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The Effect of Postharvest Storage Temperatures on Fruit Flavor Constituents in 'Wushancuili' Plum

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Abstract: Chinese plum (*Prunus salicina*) cv. Wushancuili has a green coloration, high fruit quality, and is economically important in eliminating poverty and protecting ecology in the Yangtze River Three Gorges Reservoir. However, large-scale production and synchronous ripening times present a huge postharvest storage challenge. This study investigated the effect of different postharvest storage temperatures on the 'Wushancuili' plum fruit flavor. The dynamics of soluble sugars, organic acids, and aroma substances were investigated at four temperatures mimicking large-scale commercial storage applications: 0–2 °C, 4–6 °C, 8–10 °C, and 20 °C, for 0, 3, 5, 7, 10, 15, and 20 days. Storage under the 0–2 °C regime was the best at preserving fruit flavor and reducing decay compared to the other settings. At 0–2 °C, fruit maintained a stable level of soluble sugars and organic acids during storage. Moreover, this storage temperature facilitated the formation of aroma compounds such as alcohols, aldehydes, ketones, and acids, which contributed to the distinct fruit aromatic characteristics. Taken together, our findings indicate that 0–2 °C is the most favorable temperature for commercial storage and maintenance of the 'Wushancuili' plum flavor.

Keywords: Chinese plum; storage temperature; soluble sugars; organic acids; aromatic compounds

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1. Introduction

Chinese plum (*Prunus salicina* Lindl) belongs to the Rosaceae family and is a typical stone fruit. It is rich in carbohydrates (such as sucrose, glucose, and fructose), organic acids, fats, proteins, dietary fiber, minerals, and vitamins [1] and can be used as fresh food or made into dried fruit or jam [2]. Chinese plum has a broad geographical distribution in China, with more than 1000 indigenous cultivars, such as 'Qingcuili' in Chongqing. 'Wushancuili' has been selected from a bud sport of 'Qingcuili' and produces fruit with better size, shape, quality, and yield. These advantages have driven the rapid development of the plum industry, and 'Wushancuili' has become the number one cultivar in Chongqing [3]. By 2022, the cultivation area of Chinese plum reached 95,800 hm^2, and the production was about 0.87 million tons. Now, the 'Wushancuili' industry plays a vital role in eliminating poverty and protecting ecology in the Three Gorges Reservoir of the Yangtze River [4]. However, the ripening time of 'Wushancuili' and other mutations of the 'Qingcuili' group is restricted to mid-summer. Nearly 0.5 million tons of plums are harvested in early July, which presents huge market pressure. Thus, urgent scientific guidance is required so that the harvested fruit can be stored under conditions that maintain quality, prevent deterioration, and extend their shelf life.

The profiles of soluble sugars, organic acids, and aroma substances are the major indexes for fruit flavor. In fresh fruit, the soluble sugars, including sucrose, fructose, and glucose, are central to fruit quality because of their nutritional value and sweetness. Sugar profiles and their balance with organic acids determine the taste and flavor of fruit [5]. Citric acid and malic acid are the primary organic acids found in most fruits [6].

Organic acids accumulate during the early stage of fruit development and then participate in the processes of glycolysis, tricarboxylic acid, and gluconeogenesis, leading to a gradual decrease in the fruit's sour taste [7]. Fruit aroma substances consist of volatile compounds with distinct functions and structures, produced through primary and secondary metabolism. A total of 35 aroma compounds have been identified in Japanese plums [8], 216 in pears [9], and 350 in strawberries [10]. These compounds possess high sensory and physiological value and contribute to the fruit's flavor, maturity, and commodity value. Thus, fruit aroma serves as a crucial indicator for selection by consumers [11]. In addition, it has been demonstrated that fruit aroma compounds are also involved in the regulation the resistance to senescence and biotic and abiotic stress [12]. To date, over 2000 types of aroma substances have been identified in flowers, leaves, roots, and fruits [13].

At room temperature (20 °C) or higher, the fruit deteriorates and decays rapidly during postharvest storage. Low temperatures have been demonstrated as an efficient way to inhibit the deterioration of fruit quality and extend the storage life of flesh fruit, including Chinese plum [14,15]. For example, Hao et al. [16] found that a storage temperature of around 0 °C could delay the postharvest senescence process of 'Guofeng No. 7' plum and alleviate fruit decay. However, no studies have analyzed the effect of postharvest temperatures on the dynamics of the flavor quality of Chinese plums during storage. Moreover, given the difference in geographical distribution and cultivation (or domestication) history, the postharvest storage method of 'Wushancuili' needs to be determined experimentally. In this study, we comprehensively analyzed the effect of large-scale applications of different postharvest storage temperatures for 'Wushancuili' plum fruit on changes in soluble sugars, organic acids, and aroma substances. Our results will be beneficial to scientifically guide the 'Wushancuili' postharvest storage industry.

