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Evaluation of Morphological Characteristics, Antioxidants, and Volatile Compounds of Selected New Yellow-fleshed Peach Cultivars

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***Abstract.* To further improve the self-fruiting ability, storability, and enhance flavor quality of the yellow-fleshed peach cultivar Jinhuangjin (JHJ), the Jinhuangjin 2 (JHJ 2) and Jinhuangjin 8 (JHJ 8) cultivars were bred via crossbreeding and bud selection, respectively, and derived from the JHJ cultivar. In this study, the main growth stages, morphological characteristics, contents of total phenolics and total flavonoids of 'JHJ 2' and 'JHJ 8' were compared with those of the maternal cultivar JHJ, and an analysis of the volatile compounds of 'JHJ 2' and 'JHJ 8' were conducted. The JHJ 2 cultivar matured relatively late and the harvest period was delayed until early September. The morphological characteristics of the JHJ 2 cultivar significantly differed from those of JHJ and JHJ 8 cultivars in terms of flower color, flower type, stigma position compared with anther, self-pollination ability, and angle at the leaf apex. The JHJ 8 cultivar had smaller flowers and leaves but larger fruits compared with those of the JHJ and JHJ 2 cultivars. The pulp of the JHJ 8 cultivar contained the highest amount of flavonoid and phenolics concentrations. According to the principal component analysis (PCA) of data based on gas chromatography-mass spectrometry, the contents of volatile compounds were most abundant in pulp of the JHJ 2 cultivar and highlighted the distinctions of the breeding selection (JHJ 2 and JHJ 8 cultivars) from the maternal JHJ cultivar. The present study aimed to provide insights into the characteristics of the newly developed JHJ 2 and JHJ 8 cultivars as well as antioxidants and contents of volatile compounds. The results of this study offer insights for improving the later-maturing yellow-fleshed peach cultivar.**

Peach (*Prunus persica* L. Batsch), which belongs to the *Prunus* genus in the Rosaceae family, is the third most widely grown fruit crop (after apple and pear) in temperate regions in terms of economic and nutritional value, and it ranks after apple as the second most widely grown deciduous fruit tree in the world (Dana et al. 2021; Remorini et al. 2008). Peach was first originated and domesticated in China and subsequently spread to Europe, Africa, North America, and South America based on genomic and phenotypic evidence (Cao et al. 2014). Peaches have been cultivated in China for more than 4000 years (Aranzana et al. 2010). The peach also figures prominently in Chinese traditional culture because it represents longevity, romance, and sweetness (Layne and Bassi 2008).

In China, the vast wild relatives and landraces of peaches have higher genetic diversity and integrity compared to those in other countries. Peach landraces are classified into five major groups, including northern peach group, southern peach group, yellow-fleshed peach group, flat peach group, and nectarine group, according to the characteristics of fruit, such as fruit type and flavor (Li and Wang 2020). Native to China's northwest and southwest, the golden-fleshed peach (Wang and Zhuang 2001) is a major commercial crop. It provides dietary benefits and is eaten fresh or canned. It is rich in nutrients with a mellow fragrance, and it harbors resistance to fresh browning. The yellow-fleshed peach is highly nutritious with antioxidants, including lycopene, carotenoids, and vitamin C (Cantin et al. 2009; Versari et al. 2002). Because of its outstanding characteristics, the number of peach cultivars with yellow flesh has increased in recent years. At present, the peach industry is faced with multiple challenges, such as quality degradation, serious diseases, storage damage, transportation damage, and decline in the quality of flavor, that require effective measures that result in solutions (Liu et al. 2022; Saif et al. 2019; Ren et al. 2019). The breeding and cultivation of peach cultivars with three synergistic traits, aroma complexity, optimized nutrient profiles, and delayed postharvest deterioration, could promote the development of the local peach industry (Manganaris et al. 2022).

Selecting cultivars that are well-suited to the local climate and soil can not only enhance the quality of the fruit but also increase the profitability of peach farming. Crossbreeding is the most widely used breeding method for developing new plant cultivars (Shen et al. 2015; Yamamoto et al. 2003). Among breeding approaches for the peach, crossbreeding harbors a competitive edge over natural bud mutation, seedling selection, artificial induced mutation, and landrace selection. Approximately 43% to 61% of released cultivars of peach are derived from controlled crossbreeding (Infante et al. 2008). The utilization of crossbreeding generates cultivars that inherit the elite traits of the parents; in some cases, traits, such as yield, quality, adaptability, stress resistance, and growth potential, of the offspring are superior to those of hybrid parents (Meyer et al. 2004, 2007). Crossbreeding is also widely used for rice and maize, and the heterosis generated greatly improves the total grain output and ensures global food security (Cheng et al. 2007). Sprouting selection is achieved via the natural mutation of somatic cells and is a unique breeding approach for perennial clonal fruit trees. The advantages of this method include a short breeding cycle, crops with improved traits can be quickly obtained, and high genetic stability of improved traits, which are conducive to achieving the goal of selecting and breeding from the best (Chen et al. 2020). Bud mutagenesis produced by genetic alteration in the bud can provide germplasm resources for crossbreeding as well as aid the breeding of progeny with excellent properties. Two typical cases of fruit tree breeding through bud mutation are the Yuanshuai and Red Fuji apple cultivars (Chen et al. 2022). To further improve the self-fruiting ability of 'Jinhuangjin' ('JHJ') peach, enhance storability and flavor quality, the JHJ series of fresh peach cultivars were bred via crossbreeding and bud selection.

