbic acid, total soluble sugar, and anthocyanin contents

The highest levels of ascorbic acid were observed in the following plum cultivars: 'Pivehzhan', 'Torghabeh Sabz', 'Pakutah', 'Sabz', 'Santarosa', 'Beygom', and 'President', respectively (Table 3). Total sugar content ranged from 10.42 to 60.80% in the 'Beygom' variety (Table 3). The amount of anthocyanins varied from 2.22 to 43.58 mg 100 g-1 FW in the 'Ghatretala' and 'Pivehzhan' varieties, respectively (Table 4 and Fig. 3).

Total phenol, flavonoids, and antioxidant content

Total phenol content and flavonoid levels varied between 129.8–738.6 mg 100 g^{-1} FW and 452.2–967 mg 100 g^{-1} FW, respectively. The highest phenol content was found in the 'Beygom' cultivar, while the lowest was observed in 'Ghatretala'. High flavonoid levels were noted in the cultivars 'Torghabeh Sabz', 'Ghandy', 'Pakutah', 'Torghabeh Zard', 'Bokhara', and 'California'. Antioxidant activity ranged from 14.97% ('Ghatretala') to 73.36% ('Beygom'), with significant antioxidant activity observed in 'Torghabeh Sabz', 'Pakutah', 'Ghandy', 'Santarosa', 'Sabz', and 'Torghabeh Zard' (Table 3 and Fig. 3).

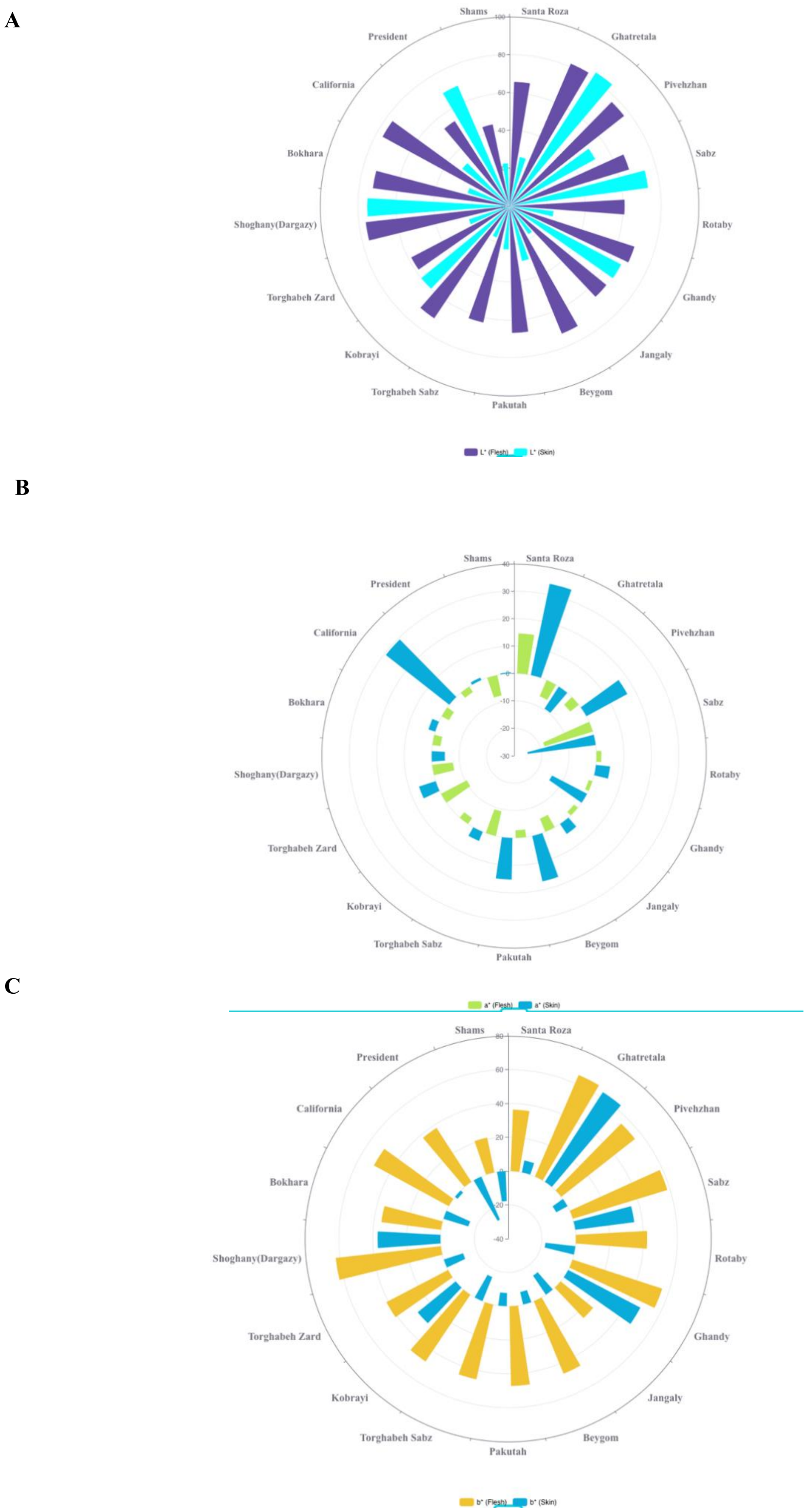

Fig. 2. Polar bar chart for the studied 17 plum cultivars based on color parameters of fruit juice (L, a, and b represented brightness, red-green coordinates).

Table 4. Indices of fruit quality (total soluble solids, titratable acidity, TSS/TA, pH, and total anthocyanin) of 17 plum cultivars.