2. Materials and Methods

2.1. Materials and Storage Treatment

'Wushancuili' fruits were collected from the orchard in Quanfa village of Wushan, Chongqing (31°021588 N, 109°731516 E), harvested at commercial maturity, and immediately transported to the storage room. Fruits with a uniform size and without visible disease or damage were selected on day 0. To mimic large-scale applications, all fruits were rapidly precooled to storage temperature (i.e., 1 °C, 5 °C, 9 °C, and 20 °C) using the ice water system (about 30 min). When the temperature of the fruit cores reached the setting temperature, we utilized gauze and a fan in the storage room to facilitate the drying of surface water adhered to the fruit at room temperature before storage, and then stored it in a refrigeration house (BD/BC-568DKEM). The temperature of the refrigeration house used in industrial storage fluctuated by ± 1 °C, below the set temperature of 10 °C. Therefore, the storage temperatures were considered as 0–2 °C, 4–6 °C, 8–10 °C, and 20 °C, respectively. The humidity of storage was controlled at 85% for these four treatments. Three biological replicates for each treatment were used, and each replication included at least 1000 fruits. Samples were collected on days 0, 3, 5, 7, 10, 15, and 20, and 20 fruits were randomly selected from each replication. The surrounding tissue around the middle of the fruit (including skin and flesh) was collected and mixed after removing the pits. These slices were immediately frozen in liquid nitrogen and stored at −80 °C.

2.2. High-Performance Liquid Chromatography (HPLC)

The extraction and determination of soluble sugars and organic acids were according to Komatsu's (1999) method [17], with some modifications. In brief, samples were ground into a fine powder with liquid nitrogen. A total of 100 mg of the powder was homogenized in 1.0 mL of 80% ethanol at 35 °C for 20 min, followed by centrifugation (10,000 rpm, 20 °C, 15 min). Then, the supernatant was transferred to a new tube, and the pelleted sediment was extracted twice more with 1.0 mL of 80% ethanol. These supernatants were mixed and dried under vacuum at 45 °C (Eppendorf Concentrate Plus, Hamburg, Germany). The dried extracts were resuspended in 500 μL of nanopore water. After being passed

through a 0.22 μm syringe filter, a 10 μL aliquot of the supernatant was analyzed using the HPLC system.

The HPLC system used for analyzing soluble sugars was equipped with a Shimadzu column (4.6 mm × 250 mm) and a Waters Differential Refractive Index Detector employing nitrogen as the carrier gas (Waters, Milford, MA, USA). The mobile phase consisted of a 0.5 μm NH_2 column and acetonitrile/water (80:20, *v*:*v*). The column temperature was kept at 40 °C, and the flow rate of solvent was 1.2 mL·min^{-1}. The flow rate of gas was set at 40 P, and the drift tube was maintained at 65 °C. The determination of organic acids was conducted on an ODS column (0.5 μm particle size, 4.6 mm × 250 mm; YMC, Wilmington, NC, USA) and a Waters 2996 PDA detector with a wavelength of 210 nm. The mobile phase was 50 mM $(NH_4)_2HPO_4$ solution (pH = 2.7, adjusted by H_2PO_3). The flow rate was set at 0.5 mL·min^{-1}, and the column temperature was 25 °C.

Both soluble sugars and organic acids were quantified by comparing the peak area against the standard curve, and their concentration was expressed in mg g^{-1} FW (fresh weight). Total soluble sugars = fructose + glucose + sucrose; total organic acids = oxalic acid + tartaric acid + quinic acid + malic acid + citric acid.

2.3. Headspace Solid Phase Microextraction Gas Chromatography Mass Spectrometry (HS-SPME GC–MS)

HS-SPME was used to extract fruit aroma substances, using the specific method referred to by Deng Rui et al. [18]. The frozen samples were ground into a fine powder. A total of 6.0 g of the powder was transferred into a 50 mL glass vial, and 3.0 g sodium sulfate and 10 μL of internal standard 3-nononone (0.04 mg/mL) were added. Then, the vial was immediately sealed and gently vortexed.