In recent years, the breeding of fresh edible yellow-fleshed peach is mainly concentrated in clingstone peach cultivar. Clingstone/freestone is controlled by a pair of alleles, and clingstone is dominant over freestone, leading to scarce freestone cultivars and strong domestic market demand. After 13 years of persistent breeding work by the research team of Fruit Production and Marketing Service Center of Yiyuan

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County in Shandong Province of China and the Agricultural Technology Extension Station of Dongli Town of China, the late-ripening cultivar JHJ was bred and was superior to the previous cultivar Huangjin Peach in terms of maturity, adaptability, and disease resistance. The strong purchase intent for this cultivar was driven by its commercial advantages such as large size (350 g per single gram), defect-free appearance, natural sweetness (16 to 18°Brix without additives), and endocarp lignification patterns enabling freestone formation. However, because of differences in the growth and development process between the stigma and stamen and the small size of the flower, artificial pollination is required. Additionally, some growers have difficulty mastering specific cultivation techniques, such as not using disease-resistant rootstocks, pH imbalance without lime amendment, and inadequate canopy pruning (light penetration <30%), and unscientific pruning practices for yellow peach trees will violate the tree's growth physiology, leading to reduced yield and fruit quality. To overcome these problems, the application of hybridization and bud mutation breeding using the JHJ cultivar as the maternal plant derived the generation of Jinhuangjin 2 (JHJ 2) and Jinhuangjin 8 (JHJ 8) cultivars. In this study, the most important morphological characteristics, contents of antioxidants, and volatile compounds of 'JHJ', 'JHJ 2', and 'JHJ 8' were analyzed and compared. Thus, the aim of the present study was to provide insights into the characteristics of the newly developed JHJ 2 and JHJ 8 cultivars.

Materials and Methods

Materials and experimentation site description. The experimental materials were JHJ, JHJ 2, and JHJ 8 cultivars. The JHJ cultivar was the offspring of 'Huangjin Peach'. The JHJ 2 cultivar was the crossbred offspring between the JHJ cultivar (the maternal plant) and Shuguang, Zhonghuashoutao, and Yuhualu cultivars (mixed pollen of the paternal plants). The JHJ 8 cultivar was a selection of bud mutation and a bud variant of the JHJ cultivar. The three peach cultivars of 5-year-old seedlings with an open-center tree structure were transplanted and grown in a 667-m^2 orchard with row spacing of 4 m × 3 m in 2017. Spacing zones were set up between the three test orchards. At the beginning of the bud germination period, weak branches and weak flowers were removed. Decomposed organic manure (15 to 20 kg/tree) and compound fertilizer (nitrogen:phosphorus:potassium = 1:0.5:1) were applied in late autumn. Soil moisture was maintained at 50% to 60% to enhance bud formation via drip irrigation. The winter pruning practice included removing branches older than 3 years, retaining three to four scaffold branches with 45° angles, and keeping six to eight fruits per 30-cm branch for optimal size. In the dormant season, lime sulfur is sprayed to sanitize orchards. The same standard and conventional managements were applied to all trees of all cultivars to ensure that the growth of trees was robust.

The study was conducted in Yiyuan County, Shandong Province, China (lat. 36.18°N, long. 118.17°E), from 2022 to 2023. The test site had a typical temperate and monsoonal climate with four distinct seasons. Average annual sunshine duration, temperature, and precipitation were 2592.7 h, 11.9 °C, and 690 mm, respectively. The soil of the test plot was clay, and the pH was 6.8. The site was equipped with irrigation facilities and a drainage well.

Observation of growth stage. During each growth stage in each plot during the two study years, the average duration of the first flowering phase (when the ratio of the number of opened flowers to the total flowers per branch reached 10%), initial fruit formation (when ovary began enlargement after anthesis), fruit maturation period (from initial fruit formation to final size stage), and all leaves fallen (when 90% of leaves had fallen) were evaluated. The growth stage of selected twigs was observed daily.

Evaluation of botanical characteristics. To evaluate the botanical characteristics of JHJ, JHJ 2, and JHJ 8 cultivars, various traits, including flower color, flower type, positions of the stigma and anther, self-pollination ability, gland phenotype, leaf shape, leaf margin, angle at the leaf base, angle at the apex, stone adherence to flesh, fruit shape, shape of the pistil end, flesh color, flesh texture, as well as stone shape, in each peach cultivar were measured directly on the field using peach descriptors developed by the International Union for the Protection of New Varieties of Plants [peach; *Prunus persica* (L.) Batsch] (UPOV 2021). To evaluate flower bud density, the thickness of flower branches, length of the flower branch internode, leaf length, leaf width, petiole length, number of leaf glands, fruit weight, and fruit firmness of JHJ, JHJ 2, and JHJ 8 cultivars, samples were chosen from a total of 20 trees for each cultivar each year from 2022 to 2023. Representative peach flower branch, mature leaf, or fruits per cultivar set in the middle and periphery of the tree crown were collected at the same time. Samples of the three cultivars in the same growth period were collected using the diagonal point sampling method (from the corner of the sampling area to another corner). All lines used for sampling were of the same distance. At each sampling point, typical peach trees with normal growth were selected as the sampling object. On each peach tree, the selection criteria was based on growth position and orientation of samples. The thickness of flower branches, length of flower branch internode, leaf length, leaf width, and petiole length were measured using 0.01-mm vernier calipers (Mitutoyo, Kawasaki-shi, Kanagawa-ken, Japan). The average fruit weight was determined using a 0.01-g electronic balance (Qianju, Jinhua, Zhejiang, China), and the flesh firmness of each fruit was determined using a hardness tester (Aliyiqi, Leqing, Zhejiang, China).