Cultivar	TSS (Brix)	TA (mg 100 g^{-1} FW)	TSS/TA	pH	AA (mg 100 g^{-1} FW)	AC (%)	TS (mg 1000 g^{-1} FW)	Dm (%)
Santarosa	14.36 ± 0.21^{b}	0.63 ± 0.005^{b}	16.23 ± 0.26^{hi}	3.25 ± 0.007^{l}	7.59 ± 0.4^{a-e}	64.13 ± 0.2^{a-e}	41.24 ± 1.8^{cd}	18.22 ± 0.4^{bc}
Ghatretala	11.10 ± 0.21^{efg}	0.80 ± 0.05^{a}	20.51 ± 0.48^{gh}	3.35 ± 0.008^{j}	2.53 ± 0.1^{h}	14.97 ± 2.8^{h}	25.54 ± 0.3^{ef}	19.34 ± 0.7^{abc}
Pivehzhan	9.46 ± 0.27^{g}	0.34 ± 0.02^{def}	27.52 ± 1.91^{ef}	3.56 ± 0.02^{h}	9.24 ± 0.5^{a}	23.51 ± 3.5^{gh}	10.42 ± 0.7^{g}	17.79 ± 1.08^{bc}
Sabz	9.90 ± 0.20^{g}	0.58 ± 0.01^{b}	17.03 ± 0.48^{hi}	3.28 ± 0.006^{kl}	8.03 ± 0.4^{a-d}	61.59 ± 0.7^{a-f}	34.42 ± 1.1^{cde}	18.24 ± 1.07^{bc}
Rotaby	13.38 ± 0.13^{bcd}	0.58 ± 0.01^{b}	23.13 ± 0.50^{fg}	3.30 ± 0.006^{k}	4.51 ± 0.2^{fgh}	30.97 ± 6.7^{g}	43.12 ± 0.7^{cd}	20.70 ± 1.4^{abc}
Ghandy	13.49 ± 0.31^{bcd}	0.32 ± 0.004^{efg}	41.21 ± 1.01^{b}	3.72 ± 0.005^{g}	5.94 ± 0.4^{b-g}	65.23 ± 1.35^{a-d}	59.88 ± 4.6^{a}	19.58 ± 1.07^{abc}
Jangaly	11.86 ± 0.10^{def}	0.87 ± 0.01^{a}	13.52 ± 0.10^{i}	3.29 ± 0.005^{k}	5.17 ± 0.1^{d-h}	53.29 ± 1.1^{c-f}	32.48 ± 0.7^{de}	15.73 ± 1.03^{c}
Beygom	12.95 ± 0.10^{bcd}	0.37 ± 0.007^{c-f}	34.97 ± 0.95^{cd}	3.51 ± 0.005^{i}	7.15 ± 1.3^{a-f}	73.36 ± 1.21^{a}	60.80 ± 3.4^{a}	21.50 ± 1.7^{abc}
Pakutah	16.49 ± 1.19^{a}	0.62 ± 0.009^{b}	46.46 ± 1.05^{a}	3.57 ± 0.005^{h}	8.47 ± 1.2^{abc}	66.03 ± 0.5^{abc}	42.74 ± 0.3^{cd}	21.40 ± 1.8^{abc}
Torghabeh Sabz	16.10 ± 0.40^{a}	0.39 ± 0.009^{cde}	41.15 ± 1.04^{b}	3.56 ± 0.002^{h}	8.69 ± 0.1^{ab}	69.78 ± 1.27^{ab}	58.76 ± 2.2^{a}	25.84 ± 0.6^{a}
Kobrayi	10.26 ± 0.2^{fg}	0.41 ± 0.007^{cd}	34.77 ± 0.75^{cd}	3.75 ± 0.003^{f}	6.16 ± 0.3^{b-f}	51.14 ± 3.5^{ef}	36.78 ± 1.8^{cd}	24.14 ± 1.4^{ab}
Torghabeh Zard	12.08 ± 0.26^{cde}	0.26 ± 0.003^{g}	17.89 ± 0.22^{hi}	4.11 ± 0.004^{e}	5.72 ± 0.5^{c-g}	62.83 ± 0.6^{a-f}	39.60 ± 1.4^{cd}	23.18 ± 1.8^{ab}
Shoghany (Dargazy)	13.93 ± 0.13^{b}	0.29 ± 0.01^{fg}	47.64 ± 1.73^{a}	4.48 ± 0.006^{a}	4.51 ± 0.2^{fgh}	48.92 ± 2.1^{f}	13.32 ± 0.9^{g}	21.90 ± 1.7^{abc}
Bokhara	14.36 ± 0.27^{b}	0.39 ± 0.01^{cde}	36.57 ± 1.10^{c}	4.42 ± 0.002^{b}	4.84 ± 0.3^{e-h}	51.55 ± 3.7^{def}	55.08 ± 0.7^{ab}	23.70 ± 0.6^{ab}
California	14.03 ± 0.10^{b}	0.44 ± 0.004^{c}	31.55 ± 0.36^{de}	4.23 ± 0.006^{c}	8.47 ± 0.5^{abc}	56.61 ± 0.8^{b-f}	36.22 ± 1.4^{cde}	19.13 ± 1.02^{abc}
President	13.71 ± 0.10^{bc}	0.88 ± 0.01^{a}	15.47 ± 0.24^{i}	4.20 ± 0.008^{d}	6.38 ± 0.4^{a-f}	58.07 ± 4.26^{b-f}	17.20 ± 0.8^{fg}	24.17 ± 2.1^{ab}
Shams	13.93 ± 0.13^{b}	0.44 ± 0.002^{c}	31.14 ± 0.37^{de}	3.74 ± 0.003^{fg}	3.19 ± 0.2^{gh}	53.99 ± 1.6^{c-f}	45.24 ± 4.7^{bc}	21.27 ± 1.3^{abc}

Data (means ± SD) followed by different small letters indicate a significant difference at $P \leq 0.05$ based on Duncan's test. (TSS: total soluble solids; TA: total acidity; TS: total sugar; AA: ascorbic acid; AC: antioxidant capacity; Dm: dry matter).

