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Phenotypic Variations in External and Internal Fruit Quality Traits of Different Plum Accessions

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Abstract

Chinese plum (*Prunus salicina* Lindl.) is a fruit tree with a range of different fruit characteristics, such as different sizes, shapes, flavors, textures, and colors. The relationships between the economic characteristics, nutritional components, functional components, and antioxidant activities of plum fruit have rarely been reported. In order to select new and superior varieties of Chinese plum that are suitable for promotion in north China, eight Chinese plum varieties mainly cultivated in Henan Province (‘Purple amber plum’, ‘Green crisp plum’, ‘French plum’, ‘Princess plum’, ‘Huangganli’, ‘Huangjuli’, and ‘Friar plum’ from Zhengzhou city, and ‘Friar plum’ from Pingdingshan city) and five new breed accessions (‘7–15 plum’, ‘4–12 plum’, ‘1–24 plum’, ‘3–11 plum’, and ‘4–22 plum’) were used as subjects, with the main appearance indexes, nutrient components, functional components, and extract antioxidant activities from these fruits determined and analyzed. The results show that the same accessions of Chinese plum in different regions had the same fruit shape index values, whereas their fruit sizes, nutrient components, functional components and antioxidant activities showed significant differences. The total sugar content was extremely significantly positively correlated with reduced sugar contents and vitamin C (Vc) contents in the different accessions, with correlation coefficients of 0.926 and 0.708, respectively. The flavonoid contents and total phenolic contents in different accessions of plum fruits had an extremely significant positive correlation, with a correlation coefficient of 0.979 obtained. The flavonoid contents and total phenolic contents were significantly positively correlated with the ·OH scavenging capacity, showing correlation coefficients of 0.664 and 0.650, respectively. ‘Princess plum’ and ‘French plum’ had high flavonoid contents, total phenolic contents, and ·OH scavenging capacity levels; the ‘4–12 plum’ had a high triterpenoid acid content and DPPH· scavenging capacity; and ‘Huangganli’ had a high triterpenoid acid content and $\cdot O_2^-$ scavenging capacity. These results confirm that Chinese plums are a good source of natural phenolic antioxidants.

Additional key words: antioxidant activity, functional components, nutritional components, phenotypic traits, *Prunus salicina* L.

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Introduction

Chinese plum (*Prunus salicina* Lindl.) belongs to the genus *Prunus* of the family Rosaceae and is one of the most important deciduous fruit trees in the world. Having a beautiful appearance and providing rich nutrition, plum fruits can be eaten fresh, dried or processed, and are well received by consumers (Liu et al., 2018). At present, there are two main types of plum in commercial production: Chinese plum and European plum (*P. domestica*). Chinese plum, also known as Japanese plum, originated in China and has a long history of cultivation and rich germplasm resources. Chinese plum is distributed or cultivated in nearly all provinces and regions of China, and due to its wide distribution and strong environmental adaptability, it is also one of the most prominent commercial cultivation species in the world (Liu et al., 2018). According to the Food and Agriculture Organization of the United Nations (FAO), in 2020, the cultivated area and yield of Chinese plum ranked first in the world, with the cultivated area of plum in China being approximately 1.95 million hectares, and the yield being about 6.48 million tons. Among the deciduous fruit trees in the north of China, the cultivated area of plum is larger than those of apple (1.91 million hectares), pear (0.87 million hectares), peach (0.78 million hectares), and grape (0.77 million hectares).

Plums are among the world's most favored fruit due to their attractive appearances, abundant nutrients, and excellent flavor, and they show a wide range of fruit characteristics, such as different sizes, shapes, flavors, textures, and colors. The vitamin C, dietary fiber, and polyphenol contents as well as the antioxidant activity of plum fruits are higher than those of other fruits (Ma et al., 2018). At present, some progress has been made with regard to knowledge of plum fruits, such as their vitamin C content (Sikora et al., 2013; Nisar et al., 2015) and nutrient components (Lozano et al., 2009). The total phenolic content and antioxidant capacity of the plum cultivar 'Black Splendor' are 400 $mg \cdot g^{-1}$ and $2.5 g \cdot kg^{-1}$, respectively (Puerta-gomez and Cisneros-zevallos, 2011). Kim et al. (2003a) found a positive relationship between the total phenolic content and the antioxidant capacity of fresh plum, suggesting that polyphenolics play an important role in free radical scavenging. The antioxidant capacity levels of six different plum cultivars and 'Gala' apples were studied, with the results showing that the total antioxidant capacity of plums was higher than that of 'Gala' apples (Kim et al., 2003b). Cosmulescu et al. (2015) found that the levels of total phenolics and flavonoid compounds changed depending on the plum cultivar and fruit part, with a positive relationship found between the total phenolics and the total antioxidant capacity. Meanwhile, the relationship between the polyphenol content and the antioxidant activity of plum fruits has also been reported in China (Zhou et al., 2017; Weng et al., 2018). However, the relationships among the economic characteristics, nutritional components, functional components, and antioxidant activity of plum fruit have rarely been reported.

In this study, phenotypic data were determined and analyzed for eight widely planted cultivars and five superior accessions of Chinese plum in Henan Province, China. We found that the same Chinese plum accession in different regions had the same fruit shape index values, whereas their fruit sizes, nutrient components, functional components, and antioxidant activities showed significant differences. We also discovered significant variations and correlations of the external and internal fruit quality traits of these plum accessions. The study outcomes here provide fundamental knowledge pertaining to cultivar selection and the development of the Chinese plum industry.