Determination of total phenolics and total flavonoids contents. The total phenolics and total flavonoids contents were extracted according to the modified methods described by Liu et al. (2015) and Zhou et al. (2020), respectively. Each sample was measured in triplicate. The total phenolics content was determined using the Foline-Ciocalteu method with some modifications. Then, 0.1 g of fresh yellow peach pulp was weighed and placed in a centrifuge tube with 1 mL of water added for homogenization. Then, the mixture was subjected to a boiling water bath for 30 min; after cooling, it was centrifuged at 8000 rpm for 10 min, and the subsequent 5 mL supernatant was collected. Thereafter, 1 mL of the sample to be tested was taken, 5 mL of Folin-Ciocalteu reagent was added, and the mixture was stirred well. Subsequently, 4 mL of 7.5% sodium carbonate solution was added, mixed well, and allowed to stand for 30 min. The absorbance was measured at a wavelength of 765 nm. The content of total phenolic compounds in the sample was calculated based on the standard curve. Based on the standard curve and absorbance value of the sample, the concentration of phenolic compounds in the sample was calculated. The results were expressed as the gallic acid equivalent (GAE) using the following unit: mg GAE/g fresh sample. The total flavonoids content was determined using a colorimetric method. Fresh yellow peach pulp (0.2 g) was accurately weighed and 3 mL of 60% ethanol was added. The mixture was heated in a water bath at 70 °C for 30 min, cooled, and centrifuged at 8000 rpm for 10 min; subsequently, 5 mL of supernatant was collected. Rutin was chosen as the standard, and the results were expressed as mg rutin equivalents with the following unit: mg RE/g fresh sample.

Gas chromatography-mass spectrometry analysis of volatiles. Headspace solid-phase microextraction and gas chromatography-mass spectrometry (model GCMS-QP2020NX; Shimadzu, Nakagyo-ku, Kyoto, Japan) were performed to extract and resolve volatile compounds of peach fruits (Rawat et al. 2007). Acquired mass spectra were compared with spectra in the National Institute of Standards and Technology Library (NIST17-1, NIST17-2, and NIST17-S), and the relative contents of the identified compounds were confirmed by dividing individual peak areas by the total peak area. Each sample was measured in triplicate. The 65-μm divinylbenzene/polydimethylsiloxane fibers were previously conditioned at 250 °C for 30 min. The collected peach flesh was quickly cut into pieces with a volume of 0.2 × 0.2 × 0.2 cm, 5.0 g of the mixed samples was placed in a 50-mL conical flask, and 3 μL of 2-Octanol at a concentration of 0.01644 $g \cdot L^{-1}$ as the internal standard was added. Then, the conical flask was placed in a magnetic force rotor and sealed with tin foil. The temperature was set to 40 °C, followed by headspace solid-phase microextraction sampling for 30 min. Then, the extraction head was inserted in the gas chromatography-mass

Table 1. Time of the first flowering phase, initial fruit formation and maturation period, and leaf falling of JHJ, JHJ 2, and JHJ 8 cultivars.

Cultivar	First flowering phase	Initial fruit formation	Fruit maturation period	Time of leave fallen
JHJ	1 to 7 Apr	1 Aug	130 d	1 Nov
JHJ 2	1 to 7 Apr	10 Aug	140 d	1 Nov
JHJ 8	1 to 7 Apr	20 Jul	120 d	1 Nov

spectrometry sample inlet for analysis with a desorption time of 5 min. The relative content (%) of each volatile compound in peach fruit was determined by peak area normalization using the following formula:

$$\text{Relative content} = (Ai/\Sigma A) \times 100;$$

where Ai represents the peak area of an individual compound and ΣA denotes the total peak area of all detected volatiles.

Statistical analysis. SPSS (IBM SPSS Statistics version 23.0; IBM Corp., Armonk, NY, USA) was used to compare means and conduct a one-way analysis of variance (ANOVA). An ANOVA and Duncan's multiple range test ($P < 0.05$) were conducted to analyze the significant differences among cultivars. A principal component analysis (PCA) was performed using SIMCA software (SIMCA Multivariate Data Analysis version 14.1; Sartoriu Corp., Göttingen, Germany).

Results

Phenological traits. Phenology refers to the annual calendar of biological events in plants comprising reproductive growth such as flowering, fruit set, and the fruit ripening process including fruit expansion to maturity, which is essential for the establishment of the growth model to guide crop management and improve the efficacy of fruit production (Mounzer et al. 2008). The three cultivars exhibited negligible differences in flowering time synchronization when they reached 90% bloom. As shown in Table 1, initial time of flowering of three cultivars occurred in early April (1 Apr–7 Apr). The phenology differences of the three cultivars were mainly reflected in the fruit ripening stage. Fruit development was initiated from mid to late August for the JHJ 2 cultivar; however, the JHJ or JHJ 8 cultivar showed the phenological stage of fruit development at least 2 or 4 weeks early, respectively, leading to relative delays in picking fruits of the JHJ 2 cultivar until early September. The leaf falling times of the three cultivars were consistent in early November. The JHJ 2 cultivar provided a reference and germplasm resource for the breeding of very late-maturing yellow-fleshed peach cultivar.