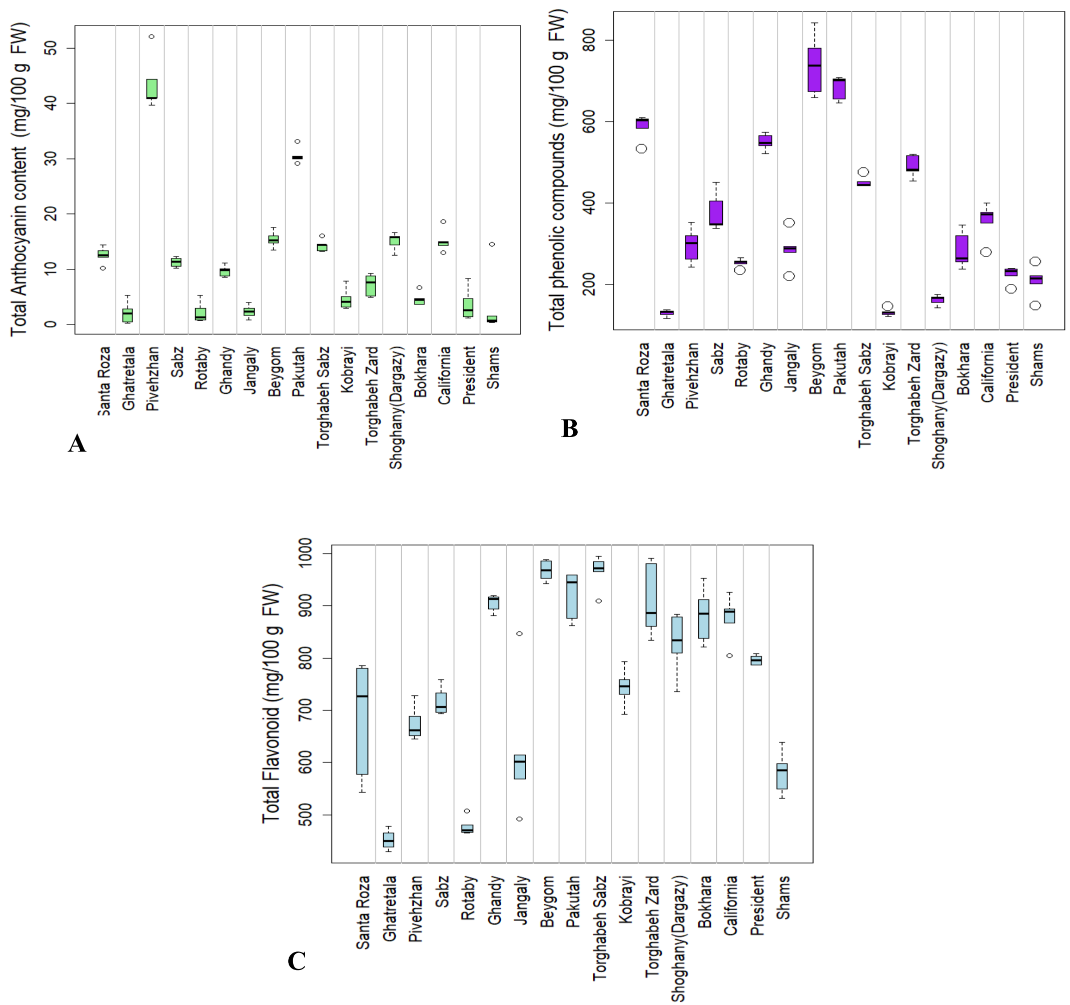

Fig. 3. Box plot of total anthocyanin content (A), total phenolic compound (B) and total flavonoid (C) in fruit juice of 17 plum cultivars.

Dry matter

Dry matter varied between 15.73 ('Jangaly') and 25.84% ('Torghabeh 'Sabz') (Table 3), and also from 1.7 ('Ghandy') to 2.5% ('Ghatretala') (Esehaghbeigy et al. 2013). Smanalieva et al. (2019) showed that the fresh- and dry-purpose fruit cultivar 'Elena' had a higher dry matter content (fresh: 19.29%; dried: 75.11%).

Multivariate analysis

In the present study, phenol content showed a positive correlation with TSS (r = 0.39), ascorbic acid (r = 0.55), anthocyanin (r = 0.37), antioxidant (r = 0.67), flavonoid (r = 0.59) and total sugar (r = 0.57) (Table 5). There was no correlation between antioxidants and anthocyanin contents in the plum cultivars, as well as no correlation between phenol and antioxidants (Reig et al., 2013). Additionally, a positive correlation was observed between the dry matter content and TSS (r = 0.40), pH (0.51), antioxidant activity (r = 0.28), flavonoid (0.47), and total sugar (0.26). Conversely, a negative correlation occurred between the dry matter content and TA (Table 4).

Table 5. Simple correlations among biochemical and morphological variables utilized in the studied of 17 plum cultivars.

	TSS	TA	TSS/TA	pH	AA	A	TP	AC	TF	TS	Dm
TSS	1										
TA	-0.03^{ns}	1									
TSS/TA	0.48**	-0.59**	1								
pH	0.25*	-0.40**	0.37**	1							
AA	0.08^{ns}	-0.17^{ns}	0.12^{ns}	-0.12^{ns}	1						
A	-0.014^{ns}	-0.31**	0.35**	-0.05^{ns}	0.70**	1					
TP	0.39**	-0.20*	0.18^{ns}	-0.24*	0.55**	0.37**	1				
AC	0.49**	-0.21*	0.23*	0.13^{ns}	0.41**	-0.03^{ns}	0.67**	1			
TF	0.44**	-0.51**	0.54**	0.48**	0.53**	0.29**	0.59**	0.76**	1		
TS	0.45**	-0.30**	0.31**	-0.15^{ns}	0.04^{ns}	-0.24*	0.57**	0.57**	0.41**	1	
Dm	0.40**	-0.30**	0.41**	0.51**	-0.04^{ns}	-0.19*	-0.05^{ns}	0.28**	0.47**	0.26*	1

*, **, and ^{ns} correlation was significant at $P \leq 0.05$ and 0.01 levels, respectively, and non-significant (TSS: total soluble solids; TA: total acidity; AA: ascorbic acid; A: total anthocyanin; TP: total phenols; AC: antioxidant capacity; F: total flavonoid; S: total sugar; Dm: dry matter).