Materials and Methods

Plant materials

Thirteen plum accessions were used in this study, specifically eight widely planted cultivars ('Purple amber plum', 'Green crisp plum', 'French plum', 'Princess plum', 'Huangganli', 'Huangjuli', and 'Friar plum' from Zhengzhou city, and 'Friar plum' from Pingdingshan city) and five newly selected advanced accessions from our laboratory ('7 – 15 plum’, ‘4－12 plum’, ‘1－24 plum’, ‘3－11 plum’, and ‘4－22 plum’). Trees of these accessions were planted in the orchards of the Zhengzhou Fruit Research Institute of the Chinese Academy of Agricultural Sciences (ZFRI-CAAS) (Zhengshou 35°09' N, 113°47' E; Pingdingshan 33°74' N, 113°31' E) at a density of 2.5×4.0 m. According to our observations, the soil conditions of the two experimental fields in Zhengzhou and Pingdingshan city are sandy loam and flat terrain, and the corresponding soil organic matter contents are 21.55 g/kg and 23.62 g/kg, with pH values of 6.80 and 5.74, respectively. Both Zhengzhou city and Pingdingshan city have a temperate continental monsoon climate with four distinct seasons; the respective average annual temperatures are 14.4°C and 14.8°C, the average annual rainfall levels are is 640.9 mm and 800.1mm, the frost-free periods are 220 days and 217 days, and the annual sunshine durations are approximately 2400 hours and 2200 hours (Li et al., 2010; Wang, 2021).

The selected plum trees were six years old, with robust tree potential, normal growth, and fruit-bearing capacity. The trees were maintained under conventional management and pest control practices and were grown to a tall spindle shape, with fundamentally the same canopy size and tree potential. For fruit sampling, three replicates were established for each accession; each replicate consisted of three trees, and ten fruit were collected from each tree. The tested materials were completely ripe fruit suitable for immediate consumption (ready-to-eat) and were disease-free and without pest or mechanical damage (D’ Ambrosio et al., 2013). Only fruit located in external canopies without shading by leaves were collected to determine for their adequate light acquisition (Huang et al., 2019b).

Analysis of botanical and external characteristics

The botanical and external characteristics, including the full-bloom stage, fruit development period, fruit ripening period, fruit peel color, fruit shape, fruit vertical, lateral, and transversal diameter, fruit shape index, and average fruit weight, were investigated and recorded for the eight widely planted Chinese plum cultivars and five newly selected advanced accessions. Fruit weights were determined using electronic scales, and the vertical diameters, lateral diameters, and transverse diameters of different plum fruits were determined using a slide gauge with a precision of 0.01 millimeter.

Fruit sample preparation

Plum peels were separated manually, and the equatorial part of the plum pulp in each case was chipped, mixed, quickly frozen with liquid nitrogen, and then placed in a −80°C ultra-low-temperature refrigerator for the determination of the reducing sugar, total sugar, total acids, vitamin C content, flavonoid content, total phenol content, triterpenoid acid content, and antioxidant activity.

Analysis of the main nutrient components

The extraction and determination of reducing sugar from plum fruit were performed following the method described by Yu et al. (2021). The total soluble sugar content was determined by the sulfuric acid-anthrone colorimetric method (Li, 2000). The total acid content was determined by sodium hydroxide titration (Wang, 2011), and the vitamin C content was determined by 2, 6-dichloroindophenol titration and measured according to the ascorbic acid content (Wang, 2011).

Analysis of functional substances and antioxidant activity

A total of 4 g of freshly abraded specimens of plum pulps was homogenized with 4 mL pf 80% methanol at 30°C for 10 min via ultrasonic extraction and then centrifuged for 10 min at a speed of 4500 g. The supernatants were collected and the residue was repeatedly extracted with 4 mL of 80% methanol once again. After these two procedures, the extracted solution was combined with a constant volume of methanol to a level of 10 mL and then frozen in an −80°C ultra-low-temperature refrigerator for the determination of the flavonoid content, total phenol content, triterpenoid acid content and antioxidant activity.

The flavonoid content was determined by the aluminum nitrate colorimetric method (Tang et al., 2008), and the standard curve was established with rutin as the standard substance. The total phenolic content was determined according to the Folin – Ciocalteu method (Bonilla et al., 2003; An et al., 2016), with gallic acid as the standard substance. The total triterpenoid acid content was determined by referring to the method of Zhou et al. (2004), with oleanolic acid used as the standard substance.

The determination of the hydroxyl radical (·OH) scavenging ability was conducted according to the sodium salicylate complex method (Xu and Hu, 2006). The superoxide anion radical ($\cdot O_2^-$) scavenging ability was determined according to autoxidation with the pyrogallol method (Guo et al., 2008b). The 1,1-diphenyl-2-picrylhydrazyl radical 2,2-diphenyl-1- (2,4,6-trinitrophenyl) hydrazyl (DPPH) free radical (DPPH·) scavenging ability was determined according to a method devised by Yolanda et al. (2014), with ascorbic acid as the control, and was calculated according to the standard curve of ascorbic acid.

Statistical analysis

Data were represented as the means ± SD based on three independent replicates. A correlation analysis was conducted using SPSS20.0 (IBM, Armonk, NY, USA). A *P*-value of < 0.05 was considered statistically significant. Figures were generated using Excel 2019 (Microsoft, Redmond, WA, USA) and Origin 2021 (OriginLab Corporation, Northampton, MA, USA).

Results

Phenotypic analysis of plums

The phenological period and external characteristics of the tested plums are correspondingly shown in Table 1 and Table 2. An analysis of variance of the fruit weight and fruit shape of the plums exhibited significant differences among the accessions. The vertical diameters of the plum fruits ranged from 26.39 to 52.96 mm, with an average of 43.35 mm; the lateral diameters of the plum fruits ranged from 25.27 to 63.02 mm, with an average of 45.39 mm; the transverse diameters of the plum fruits ranged from 27.11 to 65.38 mm, with an average of 46.00 mm.

The average fruit weight of different plum accessions was 56.99 g (ranging from 10.85 to 118.02 g); among them, the 'Friar plum' from Pingdingshan city had the greatest average fruit weight, which was significantly greater than that of the 'Friar plum' from Zhengzhou city, followed by the '4 – 12 plum', 'Huangjuli', 'French plum', and 'Huangganli'. There were also significant differences in the average fruit weights of the other plum accessions; ranked from high to low, they are the ‘7 − 15 plum’, ‘Purple amber plum’, ‘Princess plum’, ‘1 − 24 plum’, ‘3 − 11 plum’, ‘Green crisp plum’, and the ‘4 − 22 plum’ types.