The first flowering phase was when the ratio of the number of opened flowers to the total flowers per branch reached to 10%. Initial fruit formation was considered when the ovary began enlargement after anthesis. The fruit maturation period was from the initial fruit formation to the full size stage. All leaves fallen referred to when 90% of leaves had fallen.

Botanical characteristics. Botanical characteristics are an important means to clarify the differences among cultivars and have profound significance in terms of the optimization and improvement of peach cultivars. They aid in the promotion of the healthy development of the peach industry. Generally, variations in morphological traits were observed among the three cultivars. The JHJ cultivar had an open branching angle that differed from that of the JHJ 2 and JHJ 8 cultivars. The branch of the latter two cultivars opened at smaller angles and were classified as the semi-open type. However, all three cultivars demonstrated strong tree vitality. As shown in Fig. 1 and Table 2, the characteristics of the JHJ and JHJ 8 cultivars significantly differed from those of the JHJ 2 cultivar in terms of flower color, flower type, stigma position compared with anther, and self-pollination ability. The flower color of the JHJ 2 cultivar was light pink, and the flower type was rosette. The stigma position compared with the anther was at same level, ensuring pollination. The diameter of flower branches and length of the flower branch internode of the JHJ 8 cultivar were relatively smaller than those of the JHJ cultivar, resulting in lower flower bud density (Table 2).

All cultivars presented an elliptical leaf shape with a shallow serrate margin and dark green color (Fig. 2). As shown in Table 3, the largest leaf length and width were observed in the JHJ or JHJ 2 cultivars, respectively. The leaf petiole length ranged from 0.78 to 0.99 cm among the three cultivars, and the JHJ 2 cultivar had the longest leaf petiole length. The JHJ 8 cultivar had a relatively smaller leaf length, leaf width, and leaf petiole length. The leaf petiole length as a plastic trait is critical to enhancing light interception (Li et al. 2021) and determining planting density (Li et al. 2024). The leaf glands of the three cultivars had a reniform shape, and each cultivar had two leaf glands per leaf. Angles at the leaf apex and at the leaf base for each individual leaf showed tiny variations within three cultivars. The JHJ and JHJ 8 cultivars had a small angle at the leaf apex. However, the JHJ 2 cultivar had a medium

Fig. 1. Flower morphology of (**A**) JHJ, (**B**) JHJ 2, and (**C**) JHJ 8 cultivars.

Table 2. Flower morphological traits of JHJ, JHJ 2, and JHJ 8 cultivars.

Cultivar	Diameter of flower branches (mm)	Length of flower branch internode (cm)	Flower bud density (buds/m)	Flower color	Flower type	Stigma position compared with anther	Self-pollination ability
JHJ	5.00 ± 0.19 a	2.42 ± 0.11 a	50.23 ± 1.54 a	Purple pink	Campanulate	Above anther	Weak
JHJ 2	4.01 ± 0.16 b	2.30 ± 0.08 ab	40.15 ± 1.76 b	Light pink	Rosette	Same level	Strong
JHJ 8	4.37 ± 0.17 b	2.07 ± 0.06 b	42.10 ± 1.89 b	Purple pink	Campanulate	Above anther	Weak

Data are displayed as the mean ± standard deviation. Values within a column followed by different lowercase letters showed significant differences according to Duncan's multiple range test ($P < 0.05$).

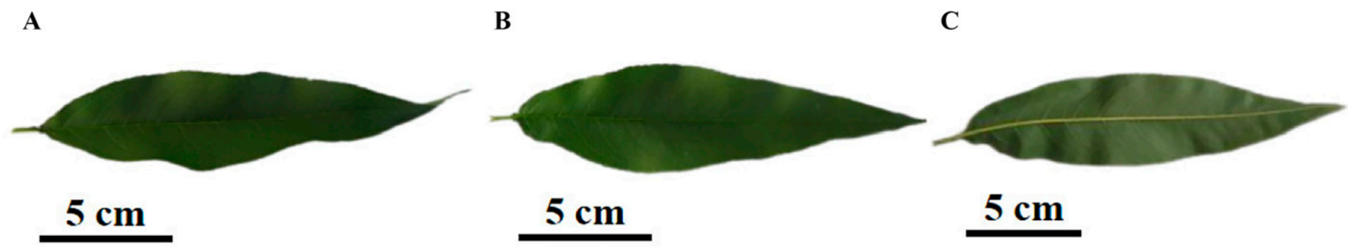

Fig. 2. Leaf morphology of (**A**) JHJ, (**B**) JHJ 2, and (**C**) JHJ 8 cultivars.

Table 3. Leaf morphological traits of JHJ, JHJ 2, and JHJ 8 cultivars.

Cultivar	Leaf length (cm)	Leaf width (cm)	Petiole length (cm)	No. of leaf glands	Leaf gland traits	Leaf shape	Leaf margin	Angle at the leaf base	Angle at the leaf apex
JHJ	16.87 ± 0.33 a	3.58 ± 0.07 ab	0.88 ± 0.02 b	2.0 ± 0.0 a	Reniform	Elliptical	Shallow serrate	Acute	Small
JHJ 2	15.76 ± 0.19 b	3.65 ± 0.06 a	0.99 ± 0.02 a	2.0 ± 0.0 a	Reniform	Elliptical	Shallow serrate	Acute	Medium
JHJ 8	15.96 ± 0.24 b	3.40 ± 0.06 b	0.78 ± 0.02 c	2.0 ± 0.0 a	Reniform	Elliptical	Shallow serrate	Acute	Small

Data are displayed as the mean ± standard deviation. Values within a column followed by different lowercase letters showed significant differences according to Duncan's multiple range test ($P < 0.05$).

angle at the leaf apex. The angle at the leaf base of the three cultivars was acute.