Volatile analysis was performed using gas chromatography–mass spectrometry equipment (GC-MSQP-2010) equipped with an Rtx-1MS chromatographic column (30 mm × 0.25 mm × 0.25 μm). The temperature program was started at 35 °C for 2 min, increased to 120 °C, and held for 1 min. The temperature was increased to 180 °C at 10 °C min^{-1} and then to 230 °C at a rate of 20 °C min^{-1}. This temperature was maintained for 5 min, with no split injection. Helium was used as the carrier gas with a flow rate of 1.03 mL·min^{-1} and the mass spectra (electron impact, 70 eV; ion source temperature, 200 °C; scan range, 45–450 amu). Volatile compounds were identified using the NIST library (NIST05). The relative mass percentage of each component was calculated using the peak area normalization method, and 3-nononone served as the internal standard for quantification.

2.4. Statistical Analysis

All data are expressed as the mean ± standard deviation of three biological replicates. The least significant difference test (LSD) at a significance level of 0.05 was analyzed by SPSS 18.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Changes in Soluble Sugar Content during Storage at Different Temperatures

At 20 °C, the fruit decay rate reached about 30% on day 10, by which time the fruits had lost their commercial value. Thus, samples were unavailable after day 10 for the 20 °C storage treatment [19]. Three soluble sugars, sucrose, glucose, and fructose, were analyzed (Figure 1). The change in total soluble sugars was similar to glucose. Moreover, the highest dynamic was reflected in sucrose content, and the highest value was observed at the time point of fruit decay (Figure 1). These results indicated that glucose was the major soluble sugar, and the highest fluctuation was harbored by sucrose during postharvest storage.