The fruit shape index results show that there were differences in the fruit shapes of the plum accessions. The fruit shape index value for ‘Purple amber plum’ was greater than 1.1, showing an oblong shape. The fruit shape index values of ‘Huangjuli’, ‘French plum’, and ‘Princess plum’ were between 1.0 and 1.1, showing a round shape. The fruit shape index

Table 1. Phenological Periods and Botanical Characteristics of Different Cultivars of *P. salicina* Fruits

Plum cultivars	Full-bloom stage	Fruit development period (d)	Fruit ripening period	Fruit peel color	Fruit pulp color	Fruit shape
Purple amber plum	Mid. March	96	Early Maturing	Purple red	Yellow	Oblong
Green crisp plum	Mid. March	110	Mid. Maturing	Blue green	Yellow white	Oblate
Huangganli	Mid. March	120	Mid-late Maturing	Red	Light yellow	Oblate
Huangjuli	Mid. March	120	Mid-late Maturing	Yellow green	Light yellow	Round
French plum	Late March	120	Mid-late Maturing	Purple red	Yellow	Round
Princess plum	Mid. March	125	Late Maturing	Red	Yellow	Round
Friar plum (Zhengzhou)	Late March	130	Late Maturing	Purple black	Yellow	Oblate
Friar plum (Pingdingshan)	Mid. March	125	Late Maturing	Purple black	Yellow	Oblate
7-15 plum	Mid. March	108	Mid. Maturing	Red	Yellow	Oblate
4-12 plum	Mid. March	95	Early Maturing	Red	Yellow	Oblate
1-24 plum	Mid. March	122	Late Maturing	Red	Light yellow	Oblate
3-11 plum	Mid. March	120	Late Maturing	Purple red	Yellow	Oblate
4-22 plum	Mid. March	110	Mid. Maturing	Red	Yellow	Oblate

Table 2. Phenotypic Analysis of Different Cultivars of *P. salicina* Fruits

Plum cultivars	Vertical diameter (mm)	Lateral diameter (mm)	Transverse diameter (mm)	Fruit shape index	Average fruit weight (g)
Purple amber plum	49.74 ± 2.74 bc	48.64 ± 0.85 c	43.98 ± 0.90 ef	1.13 ± 0.01 a	58.33 ± 0.75 de
Green crisp plum	32.62 ± 1.11 g	39.48 ± 0.46 e	40.30 ± 0.52 h	0.81 ± 0.01 h	30.96 ± 0.58 h
Huangganli	45.88 ± 1.36 d	47.09 ± 0.44 c	47.19 ± 0.75 d	0.97 ± 0.01 e	63.21 ± 0.44 d
Huangjuli	50.49 ± 3.41 bc	49.12 ± 0.73 c	50.21 ± 0.80 c	1.01 ± 0.01 cd	72.73 ± 0.80 c
French plum	48.23 ± 4.50 c	47.28 ± 1.40 c	47.46 ± 1.22 d	1.02 ± 0.01 bc	63.46 ± 1.27 d
Princess plum	44.03 ± 2.92 d	44.37 ± 0.76 d	42.45 ± 0.92 fgh	1.04 ± 0.02 b	45.97 ± 0.93 fg
Friar plum (Zhengzhou)	41.48 ± 3.54 e	48.11 ± 1.01 c	51.10 ± 0.76 bc	0.81 ± 0.01 h	61.36 ± 1.10 d
Friar plum (Pingdingshan)	52.96 ± 7.19 a	63.02 ± 1.18 a	65.38 ± 1.87 a	0.81 ± 0.01 h	118.02 ± 1.47 a
7-15 plum	44.19 ± 1.84 d	43.58 ± 0.55 d	44.86 ± 0.63 e	0.99 ± 0.01 de	51.76 ± 0.56 ef
4-12 plum	51.86 ± 3.06 ab	51.74 ± 0.99 b	52.98 ± 0.63 b	0.98 ± 0.01 de	82.78 ± 0.80 b
1-24 plum	37.53 ± 1.16 f	40.99 ± 0.38 fe	41.44 ± 0.62 gh	0.91 ± 0.01 f	40.70 ± 0.46 g
3-11 plum	38.13 ± 2.09 f	41.33 ± 0.81 e	43.61 ± 0.52 efg	0.87 ± 0.01 g	40.68 ± 0.83 g
4-22 plum	26.39 ± 0.61 h	25.27 ± 0.55 f	27.11 ± 0.58 i	0.97 ± 0.00 e	10.85 ± 0.56 i
Mean	43.35	45.39	46.01	0.95	56.99
CV	0.18	0.19	0.19	0.11	0.46

Note: Values are the means ± standard deviation of three replications. Data followed by different letters are significantly different from each other ($p < 0.05$). CV, coefficient of variability.

values of the other plum accessions were less than 1.0, showing an oblate shape and conforming to the fruit shapes in Table 1. Furthermore, the 'Friar plum' types from Zhengzhou city and Pingdingshan city had the same fruit shape index value of 0.81.

Nutrient components of plums

Quantitative differences in the main nutrient component concentrations were determined among the thirteen tested plum accessions at the ripening stages (Table 3). The reducing sugar contents ranged from 1.68% to 7.65%, with the average being 3.45%. Of all tested accessions, the reducing sugar content of the '7 – 15 plum' was highest, followed by that of 'Green crisp plum' and '4 – 12 plum', recording percentages of 7.08% and 6.00%, respectively. Meanwhile, '3 – 11 plum' had the lowest reducing sugar content of 1.68%. The content of total sugar ranged from 5.95% to17.98 %, with the average being 9.31%. Matching the reducing sugar outcome, '7 – 15 plum' had the highest total sugar content as well. In addition, the total sugar contents of '7 – 15 plum', 'Crisp green plum', '4 – 12 plum', and 'Princess plum' all exceeded 10% at 15.02%, 13.17%, 11.49%, and 10.25%, respectively, indicating that these four plum accessions have rich sugar contents. The lowest total sugar content was detected in the '3 – 11 plum'. The total acid contents ranged from 0.69% to 1.59%, with the average being 1.03%. The '4 – 12 plum' had the highest total acid content, and the 'Purple amber plum' had the lowest. The sugar-acid ratio is the ratio of total sugar to total acid, and it ranged from 5.51 to 16.54. Among the accessions, the sugar – acid ratios of 'Green crisp plum', '4 – 12 plum', 'Purple amber plum', 'Princess plum', 'Friar plum', 'French plum', and '7 – 15 plum' were all above 10, and these all have a sweet taste, which is more in line with the taste preferences of Chinese consumers. The average vitamin C content was 4.36 mg/100g, and that of the '4 – 12 plum' was highest, followed by the 'Princess plum', 'Green crisp plum', and '7 – 15 plum'. The vitamin C content of the '3 – 11 plum' was lowest at only 1.71 mg/100g.