As shown in Fig. 3 and Table 4, fruits of three cultivars were all circular-type, belonged to the yellow-fleshed group, had a pointed fruit pistil end, and had moderate asymmetry. The weight of individual fruit ranged between approximately 220 g to 320 g among three cultivars, and the JHJ and JHJ 8 cultivars had relatively larger fruits. Additionally, the fruit of the JHJ 8 cultivar had more firmness, which correlated with its flesh texture. The flesh of the JHJ and JHJ 2 cultivars had a semi-solid texture, and the flesh of the JHJ 8 cultivar had a stony-hard texture. At physiological maturity, the flesh of melting fruit is soft and easily susceptible to physical injuries, thus reducing the value of the commodity, whereas flesh of stony-hard fruit remain firm even when fully ripe. Generally, these different behaviors are accompanied by the exhibition of a more pronounced aroma in melting flesh peaches than in stony-hard one (Zhang et al. 2024). Because of the high preservation quality of the stone-hard peach cultivar, its demand by the fresh and processing markets is expected to increase. These results provide valuable insights into cultivar selection, flavor optimization, and consumer preference.

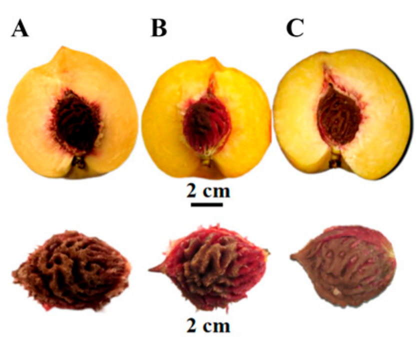

Fig. 3. Fruit longitudinal section (upper) and stone morphology (lower) of (**A**) JHJ, (**B**) JHJ 2, and (**C**) JHJ 8 cultivars.

Total flavonoid and total phenolic contents. The total antioxidant capacity of fruits varies depending on the content of natural antioxidants. Flavonoids, as an important class of plant pigments, are considered to be one of the most important bioactive compounds that restrain the formation and propagation of free radicals (Chen et al. 2020). Phenolics are compounds with an aromatic structure containing hydroxyl groups. In plants, phenolics are involved in maturation and physical changes of vegetable tissues via the activity of components that result in physical and chemical changes (Calado et al. 2015). The total phenolic and total flavonoid contents in pulp of the three peach cultivars were detected (Fig. 4). Among the three cultivars, the pulp of the JHJ 8 cultivar contained the highest concentration of these two antioxidants. The total flavonoid content in pulp of the JHJ 8 cultivar was 1.18-times and 1.19-times higher than that in the JHJ and JHJ 2 cultivars, respectively, and the total phenolic content was 1.43-times and 1.36-times higher than that of the JHJ and JHJ 2 cultivars, respectively (Fig. 4).

Contents of volatile compounds. Volatile compounds are important indicators of fruit quality and flavor. In this study, the data of contents of volatile compounds of pulp of three cultivars showed that approximately 99, 126, and 104 types of volatile components were detected in the JHJ, JHJ 2, and JHJ 8 cultivars, respectively, and the contents of volatile compounds were most abundant in the JHJ 2 cultivar (Fig. 5).

According to studies of the contents of volatile compounds of peaches, more than 100 volatiles have been identified in peach fruit; among these, aroma-related volatiles stimulate the appeal to consumers by influencing the intricate flavors of the fruits (Klee 2010). The volatiles, including lactones, esters, aldehydes, terpenes, alcohols, and ketones as aroma-active compounds, were significantly positively correlated with favor of customers (Wang et al. 2009; Xin et al. 2018).

The main contents of volatile compounds in the pulp of 'JHJ', 'JHJ 2', and 'JHJ 8' were detected and analyzed (Table 5). According to the data, volatile substances were categorized into five groups, including six esters, two alcohols, four aldehydes, eight alkanes, and three aromatic hydrocarbons. Seven volatile compounds were commonly identified in all cultivars, including ethyl acetate, (E)-3-hexen-1-ol acetate, (Z)-2-hexen-l-ol acetate, hexyl acetate, ethanol, (E)-2-hexenal, and fluorene.

The volatile compounds were mainly composed of esters, alcohols, and aldehydes. Esters are the main flavor components of most fruits that contribute to the aroma of ripe peaches. The cultivars JHJ, JHJ 2, and JHJ 8 differed in the types of ester compounds represented the fruity note they contained as shown in Table 5. The relative content of ethyl acetate in fruits of

Table 4. Fruit morphological traits of JHJ, JHJ 2, and JHJ 8 cultivars.

Cultivar	Mean fruit wt (g)	Fruit firmness ($kg \cdot cm^{-2}$)	Stone adherence to flesh	Fruit shape	Shape of the pistil end	Flesh color	Flesh texture	Stone shape
JHJ	319.4 ± 6.0 a	7.00 ± 0.06 b	Freestone	Circular type	Dominantly pointed	Yellow	Slow-melting	Ovate
JHJ 2	222.2 ± 4.4 b	7.08 ± 0.06 b	Freestone	Circular type	Pointed	Yellow	Slow-melting	Elliptic
JHJ 8	312.3 ± 6.2 a	8.16 ± 0.05 a	Freestone	Circular type	Flat	Yellow	Stony-hard	Elliptic

The data are displayed as the mean ± standard deviation. Values within a column followed by different lowercase letters show significant differences according to Duncan's multiple range test ($P < 0.05$).