To assess the dispersion of plum cultivars, PCA was conducted. The first two principal components explained 31.40% and 20.80% of the variance, respectively, contributing to a cumulative variance of 52.6%. The eigenvalues of the third and fourth components were relatively small (14.8% and 9.20%) and are not discussed further. PC1 showed strong positive correlations with total acidity, firmness, volume, fruit length, reducing power activity, and TSS. PC2, on the other hand, was strongly and negatively correlated with weight, width, thickness, surface area, and aspect ratio (Fig. 4A). Based on their physical and chemical properties, the different plum cultivars were classified into six distinct groups: 1.) 'California,' 'Bokhara,' and 'Shams' 2.) 'Rataby' and 'Kobray,' 3.) 'Shoghany,' 'President,' 'Ghatretala,' 'Jangaly,' and 'Pivehzhan,' 4.) 'Beygom,' 'Toghabeh Sabz,' and 'Pakutah,' 5.) 'Ghandy' and 6.) 'Santarosa' and 'Sabz' (Fig. 4B). 'Santarosa' and 'Sabz' appeared distinct from all other cultivars along the first axis, where weight, width, thickness, surface area, and aspect ratio are most influential.

Moreover, when grouping the cultivars based on increasing dissimilarity, a hierarchical agglomerative cluster analysis was performed (Fig. 5). The first group (I), which included 'Ghandy' to 'Pakutah', was characterized by cultivars with medium to low weight, surface area, volume, total acidity, and geometric diameter in fruit juice, and medium to high TSS/TA ratio, total flavonoid, total sugar, and total antioxidant activity. The second group (II), which included 'Bokhara' to 'Torghabeh Zard' with medium to high pH and total flavonoid levels, and the third group (III), which included 'Jangaly' to 'Ghatretala', had medium to high S.F.C. and total acidity, and medium to low values of total anthocyanin content, total phenolics, ascorbic acid, and surface area. The cultivars of the fourth group (IV) were 'Jangaly' and 'Ghatretala', which exhibited some of the highest values of total antioxidant activity. The cultivars of the fourth group ((IV) were 'Shoghany' to 'President', which had low values for total sugars, antioxidant activity, and total phenolic content, medium to high values for surface area, geometric diameter, length, and weight. 'Pivehzhan' showed one of the highest antioxidant activities. The fifth cluster (V), which included 'Sabz' and 'Santarosa', had low diameter, TSS/TA ratio, pH, and total flavonoids, and medium to high surface area, thickness, width, and volume.

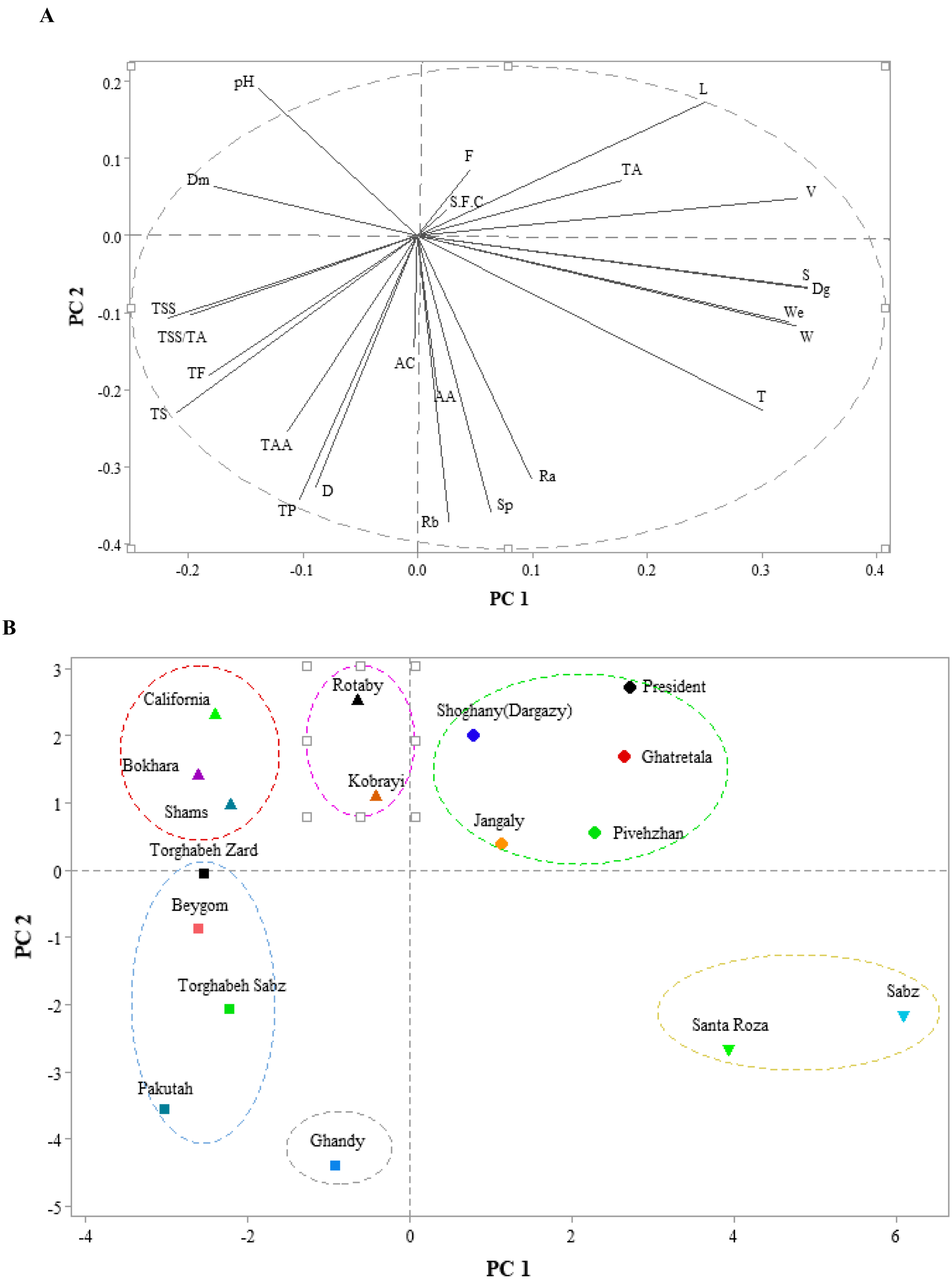

Fig. 4. The dispersion of the studied plums based on the first and the second principal components (PC1/PC2): variable plot (A) and observation score (B). (L, Length; W, Width; T, Thickness; We, Weight; V, Volume; D, Density; F, Firmness; Dg, Geometric Mean Diameter; Sp, Percent Sphericity; S, Surface area; Ra, Aspect Ratio (Height to length); TSS, Total soluble solids; TA, Total Acidity; AA, Ascorbic acid; A, Total Anthocyanin; TP, Total phenolic; AC, Antioxidant Capacity; F, Total Flavonoid; S, Total Sugar; Dm, Dry matter).