Table 3. Contents of Main Nutrient Components in Different Cultivars of *P. salicina* Fruits

Plum cultivars	Reducing sugar (%)	Total sugar (%)	Total acid (%)	Sugar – acid ratio	Vc content (mg/100g)
Purple amber plum	2.54 ± 0.10 e	9.36 ± 0.13 d	1.24 ± 0.03 c	7.55	2.54 ± 0.10 gh
Green crisp plum	7.08 ± 0.04 b	13.17 ± 0.11 b	0.79 ± 0.03 gh	16.54	6.92 ± 0.06 c
Huangganli	2.51 ± 0.05 ef	9.04 ± 0.08 e	0.96 ± 0.01 e	9.42	2.00 ± 0.13 i
Huangjuli	1.92 ± 0.01 g	7.89 ± 0.08 g	1.08 ± 0.04 d	7.31	2.79 ± 0.17 g
French plum	2.49 ± 0.03 ef	8.74 ± 0.03 f	0.87 ± 0.00 f	10.05	2.95 ± 0.08 g
Princess plum	2.33 ± 0.01 ef	10.25 ± 0.07 c	0.69 ± 0.00 i	14.86	7.83 ± 0.21 b
Friar plum (Zhengzhou)	3.02 ± 0.04 d	8.81 ± 0.04 ef	0.84 ± 0.00 fg	10.49	3.53 ± 0.09 f
Friar plum (Pingdingshan)	2.30 ± 0.01 f	7.41 ± 0.09 h	0.75 ± 0.03 hi	9.88	3.96 ± 0.07 ef
7-15 plum	7.65 ± 0.11 a	15.02 ± 0.20 a	1.50 ± 0.01 b	10.01	6.32 ± 0.22 d
4-12 plum	6.00 ± 0.19 c	11.49 ± 0.23 de	0.77 ± 0.04 ghi	14.92	9.89 ± 0.13 a
1-24 plum	2.36 ± 0.02 ef	7.69 ± 0.02 gh	1.22 ± 0.04 c	6.30	2.14 ± 0.12 hi
3-11 plum	1.68 ± 0.07 h	5.95 ± 0.07 i	1.08 ± 0.03 d	5.51	1.71 ± 0.06 i
4-22 plum	3.02 ± 0.05 d	8.73 ± 0.06 f	1.59 ± 0.02 a	5.49	4.07 ± 0.05 e
Mean	3.45	9.50	1.03	9.87	4.36
CV	0.59	0.26	0.28	0.37	0.59

Note: Values are the means ± standard deviation of three replications. Data followed by different letters are significantly different from each other ($p < 0.05$). CV, coefficient of variability.

Functional components of plums

As shown in Table 4, an analysis of variance of the flavonoid, total phenolic, and triterpenoid acid contents in the plums exhibited significant differences ($p < 0.05$) among the accessions.

All tested plum accessions had rich flavonoids, ranging from 0.14 to 1.44 mg/g, with an average content of 0.86 mg/g. Among the accessions, 'Princess plum' was richest in flavonoids, followed by 'French plum' and 'Purple amber plum'; there were no significant differences between these and 'Princess plum'. The flavonoid contents of 'Friar plum (Zhengzhou)', '1 − 24 plum', 'Huangganli', and '4 − 12 plum' were 1.14, 1.11, 1.11, and 1.05 mg/g, respectively, and there were no significant differences among the 'Friar plum (Zhengzhou)', '1 − 24 plum', 'Huangganli', and '4 − 12 plum' types. Furthermore, 'Friar plum (Pingdingshan)' had the lowest flavonoid content at only 0.14 mg/g.

For all tested accessions, the average total phenolic content was 1.64 mg/g, with the variation range being around 0.78 − 2.39 mg/g. The total phenolic content in 'Princess plum' was significantly higher than those of the other plum accessions; those with the next highest total phenolic content were, in order, 'French plum', 'Purple amber plum', 'Friar plum', 'Huangganli', and '4 − 12 plum', and there were no significant differences among them. The lowest total phenolic content was detected in the cultivar 'Friar plum (Pingdingshan)'.

The average triterpenoid acid content in the tested accessions was 6.15 mg/g, ranging from 1.91 to 15.35 mg/g. 'Huangganli' was richest in triterpenoid acid, its content being much higher than those of the other accessions, and it was also significantly different from the other accessions. The lowest content of triterpenoid acid was detected in 'Green crisp plum'.

Antioxidant activities of plums

The results for the scavenging DPPH·, scavenging ·OH and scavenging $\cdot O_2^-$ capacities of the fruit-extracted solutions

Table 4. Contents of Functional Components in Different Cultivars of *P. salicina* Fruits