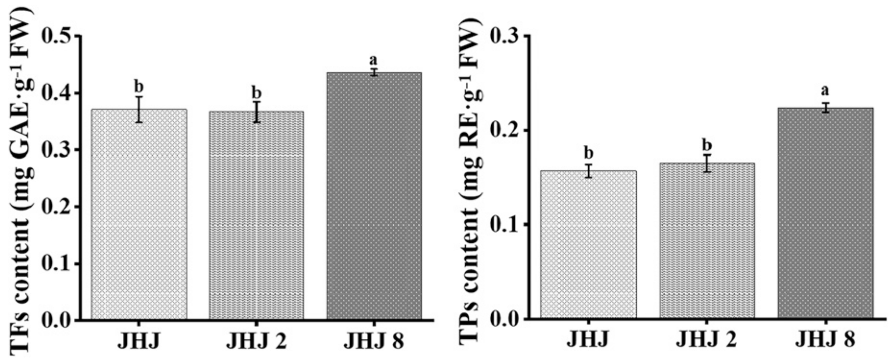

Fig. 4. Total flavonoid (TF) and total phenolic (TP) contents in the pulp of JHJ, JHJ 2, and JHJ 8 cultivars. The TF content was expressed as gallic acid equivalent (GAE; mg GAE/g fresh sample). The TP content was expressed as mg rutin equivalents (mg RE/g fresh sample). Different letters above bars indicate significant differences among cultivars according to Duncan's multiple range test ($P < 0.05$).

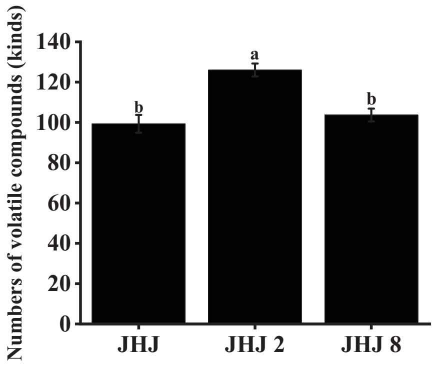

Fig. 5. Comparison of the contents of volatile compounds in the pulp of JHJ, JHJ 2, and JHJ 8 cultivars. Different letters above bars indicate significant differences among cultivars according to Duncan's multiple range test ($P < 0.05$).

'JHJ' and 'JHJ 2' was highest, and that of (E)-3-hexen-1-ol acetate was highest in 'JHJ 8'. The highest relative contents of esters among all samples were detected in 'JHJ 2', followed by 'JHJ' and 'JHJ 8'.

In this study, two alcohols, namely ethanol and 1-hexanol, were found. Among them, ethanol was detected in all cultivars at high levels. Aldehydes and alcohols are considered to represent the green and grassy notes in peach fruit, especially during the immature stage. In general, the contents of fruity note esters and lactones are positively correlated with fruit ripening, while the contents of grassy note aldehydes were opposite (Xin et al. 2018). The aldehydes detected in this study included benzaldehyde, hexanal, (E)-2-hexenal, and decanal. The cultivars JHJ, JHJ 2, and JHJ 8 differed in the types of aldehyde compounds they contained as shown in Table 5, and (E)-2-hexenal was a major component with the highest relative content detected in all cultivars.

Because of high odor thresholds, alkane volatiles probably contribute little to the aroma of peach (Pino and Quijano 2012). Previous literature showed that compounds of the alkane family represented herbaceous notes characteristic of fruits before reaching maturity (Chaudhary et al. 2018). For hexadecane, its concentration was negatively correlated with maturity of fruit (Padilla-Jiménez et al. 2021). The cultivars JHJ, JHJ 2, and JHJ 8 differed in the types of alkane compounds they contained as shown in Table 5.

Ethylbenzene was an aromatic hydrocarbon, and its presence introduced a subtle aromatic note to fruit (Xiao et al. 2024). Among the three samples, only 'JHJ 2' contains ethylbenzene.

Differences were observed in the total contents of volatile compounds among the three peach cultivars. Accordingly, the manifested contributions of individual compounds were related to the complex and diverse aroma characteristics of peach fruit.

Principal component analysis based on gas chromatography-mass spectrometry. The influence of volatile compounds on peach flavor was quantitatively assessed via the PCA of aroma-active constituents. The accumulative variance contribution rate of PC1 (17.11%) and PC2 (26.69%) was 43.8% (Fig. 6). The chart was divided into four quadrants: 'JHJ' was split throughout the second quadrant and 'JHJ 2' was split throughout the third and fourth quadrants. JHJ 8 split throughout first, second, and third quadrants had good aggregation with 'JHJ' and 'JHJ 2'. 'JHJ 2' was different from the other two cultivars, indicating that there were certain differences in the volatile compounds.

Discussion

Yellow-fleshed peach is an important peach germplasm resource. It has economically significant traits as well as unique flesh color, flavor, and taste. To enhance

Table 5. Relative contents of volatile compounds in the pulp of JHJ, JHJ 2, and JHJ 8 cultivars.