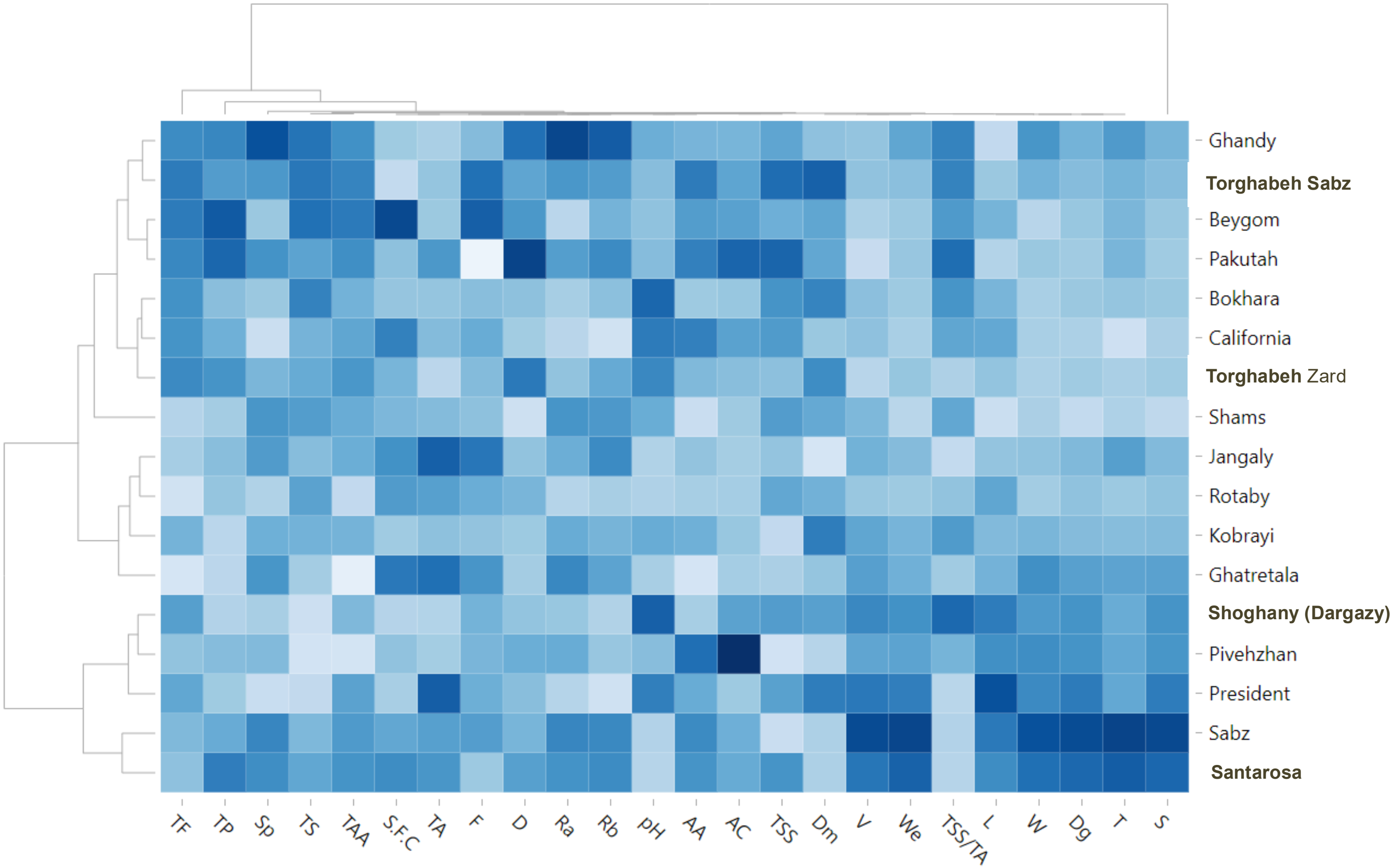

Fig. 5. Cluster display of the various plum grouped by similarities in physical and chemical properties of juice mean values (Gradient from low [light blue] to high [dark blue]). (L, Length; W, Width; T, Thickness; We, Weight; V, Volume; D, Density; F, Firmness; D_g, Geometric Mean Diameter; S_p, Percent Sphericity; S, Surface area; R_a, Aspect Ratio (Height to length); TSS, Total soluble solids; TA, Total Acidity; AA, Ascorbic acid; A, Total Anthocyanin; TP, Total phenolic; AC, Antioxidant Capacity; F, Total Flavonoid; S, Total Sugar; Dm, Dry matter).

Discussion

The length, width, flesh thickness, and weight of fruits are crucial factors that determine the quality and marketability of plum cultivars. These characteristics vary across different cultivars and are influenced by genetic factors, growing conditions, and post-harvest handling (Bilal et al., 2015). In our study, which compared 17 plum cultivars, we observed significant variation in fruit length, width, flesh thickness, and weight. For example, cultivars such as 'California' and 'Sabz' had longer and wider fruits, whereas 'Shams' and 'President' had thinner flesh and lighter overall weight.

Fruit length and width are key determinants of visual appeal, with longer and wider fruits generally preferred by consumers. Thicker flesh is often associated with juicier and more flavorful fruits, whereas thinner flesh may result in a less satisfying eating experience. Consumers tend to favor plums with a balance of sweetness, juiciness, and texture, which is strongly influenced by flesh thickness (Crisosto, 2023).