Plum cultivars	Flavonoid (mg/g)	Total phenolic (mg/g)	Triterpenoid acid (mg/g)
Purple amber plum	1.32 ± 0.04 a	2.16 ± 0.03 b	6.01 ± 0.30 d
Green crisp plum	0.34 ± 0.06 e	1.00 ± 0.03 f	1.91 ± 0.18 g
Huangganli	1.11 ± 0.03 b	2.03 ± 0.07 b	15.54 ± 0.29 a
Huangjuli	0.74 ± 0.05 c	1.38 ± 0.03 d	6.94 ± 0.16 c
French plum	1.34 ± 0.08 a	2.19 ± 0.05 b	4.40 ± 0.16 e
Princess plum	1.44 ± 0.03 a	2.38 ± 0.06 a	4.80 ± 0.21 e
Friar plum (Zhengzhou)	1.14 ± 0.08 b	2.12 ± 0.05 b	4.77 ± 0.22 e
Friar plum (Pingdingshan)	0.14 ± 0.01 f	0.77 ± 0.00 g	6.40 ± 0.29 cd
7-15 plum	0.40 ± 0.06 de	1.18 ± 0.12 e	7.15 ± 0.68 bc
4-12 plum	1.05 ± 0.05 b	2.03 ± 0.03 b	2.72 ± 0.08 f
1-24 plum	1.11 ± 0.03 b	1.76 ± 0.11 c	6.56 ± 0.13 cd
3-11 plum	0.36 ± 0.04 e	1.02 ± 0.05 ef	7.89 ± 0.06 b
4-22 plum	0.56 ± 0.08 d	1.47 ± 0.04 d	5.07 ± 0.26 e
Mean	0.85	1.65	6.17
CV	0.52	0.33	0.54

Note: Values are the means ± standard deviation of three replications. Data followed by different letters are significantly different from each other ($p < 0.05$). CV, coefficient of variability.

of the thirteen tested plum accessions are shown in Table 5. An analysis of variance of the antioxidant activities in plums exhibited significant differences ($p < 0.05$) among the accessions.

The DPPH· clearance rate of the fruit-extracted solution of the thirteen tested plum accessions ranged from 28.66% to 94.93%, and the maximum value was 3.31 times the minimum value. The average clearance rate was 79.98%, and there were great differences among the different accessions. The '1 − 24 plum' and 'Huangganli' types were the two accessions with the highest DPPH· clearance rates, at 94.93% and 94.81%, respectively, followed by '4 − 12 plum' at 94.12%. 'Friar plum (Pingdingshan)' had the lowest DPPH· clearance rate, at only 28.66%, which was far lower than the average value while also being significantly different from those of the other plum accessions ($p < 0.05$).

The ·OH clearance rate of the fruit-extracted solution ranged from 83.08% to 95.30%, with an average clearance rate of 92.23%, though in this case there were no significant differences among all tested accessions ($p > 0.05$). The ·OH clearance rates of the other twelve tested plum accessions were all above 90%, except for the clearance rate of 'Huangjuli', which was 83.08%. Furthermore, 'Friar plum (Pingdingshan)' had the strongest ability to scavenge ·OH, recording a clearance rate of 95.30%.

The $\cdot O_2^-$ clearance rate of the fruit-extracted solution ranged from 3.72% to 50.12%, and the maximum value was 13.47 times the minimum value. The average clearance rate was 25.53%, and there were great differences among the different plum accessions. Among all tested accessions, six plum cultivars ('Purple amber plum', 'Green crisp plum', 'Huangganli', 'French plum', 'Princess plum', and 'Friar plum (Zhengzhou)') not only had higher $\cdot O_2^-$ clearance rates than the other seven plum accessions but also were significantly difference from the others ($p < 0.05$). 'Friar plum (Pingdingshan)' and '1 − 24 plum' recorded the lowest $\cdot O_2^-$ scavenging capacity levels.

Table 5. Antioxidant Activities of Extracts from Different Cultivars of *P. salicina* Fruits

Plum cultivars	DPPH· Clearance rate (%)	·OH Clearance rate (%)	$\cdot O_2^-$ Clearance rate (%)
Purple amber plum	91.16 ± 0.11 abc	92.53 ± 0.15 a	31.51 ± 0.69 bc
Green crisp plum	89.13 ± 2.74 abc	95.25 ± 1.91 a	50.12 ± 0.11 a
Huangganli	94.81 ± 0.28 a	91.56 ± 0.58 a	36.47 ± 0.87 b
Huangjuli	86.90 ± 0.77 bcd	83.08 ± 5.09 b	9.94 ± 1.61 e
French plum	68.35 ± 1.01 g	93.64 ± 0.03 a	31.97 ± 5.25 bc
Princess plum	83.91 ± 1.30 cde	94.08 ± 0.43 a	44.16 ± 2.80 a
Friar plum (Zhengzhou)	72.15 ± 4.54 fg	92.94 ± 0.11 a	33.15 ± 2.30 bc
Friar plum (Pingdingshan)	28.66 ± 1.26 h	95.30 ± 0.06 a	4.90 ± 0.77 e
7-15 plum	80.50 ± 4.43 de	90.90 ± 0.03 a	29.32 ± 4.25 cd
4-12 plum	94.12 ± 0.04 ab	93.36 ± 0.09 a	7.50 ± 1.12 e
1-24 plum	94.93 ± 0.39 a	93.03 ± 0.47 a	3.72 ± 0.98 e
3-11 plum	77.89 ± 5.51 ef	91.67 ± 0.66 a	22.75 ± 0.68 d
4-22 plum	77.25 ± 0.96 ef	91.63 ± 0.83 a	26.37 ± 3.19 cd
Mean	79.98	92.23	25.53
CV	0.22	0.03	0.59

Note: Values are the means ± standard deviation of three replications. Data followed by different letters are significantly different from each other ($p < 0.05$). CV, coefficient of variability.

Relationship between inclusion contents and antioxidant capacities

The correlation coefficients between the phenotypic inclusion contents and the antioxidant activities of the nutrient components among the thirteen tested plum accessions were calculated and are listed in Table 6. The fruit vertical diameter, lateral diameter, transverse diameter, and average fruit weight have positive correlations ($p < 0.01$). The reducing sugar content was found to be positively correlated with the total sugar content and the vitamin C content ($p < 0.01$), and positively correlated with the vitamin C content as well ($p < 0.05$). The vitamin C content was found to be positively correlated with the total sugar content ($p < 0.01$), and negatively correlated with the triterpenoid acid content ($p < 0.05$).

In addition, the correlation coefficients between the functional components and antioxidant capacities among the thirteen tested plum accessions were calculated and are listed in Table 7. Extremely significant correlations were observed between the flavonoid content and the total phenolic content ($p < 0.01$), with a correlation coefficient of 0.979 obtained. The flavonoid content and total phenolic content were significantly positively correlated with the ·OH scavenging capacity, with corresponding correlation coefficients of 0.664 and 0.650.