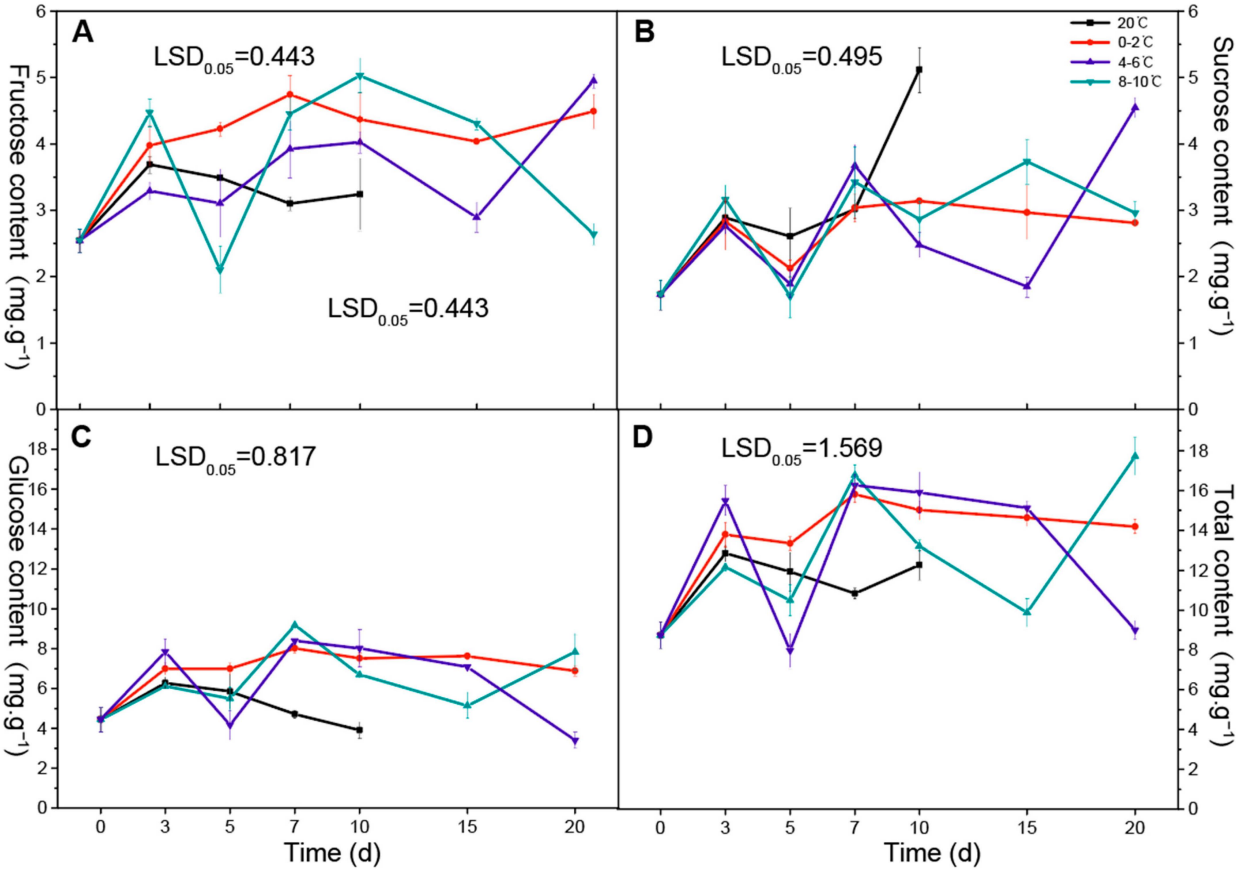

Figure 1. Effects of different storage temperatures on the content of fructose (**A**), sucrose (**B**), glucose (**C**), and total sugars (**D**) during storage. Error bars indicate the mean ± SD of three independent replicates. LSD: least significant difference ($p < 0.05$).

At 20 °C, the levels of both fructose and glucose initially increased, followed by a subsequent decrease, while sucrose exhibited an overall increasing trend in content. In contrast, at 0–2 °C, these three types of soluble sugars showed a slight increase in content and then remained relatively stable thereafter. However, the levels of soluble sugars at both 4–6 °C and 8–10 °C fluctuated greatly relative to those at 0–2 °C (Figure 1A–C). Notably, a higher level of sugars was exhibited in the 0–2 °C samples relative to 20 °C. This change was consistent with the suggestion that a low temperature could induce soluble sugar accumulation. These results indicated that 0–2 °C is the most favorable storage temperature to maintain soluble sugars in stored 'Wushancuili' fruit.

3.2. Changes in Organic Acid Content during Storage at Different Temperatures

In total, five organic acids, (citric, oxalic, tartaric, malic, and quinic acids) were identified in the stored plums. Quinic acid and malic acid were the major organic acids, and their dynamics were also reflected by the total organic acids (Figure 2). By contrast, the remaining three were only present at trace levels during storage. Even so, the tartaric acid exhibited a high level on day 0. The changes in the levels of the different organic acids varied. Oxalic acid was maintained at a relatively stable level, but there was a gradual increase in the first 10 days of 8–10 °C storage. Tartaric acid from all storage treatments showed a uniform change in levels, beginning with a rapid decline from days 0 to 3 and then remaining at a stable level. However, citric acid was characterized by an irregular change in level. Thus, we then focused on the effect of storage temperature on the level change in quinic acid and malic acid.