Weight is another essential characteristic. Heavier fruits tend to yield higher outputs, making them more profitable for growers (Correia et al., 2011). Additionally, consumers often perceive heavier fruits as more filling and satisfying. In our experiment, the cultivar 'Sabz' produced the largest and heaviest fruits, making it a strong candidate for breeding programs. However, the ideal fruit size varies depending on market and consumer preferences (Khadivi et al., 2019). While some consumers prefer larger fruits, sellers may favor medium-sized fruits for ease of sale (Massaglia et al., 2019).

Growers should consider these characteristics, along with other factors like taste, texture, and shelf life, when deciding which cultivars to plant. Similarly, consumers should also consider these traits when purchasing plums, as they are indicators of overall fruit quality. Our results align with previous studies on fruit traits such as length and weight (Ganji Moghaddam et al., 2011; Milatović et al., 2019). For instance, Khadivi et al. (2020) found that fruit shape is one of the most important traits for identifying plum cultivars, and fruit weight is a key economic trait. In our study, cultivars like 'Sabz,' 'Santarosa,' and 'California' had large, heavy fruits.

Fruits weighing less than 50 grams are categorized as small, while those weighing between 50 and 65 grams are considered average (Kitzberger et al., 2017). As shown in Table 1, cultivars such as 'Sabz,' 'Santarosa,' and 'California' had medium-sized fruits among the 17 cultivars studied. Our findings are similar to those of Esehaghbeygi et al. (2013) regarding plum thickness and geometric mean diameters, and Latifikhah et al. (2017) on fruit diameter and length-to-width ratios.

Ionica et al. (2013) noted that dimensions and fruit weight are the most important criteria for consumer acceptance of fresh fruits. In our study, the Static Friction Coefficient (SFC) ranged from 0.11 ('Torghabeh Sabz') to 0.21 ('Beygom'), similar to the range of 0.105 ('Ghandy') to 0.169 for other plum cultivars reported by Esehaghbeygi et al. (2013). Most of the fruits were round, with cordate (36%) and circular (23%) shapes being predominant, followed by elliptic and broad elliptic shapes. Other studies have also found that the most common fruit shapes are oval, round, and oblong (Kwon et al., 2018; Khadivi et al., 2020).

The results of the present study on volume and density were consistent with the findings of Esehaghbeygi et al. (2013); Kitzberger et al. (2017) and Smanalieva et al. (2019), with volumes ranging from 11.72 to 176 g cm-3, and densities from 687 to 774 kg m-3. Factors such as ripeness, water content, and storage conditions, can also affect the density and volume of plums. Ripe plums, for example, tend to have a higher water content, increasing their volume and slightly decreasing their density (Singh and Khan, 2010). On average, density of plums is ranged from 0.89-1.16 g cm^{-3} depending on the variety. This makes plums relatively dense compared to other fruits, such as apples or oranges (Gull et al., 2022). In our study, the density values ranged from 0.9-1.52 g cm^{-3}, which was higher than the average diameter of common plums. Although the 'Pakutah' variety did not perform as well as other varieties in some traits, it stood out in terms of volume.

The results of this study on plum sphericity and surface area are in line with previous studies conducted in various regions. Esehaghbeygi et al. (2013) found surface area ranging from 2298.9 to 3931.2 mm2 for Black plums, and sphericity index ranges 94.84 to 97.93 mm^2 for 'Ghandy', 'Ghatretala', and Black cultivars, Smanalieva et al. (2019) reported sphericity ranges from 0.76 to 0.83%, and surface area ranging from 125.89 to 168.21 mm2, with an aspect ratio (range: 1.48 to 1.80), which are consistent with our results. The aspect ratio of a fruit, such as a plum, can provide insights into its shape and volume.

Different plum varieties exhibit varying aspect ratios, which contribute to differences in shape. Some plums may be more elongated, while others appear round or oval. These variations are important for assessing quality, ripeness, and market value (Miragaia et al., 2021). The sphericity index, a measure of how closely a fruit resembles a perfect sphere, also provides insight into shape. Higher sphericity values indicate a rounder shape, as seen in the cultivar 'Ghandy,' while lower values suggest a more irregular or elongated form, as observed in 'California' and 'President.' By considering both aspect ratio and sphericity index, researchers and growers can better understand the physical characteristics of fruit, which can inform decisions about harvesting, storage, and marketing strategies. Consumer preferences for round or elongated plums can further influence cultivation choices (Ertekin et al., 2006; Kamat et al., 2020).

Firmness is another critical trait, significantly affecting a fruit's shelf life, transportability, and consumer appeal (Khadivi-Khub and Barazandeh, 2015). Different plum varieties show varying levels of firmness, with some softening quickly after harvest and others retaining their firmness for longer periods. Breeding programs have focused on enhancing firmness in plums. For example, a study by Qiu et al. (2021) evaluated 21 different plum varieties and identified significant differences in firmness. Varieties such as 'Jixue,' 'Meiguihong,' and 'Gulf-ruby' displayed higher firmness levels than others. Similarly, Wolf et al. (2020) worked on developing firm-fleshed plum varieties with improved flavor. The new 'Angeleno' variety, known for its firmer texture and better post-harvest storage qualities, is more attractive to consumers. By selecting and developing varieties with enhanced firmness—such as 'Beygom,' 'Torghabeh Sabz,' and 'Jangaly'—breeders can expand the plum market and offer consumers higher-quality fruit.

Our study's results also align with the L* index (brightness) of the fruit skin in 'Golden Drop' and the b* color index of the fruit flesh in 'Dargazi' (Kitzberger et al., 2017). Fruit skin color is a vital quality trait that indicates ripeness and significantly influences consumer perceptions. Generally, consumers prefer black-red plums (Khadivi-Khub and Barazandeh, 2015). Approximately 78% of the cultivars we studied had red skin, while 67% had yellowish flesh (Kwon et al., 2018). The presence of a single dominant gene largely determines fruit skin color, ranging from yellowish-green to black (Khadivi et al., 2020).