Table 6. Correlation Coefficients between Phenotypic and Nutrient Components of Different Cultivars of *P. salicina* Fruits

Variables	Vertical diameter	Lateral diameter	Transverse diameter	Sugar−acid ratio	Average fruit weight	Reducing sugar content	Total sugar content	Total acid content	Vc content
Vertical diameter	1.000								
Lateral diameter	0.898**	1.000							
Transverse diameter	0.822**	0.973**	1.000						
Sugar−acid ratio	0.316	−0.097	−0.274	1.000					
Average fruit weight	0.880**	0.964**	0.969**	−0.106	1.000				
Reducing sugar content	−0.264	−0.447	−0.405	0.275	−0.295	1.000			
Total sugar content	−0.263	−0.476	−0.468	0.380	−0.312	0.926**	1.000		
Total acid content	−0.097	0.038	0.024	−0.077	0.127	0.089	0.086	1.000	
Vc content	−0.021	−0.171	−0.146	0.219	−0.073	0.693**	0.708**	−0.319	1.000

Note: * and ** represent a correlation at a significance level of $p < 0.05$ and $p < 0.01$, respectively.

Table 7. Correlation Coefficients between Functional Components and Antioxidant Capacities of Different Cultivars of *P. salicina* Fruits

Variables	Flavonoid content	Total phenolic content	Triterpenoid acid content	DPPH· clearance rate	·OH clearance rate	$\cdot O_2^-$ clearance rate
Flavonoid content	1.000					
Total phenolic content	0.979**	1.000				
Triterpenoid acid content	0.034	0.028	1.000			
DPPH· clearance rate	0.011	0.046	0.136	1.000		
·OH clearance rate	0.664*	0.650*	−0.037	−0.283	1.000	
$\cdot O_2^-$ clearance rate	0.152	0.208	0.314	0.241	0.281	1.000

Note: * and ** represent a correlation at a significance level of $p < 0.05$ and $p < 0.01$, respectively.

Cluster analysis and principal component analysis

Based on the fourteen indexes determined in this study, the thirteen plum accessions were systematically clustered after normalization. The results showed that all of the accessions were grouped into three distinct clusters (Fig. 1). Cluster I contained only one cultivar: 'Friar plum (Pingdingshan)'. Cluster II comprised the three accessions of '4 – 22 plum', '7 – 15 plum', and 'Green crisp plum'. Nine accessions formed Cluster III: '4 – 12 plum', '3 – 11 plum', '1 – 24 plum', 'Huangjuli, Princess plum', 'Huangganli', 'Friar plum (Zhengzhou)', 'French plum', and 'Purple amber plum'. Different indexes were associated with each of the three clusters. Cluster I was the only cultivar obtained from Pingdingshan city. Cluster II presented a small fruit size and high total sugar content. Cluster III plum fruits showed a medium fruit shape and high functional components.

Fourteen indexes of the thirteen plum accessions were processed through a principal component analysis (PCA) (Fig. 2). PC1 accounted for 33.2% of the total change; PC2 accounted for 21.3%; PC3 accounted for 17.9%; and PC1, PC2, and PC3 explained 72.4% of the variability, which reflected most of the information provided by the initial indicators. In the PC1 dimension, the reducing sugar, total sugar, total acid, and Vc contents were mainly loaded, reflecting the main nutrient components of the different plum accessions. In the PC2 dimension, the vertical diameter, lateral diameter,

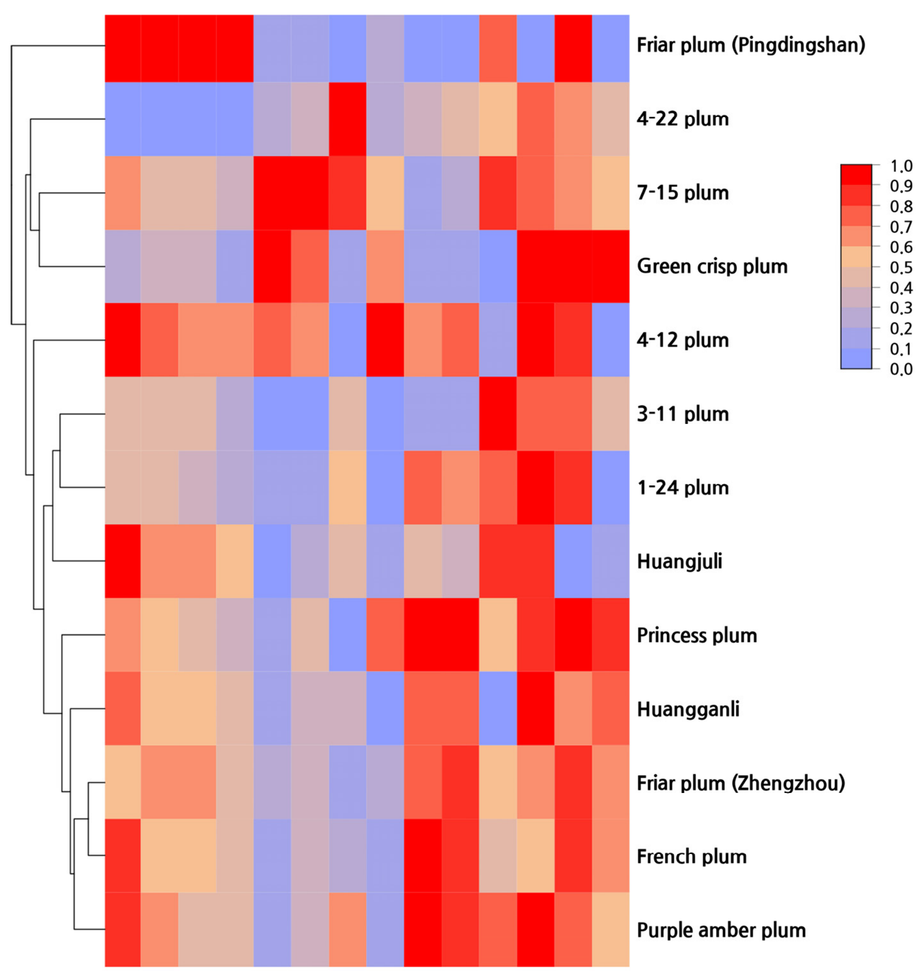

Fig. 1. Clustering diagram of different plum accessions.