Classification	Name	Molecular formula	Relative content (%) JHJ	JHJ 2	JHJ 8
Ester	Ethyl acetate	$C_4H_8O_2$	256.62 ± 1.99 b	383.34 ± 11.83 a	95.81 ± 13.49 c
	(E)-3-hexen-1-ol, acetate	$C_8H_{14}O_2$	53.54 ± 7.75 c	96.13 ± 5.91 b	147.51 ± 6.44 a
	(Z)-2-hexen-l-ol, acetate	$C_8H_{14}O_2$	28.49 ± 4.50 b	54.88 ± 4.18 a	55.37 ± 5.62 a
	Hexyl acetate	$C_8H_{16}O_2$	17.98 ± 2.57 b	40.99 ± 5.84 a	31.23 ± 5.59 ab
	2,2,4-Trimethyl-1,3-pentanediol diisobutyrate	$C_{16}H_{30}O_4$	—	10.90 ± 0.78 a	—
	Phthalic acid, ethyl pentadecyl ester	$C_{25}H_{40}O_4$	—	23.82 ± 3.22 a	—
Alcohol	Ethanol	C_2H_5OH	64.92 ± 4.62 a	74.23 ± 3.88 a	82.96 ± 8.92 a
	1-Hexanol	$C_6H_{14}O$	—	10.12 ± 2.08 b	39.38 ± 5.26 a
Aldehyde	Benzaldehyde	C_7H_6O	—	10.67 ± 1.73 a	—
	Hexanal	$C_6H_{12}O$	—	—	22.08 ± 4.28 a
	(E)-2-Hexenal	$C_6H_{10}O$	23.58 ± 3.81 a	24.67 ± 5.55 a	35.20 ± 6.17 a
	Decanal	$C_{10}H_{20}O$	—	10.09 ± 1.02 a	—
Alkane	3,3-dimethyl-octane	$C_{10}H_{22}$	—	8.31 ± 0.34 a	—
	Decane	$C_{10}H_{22}$	—	14.84 ± 1.02 a	—
	2,6,10-Trimethyltridecane	$C_{16}H_{34}$	—	10.97 ± 0.98 a	11.76 ± 0.65 a
	Hexadecane	$C_{16}H_{34}$	47.03 ± 4.81 a	—	51.13 ± 1.79 a
	5,5-Diethylheptadecane	$C_{21}H_{44}$	—	10.42 ± 0.83 a	—
	Heneicosane	$C_{21}H_{44}$	60.30 ± 5.46 a	—	44.50 ± 25.88 a
	Eicosane	$C_{20}H_{42}$	—	—	64.49 ± 2.06 a
	Pentacosane	$C_{25}H_{52}$	21.79 ± 1.34 a	—	24.79 ± 0.84 a
Aromatic hydrocarbon	Ethylbenzene	C_8H_{10}	—	11.23 ± 0.90 a	—
	Fluorene	$C_{13}H_{10}$	12.56 ± 1.61 a	10.21 ± 2.53 a	12.86 ± 0.94 a
	Phenanthrene	$C_{14}H_{10}$	11.38 ± 1.22 a	—	13.03 ± 2.50 a

— indicates no detection or a trace amount. The data are displayed as the mean ± standard deviation. Values within a column followed by different lowercase letters show significant differences according to Duncan's multiple range test ($P < 0.05$).

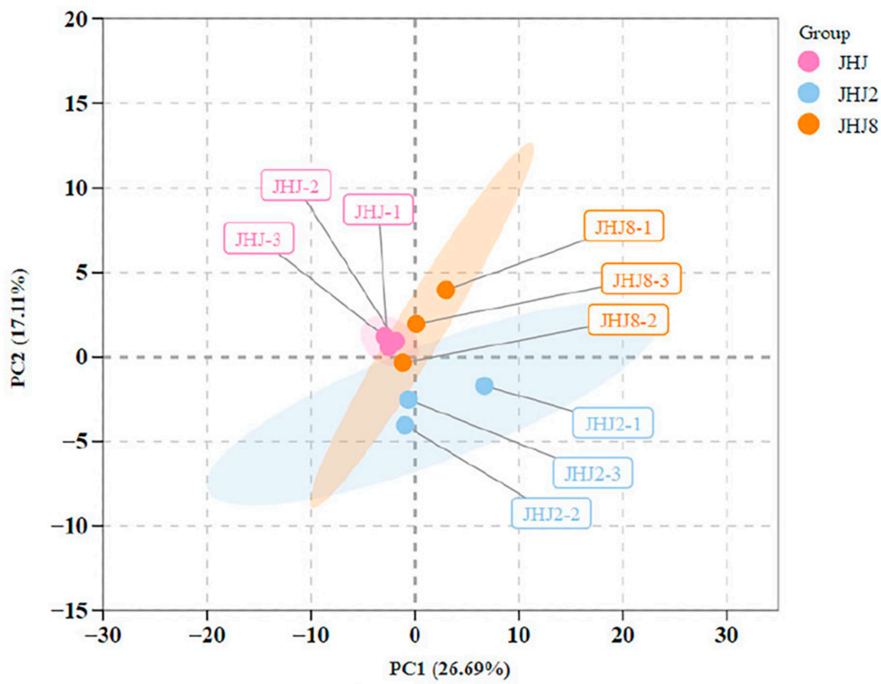

Fig. 6. Scatter plot of the principal component analysis (PCA) of JHJ, JHJ 2, and JHJ 8 cultivars.

yellow-fleshed peach production and promote the sustainable development of the local peach industry, new cultivars derived from 'JHJ' are expected to possess superior characteristics such as yellow flesh and freestone and exhibited enhanced fruit quality, storage and transportation resistance, disease resistance, and antioxidant capacity. The trait of stone adherence to the flesh of peach fruit is a quality trait controlled by one gene, and the freestone phenotype is the dominant trait (Liao et al. 2019; Meng et al. 2010). Peach fruit is a climacteric fruit that enables rapid reprogramming of metabolism at ripening, which is prone to softening and rotting after harvesting with low resistance to storage, resulting in major losses; therefore, there is an urgent need to address this problem.