In our study, the plum cultivars exhibited a range of a*, b*, and L* values, reflecting various skin and flesh colors. The color of plums is primarily determined by pigments like anthocyanins, carotenoids, and chlorophyll. Anthocyanins, in particular, are responsible for the red and purple hues in plums (Liao et al., 2023). For instance, plums with higher a* values, such as 'Santarosa' and 'Beygom,' tend to have more intense red colors, which are visually appealing to consumers. In our results, 'Santarosa' had the highest recorded anthocyanin content. On the other hand, plums with higher b* values, such as 'Ghatretala,' may display yellow or orange tones, which can also influence consumer preferences.

In our study, the parameters Total Soluble Solids (TSS), Total Acidity (TA), the TSS/TA ratio, and pH varied among different plum cultivars. Understanding these variations is crucial for selecting cultivars for various uses, including fresh consumption, processing, or storage (Taiti et al., 2023). Fruits with higher TSS levels are generally sweeter (Druzic et al., 2007; Forough et al., 2014). The TSS levels we observed were consistent with previously reported values for fresh plums, ranging from 10.2 to 24 °Brix, as noted by Ionica et al. (2013), Forough et al. (2014), Pirkhezri et al. (2014), Khadivi-Khub and Barazandeh (2015), and Maglakelidze et al. (2017). According to Kitzberger et al. (2017), fruits with TA levels below 0.6% and TSS between 10% and 12% are considered sweet.

In our study, the sweetest varieties were 'Pakutah,' 'Torghabeh Sabz,' and 'Sabz,' while 'Pivehzhan' had the highest acidity. Previous research also highlights specific cultivars like 'Ghandy' and 'Ghatretala,' which are considered tasty, juicy, and sweet (Sedaghathoor et al., 2009). The cultivar 'Ghermez' is particularly notable for its unique flavor profile—combining sour, sweet, and astringent notes—and its market appeal, due to its distinctive red color (Sedaghathoor et al., 2009).

Regarding total acidity in our study, the results were consistent with the higher acid content reported by Milošević and Milošević (2012) (0.6% to 2.1%), Kitzberger et al. (2017) (0.5% to 3.0%), and Božović et al. (2017) (1.15% to 2.47%). However, our values were lower than those reported by Druzic et al. (2007) (4.4% to 20.55%), Forough et al. (2014) (3.64% for golden plums to 6.13% for large sloes), and Pirkhezri et al. (2014) (4.4% to 20.55%).

The TSS/TA ratio, an indicator of ripeness and consumer acceptance, varied significantly among cultivars in our study. These findings align with those of Druzic et al. (2007) for the Elena cultivar (33.88 fresh, 38.29 dried), Ganji Moghaddam et al. (2011) (5.97 to 19.14), and Kitzberger et al. (2017), who reported a range of 7.51 to 19.18 in Brazilian plums. The high variability in TSS and TA levels is largely attributable to cultivar-specific traits (Milošević and Milošević, 2012). In general, *P. domestica* accessions exhibited higher TSS values compared to *P. insititia* accessions, while the latter had higher TA levels (Milošević and

Milošević, 2012).

The pH levels in our study ranged from 3.01 to 4.02, aligning with those reported by Druzic et al. (2007) for the Elena cultivar (3.83 fresh, 3.90 dried), Jalili et al. (2011) for 'Arih Alcha' (3.08) and 'Ghara-zar Alcha' (4.57), and Latifikhah et al. (2017), who found values ranging from 3.54 in Khansar to 6.7 in 'Ghohrood.'

Cultivars with higher TSS and lower TA, such as 'Pakutah' and 'Torghabeh Sabz,' are more suitable for fresh consumption, while those with lower TSS and higher TA, like 'Sabz' and 'Pivehzhan,' are better for processing or cooking. Additionally, cultivars with a balanced TSS/TA ratio and optimal pH tend to offer better flavor and higher consumer acceptance. For example, Lin et al. (2023) compared the physicochemical characteristics of different plum cultivars and found that soluble solid content (SSC) ranged from 10.1 to 21.1 °Brix, TA from 1.1% to 2.3%, and pH from 2.5 to 3.7, illustrating significant variability in these parameters across cultivars.

The levels of ascorbic acid in the cultivars in this study were found to be lower than those reported by Druzic et al. (2007) (range: 9.79 mg 100 g^{-1} FW) for the Bistrica plum cultivar, Božović et al. (2017) (range: 10.69–15.50 mg 100 g^{-1} FW), and Smanalieva et al. (2019) (range: 16.00–30.25 mg 100 g^{-1} FW). Certain plum varieties such as 'Pivehzhan', and 'Torghabeh Sabz' have been found to contain higher levels of ascorbic acid compared to others. Our study highlighted the importance of selecting plum varieties with high levels of ascorbic acid to maximize their nutritional value. Genetic factors have been shown to play a significant role in determining the ascorbic acid content in plums. Wolf et al. (2020) explored the genetic diversity of different plum genotypes and found variations in ascorbic acid content among them. Overall, it is important to consider the genotype or variety of plum when aiming to consume fruits with high levels of ascorbic acid. Selecting plum varieties with high levels of ascorbic acid can contribute to meeting the daily recommended intake of this essential nutrient (Hernández-Herrero and Frutos, 2015).

Total soluble sugar and anthocyanin content are important factors that determine the quality and health benefits of fruits (Lotfi et al., 2009). Plums are well-known for their flavors and nutritional value. Research indicates that total soluble sugar content in plums can range from 6 to 18% depending on the cultivar (Wolf et al., 2020). Plums with higher sugar content are generally perceived as sweeter. The maturity index varied from 13.52 in the 'Jangaly' variety to 47.64 in the 'Pakutah' variety, which was similar to ones obtained by Božović1 et al. (2017) on total sugars content of plum cultivars were, 10.65-15.24% and Dugalic et al. (2014) on the 'Toptaste' (16.73%), followed by 'Haganta' (14.39%), 'Tophit' (13.71%), 'Jojo' (12.46%), 'Topstar' (11.42%), and 'Top 2000' (11.17%). In our study, 'Ghandy' and 'Targhabeh Sabz' varieties are the highest sugary fruit options available, making them ideal for those who prefer sweet fruits. The results of the present study on anthocyanin showed that the levels of this trait were higher than in cherry plum fruits of 'Arslanbap' (0.64 g kg^{-1} FW 'black' and 0.14 g kg^{-1} FW 'red') and 'Myrobalan' plum (P. cerasifera Ehrh.) (1.93 to 19.86 g kg^{-1} FW) (Smanalieva et al., 2019); (range: 0.6-7.7 mg-100 g^{-1} FW) (Božović et al., 2017); (range: 0.41 mg 100 g^{-1} FW) (Ionica et al., 2013). Anthocyanin content in plums can vary significantly among cultivars, with some cultivars such as 'Pivehzhan' exhibiting higher levels than others. It is important for consumers to be aware of the differences in total soluble sugar and anthocyanin content among plum cultivars, as this can influence their preferences and choices. Additionally, understanding these differences can help researchers and breeders develop new cultivars with improved nutritional profiles and flavor characteristics (Ionica et al., 2013; Sahamishirazi et al., 2017).