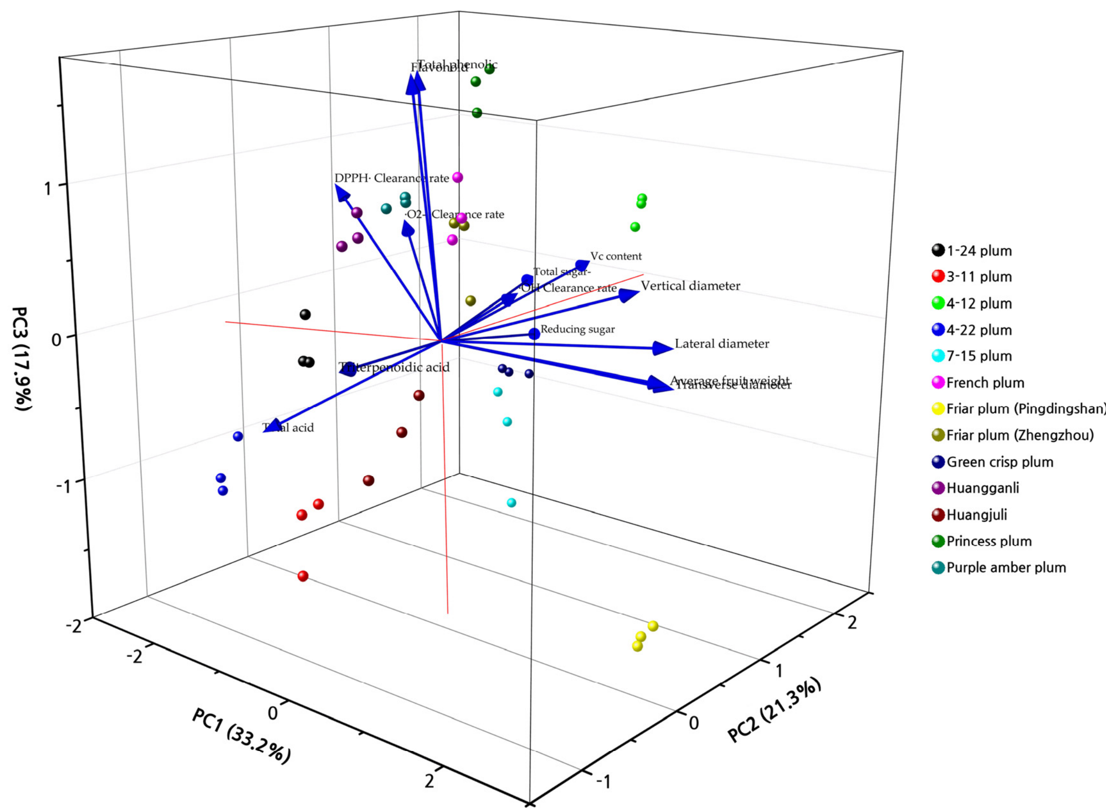

Fig. 2. Biplot graph of the principal component analysis in this study.

transverse diameter, and average fruit weight were mainly loaded, reflecting the sizes of different plum accessions. In the PC3 dimension, the flavonoid, total phenolic, and triterpenoid acid contents as well as the DPPH· clearance rate, ·OH clearance rate and $\cdot O_2^-$ clearance rate were mainly loaded, reflecting the functional components and antioxidant activities of the different plum accessions.

Discussion

Plum fruits are nutritionally rich, and there are certain differences among different plum accessions. Moreover, numerous nutrients accumulate continuously during fruit growth and development. The factors of the single fruit mass, fruit shape index, titratable acid content, vitamin C content, flavor, and color are representative quality indicators that can reflect the variety requirements for fresh fruits (Fan et al., 2009). Reducing sugar, total sugar, total acid, and vitamin C are some of the nutrients in plum fruits, while flavonoids and total phenols belong to polyphenols, which are important functional components in plum fruits. Plum fruits with high sugar, vitamin C, and polyphenol contents not only have high nutritional quality but also have a high health function (Liu et al., 2015). In this study, on the basis of a comprehensive evaluation of plum quality attributes, an investigation and an analysis of the main phenotypic components of plum fruits were carried out to ensure the effective selection of plum accessions suitable for cultivation and promotion in Henan Province and its surrounding areas.

From the differences recorded for the average single fruit mass, longitudinal diameter, side diameter, transverse diameter and fruit shape index, it can be seen that different plum accessions were found to have considerable differences in the fruit weight and fruit shape. The average single fruit mass of ‘Friar plum’ obtained from Pingdingshan city was much larger than the same type of plum obtained from Zhengzhou city, which indicates that fruit growth and development were affected by the different geographical environments and cultivation conditions. ‘Friar plum (Pingdingshan)’ and ‘Friar plum (Zhengzhou)’ had the same fruit shape index value, indicating that different geographical environments and cultivation conditions had no effects on the fruit shape despite the significant effect on the fruit weight. This finding corroborates the results presented by Liu et al. (2009), who found that the growth and development of plum fruits were affected by many factors, the most important being the growth and development of the plum accessions themselves, followed by soil, light, water, temperature, and other external factors. In the present study, we also observed that ‘Friar plum (Pingdingshan)’, ‘4－12 plum’, ‘Huangjuli’, ‘French plum’, and ‘Huangganli’ were all large fruit type accessions, and this feature can be widely promoted during the production stage.