In recent years, crossbreeding and bud mutation have been used to develop new cultivars. Among the new peach cultivars, the breeding proportion of cultivars produced by crossbreeding is approximately 43% to 61% (Eroğlu et al. 2016). The breeding work has progressed significantly by using 'JHJ' as the parental cultivar. In contrast to 'JHJ', the cross-bred cultivar JHJ 2 had a stronger self-pollination ability benefited by the same stigma and anther levels (Table 2) and abundant pollen, which provided a labor-saving cultivation mode with omitted the artificial pollination procedure. Moreover, there were certain differences in morphology traits of 'JHJ' and 'JHJ 2', such as flower color, flower type, as well as leaf angle at the base and apex, whereas the morphological difference between 'JHJ' and 'JHJ 8' was less marked (Table 2 and Table 3). In addition, the fruit maturation periods of the three cultivars were clearly distinguished from the middle of August to early September and lasted 120 to 140 d (Table 1), which was beneficial to the rational planning of the planting layout and prolonging the fruit market time. Hybrid breeding and bud mutation are effective approaches for breeding new peach cultivars and promoting the sustainable development of the peach industry. Currently, the majority of peach cultivars with excellent storage capacity are late-maturing types; early-maturing and mid-maturing cultivars with hard flesh are lacking. The urgency to develop novel cultivars by combining large fruit size (≥250 g) and high soluble solids (≥14°Brix) is critical to competitiveness in the early-season peach market. Hence, there is urgency to breed novel cultivars with large fruit size and excellent flavors to meet the demands of the early-maturity to mid-maturity market. The fruit of 'JHJ 8' had the highest firmness (up to 8.16 kg·cm^{-2}) ($P < 0.05$) and a stony-hard texture. The unique traits of 'JHJ 8' fruits provided this cultivar with higher storage tolerance than that of the other two, thus overcoming the shortcomings associated with the vulnerability of peaches during harvest and transporting after maturity.

Fruits are a key component of the human diet and a major source of antioxidant compounds (Balasundram et al. 2006; Zhu and Xiao 2019). In addition to sugar, vitamins, carotenoids, and other nutrients, fresh peaches are rich in phenolic compounds, which provide various health benefits (Stojanovic et al. 2016). Several studies have shown that phenolic compounds have a high antioxidant capacity, inhibit or reduce the damage caused by free radicals to cells, reduce risks of chronic diseases, and prevent cancer and aging in humans (Liu et al. 2018). Phenolics and flavonoids are secondary metabolites in plants (Lima et al. 2013). The contents of total phenolic and flavonoid were most abundant in 'JHJ 8' ($P < 0.05$) (Fig. 4). It was speculated that bud mutation enhanced the antioxidant capacity to some extent. Hybrid breeding and bud mutation could be used to enhance the quality of fruits, increase the content of antioxidant compounds, improve the genetic stability of trees, and increase the yield and efficiency of new peach cultivars.

Volatile components confer important sensory qualities to peach fruit and can affect consumer preferences for peach fruit. More than 190 types of volatile components have been identified in peach fruits, including alcohols and aldehydes, which represented a grassy aroma, and esters and lactones, which represented fruity aroma (Wang et al. 2009). These compounds exist around or inside the fruit and form a unique aroma for each cultivar. Approximately 99, 126, and 104 types of volatile components were detected in the pulp of 'JHJ', 'JHJ 2', and 'JHJ 8', respectively, and the contents of volatile compounds were most abundant in the pulp of 'JHJ 2'. Despite being different cultivars, the characteristic aroma volatiles were relatively similar, and 'JHJ 2' slightly differed from the other two cultivars, which was revealed by the PCA (Fig. 6). The formation of volatile components in fruits of new cultivars is usually affected by the original cultivated cultivar (Wang et al. 2009). Volatile substances are a more effective and noninvasive physiological index for detecting the maturity of peach fruits, which can have implications for the postharvest transportation and shelf life of fruit. Studies of specific genetic and metabolic pathways of the aroma components in fruit will greatly aid efforts to improve fruit quality.

Conclusions

Germplasm mining and innovative utilization are of great significance to the revitalization of the fruit tree industry. Hybrid breeding and bud mutation were used to generate JHJ 2 and JHJ 8, respectively, from JHJ. The 'JHJ 2' cultivar is a very late-maturing cultivar. Based on production test data, 'JHJ 2' had a high seed-setting rate and large pollen amount and 'JHJ 8' was favored by merchants because of increased fruit firmness and resistance to storage resulting from the differing morphological characteristics (especially the differences in flower and fruit traits). Yellow-fleshed peach fruit belongs to the respiratory climacteric type, and combining measures, including the application of elite cultivars with different maturation periods, ecological layout, and logistics preservation, is necessary to enhance annual productivity and realize breeding value. The results of the present study provide insights into the characteristics of the newly created JHJ 2 and JHJ 8 cultivars, as well as antioxidants and the contents of volatile compounds; additionally, it offers insights to allow improvement of the later-maturing yellow-fleshed peach cultivar.

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