Plums are also well-known for their high content of bioactive compounds such as total phenols, flavonoids, and antioxidants, which contribute to their potential health benefits (Chen et al., 2023). The flavonoids content was lower than that reported by Druzic et al. (2007) in fresh material (125.39 mg GAE 100 g^{-1} FW) and dry fruit (357.027 mg GAE 100 g^{-1} FW). The phenol results in the present study were in line with Druzic et al. (2007); and Smanalieva et al. (2019) (ranging from 38.45 to 841.50 mg GAE 100 g^{-1} FW) in plums. The reported values were higher than those reported by Smanalieva et al. (2019) (ranging from 5.2 μg mL^{-1} of yellow plums to 6.5 μg mL^{-1}). A higher antioxidant accumulation, including total phenol and anthocyanin contents, led to enhanced ROS scavenging during storage, ultimately maintaining post-harvest quality (Taghipour et al., 2020). Forough et al. (2014) stated that cultivars with higher antioxidant activity have better stress resistance, nutritional quality, and storage properties. Commercial processing of plums may efficiently inhibit the oxidation of lipids, preventing unpleasant smells in products and increasing their shelf life (Forough et al., 2014). In a study by Lin et al. (2023), the total phenolic content of six different plum cultivars was analyzed, revealing significant variations among the cultivars, with Zihuang showing the highest phenolic content, flavonoid content and antioxidant activity. Another study by Ceccarelli et al. (2021) compared the total phenolic and flavonoid content of 17 different plum cultivars, showing significant differences among the cultivars, with ‘Sangue di Drago’ having the highest phenolic content and antioxidant activity. Overall, these studies demonstrate that the total phenolic, and antioxidant content of plums varies among different cultivars, potentially due to genetic differences, growing conditions, and post-harvest handling practices. Consumers can choose cultivars with higher phenolic and antioxidant content (such as Beygom’ and ‘Pakutah’) to maximize the potential health benefits of consuming plums.

The dry matter content of plum fruits can vary significantly depending on the cultivar, with important implications for fruit quality, including texture, flavor, and shelf life. Dry matter refers to the solid content of the fruit, excluding water. Ceccarelli et al. (2021) reported a range of 12% to 17% in dry matter content across 17 different plum cultivars, highlighting the considerable variability in solid content among cultivars (Smanalieva et al., 2019). Several factors influence dry matter content, such as growing conditions, maturity at harvest, and post-harvest handling. Fruits that fully ripen on the tree before being harvested tend to have higher dry matter content compared to those harvested prematurely (Cupic et al., 2014).

Consumers often prefer plum cultivars with higher dry matter content for their firmer texture and more intense flavor, as seen in cultivars like 'Torghabeh Sabz.' However, individual preferences can vary, with some consumers preferring plums with lower dry matter content.

The coefficient of variation (CV) is a useful indicator of variability among plum cultivars. A CV greater than 20% suggests significant differences between cultivars, while a CV of 0% indicates no difference and stability among accessions (Khadivi et al., 2019). In our study, traits such as skin weight, stone weight, thickness, and color indices (a*, b*, and L* in skin, and b in pulp) had CVs greater than 20%. Regarding biochemical traits, most had CVs higher than 20%, except for TSS, pH, and dry matter, which showed lower variability. This aligns with previous findings, which noted that traits such as fruit shape, density, color, and firmness often exhibit the greatest variation among cultivars (Khadivi-Khub and Barazandeh, 2015).

Conclusion

It is important for consumers, dealers, and growers to be aware of the differences in chemical and physical characteristics among plum cultivars, as these factors significantly influence their preferences and decisions. For fresh consumption, consumers tend to prefer cultivars with higher total soluble solids and lower total acidity, such as ‘Pakutah’ and ‘Torghabeh Sabz’, which offer a sweeter taste. On the other hand, cultivars with lower TSS and higher TA, such as ‘Sabz’ and ‘Pivehzhan’, are better suited for processing or cooking due to their balanced acidity.

Fruit size, including length, width, and weight, can also vary based on market and consumer demands. For instance, larger and heavier fruits like ‘Sabz’ and ‘California’ are often preferred by consumers, while dealers may favor medium-sized fruits for easier handling and selling. Plum cultivars with higher dry matter content, such as ‘Torghabeh Sabz’, are preferred by sellers and consumers alike due to their firmer texture, which enhances shelf life and texture appeal.

Plums are highly valued for their bioactive compounds, including phenols, flavonoids, and antioxidants, which contribute to potential health benefits. Nutritional content varies among cultivars, with some varieties, like ‘Pivehzhan’ and ‘Torghabeh Sabz’, showing higher levels of ascorbic acid (vitamin C), making them nutritionally desirable. Additionally, cultivars with improved firmness, such as ‘Beygom’, ‘Torghabeh Sabz’, and ‘Jangaly’, are better suited for transportation and storage, ensuring they remain fresh during distribution.

For health-conscious consumers, selecting cultivars with higher phenolic and antioxidant content, such as ‘Beygom’ and ‘Pakutah’, can help maximize the health benefits of plum consumption. Furthermore, understanding these differences aids researchers and breeders in developing new plum cultivars with enhanced nutritional profiles, better flavor characteristics, and longer shelf life, ultimately broadening market opportunities for both growers and sellers.

Conflict of Interest

The authors indicate no conflict of interest in this work.

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