Fruit quality largely depends on the contents of total sugar and total acid, but the type and proportion of the sugar and acid components are closely related to fruit sweetness and acidity (Wu et al., 2003). It is frequently reported that with the ripening of fruit, the color, aroma, and taste change significantly, with these factors finally reaching an edible state matching people’s consumption needs. Edible quality changes are mainly caused by the transformation of sugars and acids, and the compositions and contents of sugars and acids are among the important factors affecting the taste of fruit (Lakkakula et al., 2011). The flavor and quality of fruits stem from the comprehensive action of sugars, acids, and other substances, and the sugar－acid ratio is an important factor affecting the sweet and sour flavor and fresh food quality of fruits, playing a crucial role in the overall quality of fruits (Asencio et al., 2018). However, the association between different sugars and acids, as well as their effects on the flavor of fruit flesh, can differ in different plum accessions. In the present study, in terms of the average single fruit mass, the sugar－acid ratio, vitamin C content, and other indicators, ‘7－15 plum’ and ‘4－12 plum’ were superior to the other plum accessions, showing the characteristics of a large average single fruit mass, high sugar－acid ratio and high vitamin C content. Although the fruit sizes of ‘Princess plum’ and ‘Green crisp plum’ were small, their sugar－acid ratios and vitamin C contents were high; these accessions have been increasingly developed in recent times. In particular, ‘Green crisp plum’ has a bright green color, a fresh taste, ripens early, is of excellent quality, and is suitable for storage and transportation, giving this cultivar broad development prospects.

Fruits with high antioxidant activity are not only beneficial to human health but also have strong stress resistance and good storage and transportation characteristics (Lata, 2007). Therefore, increasing amounts of attention have been paid to the antioxidant activity of fruits, which is mainly derived from the phenolic and flavonoid substances in fruits (Cao et al., 1997; Kim et al., 2003a). In this study, an analysis of variance of the flavonoids, total phenols, and triterpenoid acid contents in plums showed significant differences among the accessions, corroborating the results presented by Guo et al. (2008a), who found that the flavonoid contents of apples, grapes, pears, and other deciduous fruit differed among different cultivars of the same tree species. Previous studies have shown that during the development and ripening process of grapes, the activities of key enzymes and regulatory factors for the synthesis of flavonoids and total phenols in phenylpropanoid metabolic pathways increase continuously, which is conducive to the synthesis and accumulation of flavonoids and total phenols (Wang et al., 2010). In the present study, ‘Princess plum’, ‘French plum’, and ‘Purple amber plum' were richest in flavonoid and total phenol contents, 'Huangganli', '3－11 plum', and '4－12 plum' were richest in the triterpene acid content, and they were all functional fruits. The flavonoid and total phenol contents in 'Friar plum (Pingdingshan)' were much lower than those in 'Friar plum (Zhengzhou)', possibly due to the different climatic and environmental conditions; cultivation and management levels directly affect the growth and development of trees as well as the accumulation of nutrients and functional substances in trees (Gunduz and Saracoglu, 2012).

Quantitative differences in the antioxidant capacity were found among the thirteen tested plum accessions at the ripening stages. Antioxidant methods were divided into two main measurement methods: methods based on hydrogen atom transfer (HAT) and methods based on single electron transfer (SET). The DPPH radical (DPPH·) scavenging ability relies on a SET-based method, and the hydroxyl radical (·OH) radical scavenging ability and the superoxide anion radical ($\cdot O_2^-$) scavenging ability use a HAT-based method (Prior and Cao, 1999). DPPH· is centered on nitrogen, and is relatively stable. ·OH is more harmful due to its chemical activity, and almost all of the damage caused by oxidative stress is mediated by ·OH. Moreover, $\cdot O_2^-$ is produced in the largest amounts in living organisms, which can result in nucleic acid chain breaks in the nucleus and cytoplasm and can cause tumors, inflammation, aging, blood diseases and other pathological changes in the heart, liver, lungs and skin. At present, the uptake of these three free radicals is widely used to evaluate the antioxidant capacity of substances (Liu et al., 2011). In the present study, we also observed significant correlations among the ability to scavenge DPPH·, ·OH, and $\cdot O_2^-$ in the fruit extracts from different plum accessions. They had different DPPH·, ·OH, and $\cdot O_2^-$ scavenging abilities, this may have been related to the different components and contents of the flavonoids, total phenols, triterpenoid acids, and other functional components related to antioxidant activity in the fruits of the different plum accessions.

We also observed highly significant positive correlations between the reducing sugar and total sugar contents as well as the flavonoids and total phenolics. The ·OH scavenging ability was significantly correlated with the flavonoid content and total phenolic content, indicating that flavonoids, total phenolics, and other functional components play an extremely important role in the antioxidant activity of plum fruits, being the main antioxidant active components. Therefore, the antioxidant activity of plums can be improved by genetic manipulation to increase the phenolic content in plums. However, this may increase the astringency of the fruit and affect the fruit flavor (Prior et al., 1998). In addition, the correlation analysis results show that there was no significant correlation between the antioxidant activity and the triterpenoid acid content, revealing that triterpenoid acids may not be the key component of free radical scavenging in the extracts of plum fruits.

Cluster analysis and PCA have been used effectively in comprehensive quality evaluations and pedigree divisions (Huang et al., 2019a; Bejaei et al., 2020). In the present study, thirteen plum accessions were divided into three distinct categories by means of a cluster analysis. 'Friar plum (Pingdingshan)' was grouped into a category alone, which may be related to its climatic and environmental conditions, which differ from those of the other accessions. Meanwhile, PCA was used to simplify the fourteen indexes into three relatively independent dimensions, consistent with the classification of the phenotypic traits, nutrient components, functional components and antioxidant activity in this study. The quality differences of different varieties and the screening of certain characteristic factors were analyzed by the PCA method, which has been used on apricot (Ayour et al., 2021) and plum (Qiu et al., 2021). These results showed that using a combination of cluster analysis and PCA, plum accessions can be classified and analyzed comprehensively.

Conclusion

In the present study, we studied the external and internal fruit quality traits of thirteen Chinese plum accessions. The results indicated the high nutritional value, rich functional component contents, and strong antioxidant properties of Chinese plums, and significant correlations were detected among these traits. To obtain a more comprehensive understanding of Chinese plums, a larger collection of samples is necessary in a future study, and other important traits, such as the fruit setting rate, fruit anthocyanin and carotenoid contents, and resistance to biotic and abiotic stress, can be studied. Moreover, research on discovering the genetic factors underlying these traits is also needed.

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