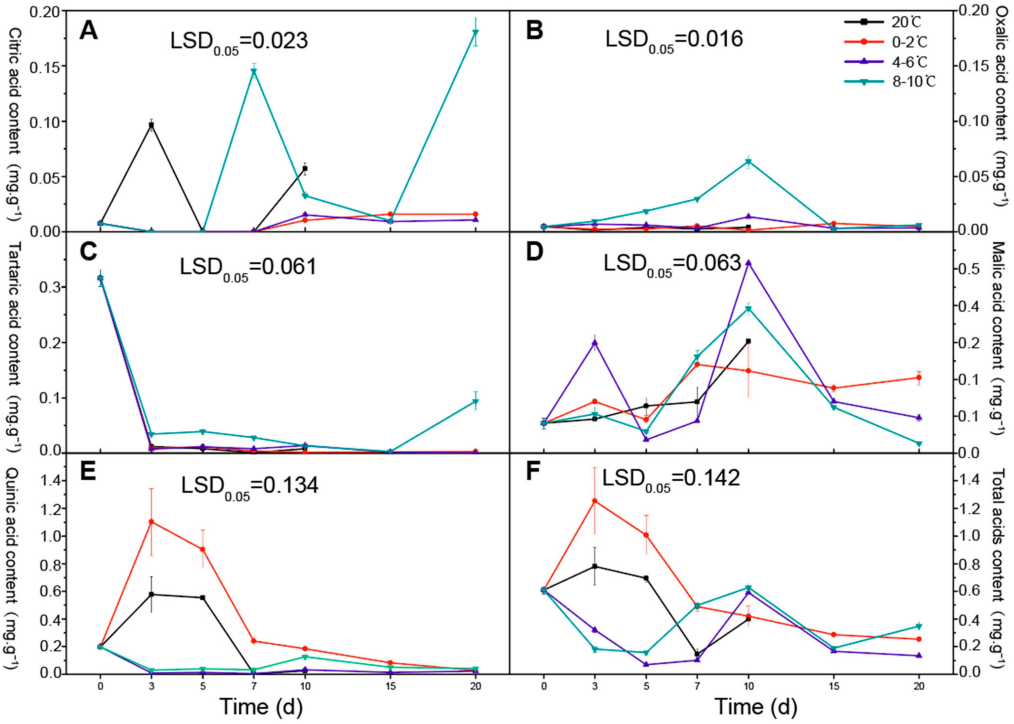

Figure 2. Effects of different storage temperatures on the content of citric acid (**A**), oxalic acid (**B**), tartaric acid (**C**), malic acid (**D**), quinic acid (**E**), and total acids (**F**) during storage. Error bars indicate the means ± SD of three independent replicates. LSD: least significant difference ($p < 0.05$).

Plums stored at 20 °C exhibited a consistent increase in malate content over time, whereas the malic acid levels fluctuated significantly in fruits subjected to both 4–6 °C and 8–10 °C treatments during storage. In contrast, the 0–2 °C treatment resulted in a slight increase in malate levels, followed by maintenance at a relatively stable level. Quinic acid, on the other hand, exhibited an initial increase on day 3, followed by a subsequent decrease to undetectable levels after storage at 20 °C. A similar but slower trend was identified in the 0–2 °C treatment. However, at 4–6 °C and 8–10 °C, quinic acid rapidly decreased on day 3 and then remained at a trace level. Considering the importance of organic acids and their ratio to sugars in determining fruit quality, it was concluded that the 0–2 °C storage temperature is most conducive to maintaining organic acids and taste for 'Wushancuili' fruit.

3.3. Aroma Components Characterized in 'Wushancuili' Fruit during Storage at Different Temperatures

The volatile aroma compounds of 'Wushancuili' samples were analyzed by HS–SPME–GC–MS system. A total of 30 aroma compounds, including 4 alcohols, 10 aldehydes, 4 esters, 4 acids, 3 ketones, 1 alkane, 1 aromatic compound, 2 terpenes, and 1 heterocyclic compound, were identified in all samples of 'Wushancuili' during storage at different temperatures (Table 1). Of these, 2-butanone, 4-(2,6,6-trimethyl-1-cyclohexen-1-yl) was present in plums stored at temperatures of 0–2 °C and 4–6 °C but was not detected in plums stored at temperatures of 8–10 °C and 20 °C. Conversely, the compounds α-terpineol and hexanoic acid were identified in plums stored at temperatures of 8–10 °C and 20 °C but not in those stored at temperatures of 0–2 °C and 4–6 °C. These findings indicated that low-temperature treatment (0–2 °C or 4–6 °C) can lead to the formation of new aroma compounds while inhibiting the production of certain other aroma compounds.

Table 1. Fruit aroma substance composition and content during storage. Values are mean ± SD (n =3). Values of each compound under all temperatures during the storage not followed by the same letter are significantly different based on two-way ANOVA ($p < 0.05$). "-" Not detected. The main factors are storage temperature (T) and storage time (D), as well as the interaction between these two factors (T × D). ns, no significance; *, $p < 0.05$; **, $p < 0.01$.

Category	Compound	Aroma Character	Temperature Treatment (°C)	0 d	3 d	5 d	7 d	10 d	15 d	20 d	Significances		
											T	D	T × D
Alcohols	1-Octanol	Pungent aroma	0–2	0.24 ± 0.35 a	0.77 ± 0.38 a	0.55 ± 0.16 a	0.15 ± 0.70 ab	0.13 ± 0.11 b	0.15 ± 0.61 ab	-	ns	ns	*
			4–6		0.32 ± 0.31 ab	0.14 ± 0.88 ab	0.49 ± 0.14 ab	0.42 ± 0.25 ab	0.15 ± 0.22 b	-			
			8–10		0.36 ± 0.15 ab	0.67 ± 0.12 a	0.14 ± 0.14 b	0.74 ± 0.44 ab	0.15 ± 0.32 ab	0.65 ± 0.76 ab			
			20		0.38 ± 0.82 ab	0.12 ± 0.26 b	0.19 ± 0.16 b	0.15 ± 0.28 ab	-	-			
	α-terpineol	Lilac aroma	0–2	-	-	-	-	-	-	-	-	-	-
			4–6		-	-	-	-	-	-			
			8–10		-	-	-	-	0.18 ± 0.22 a	-			
			20		-	0.24 ± 0.26 a	0.15 ± 0.99 a	0.75 ± 0.92 a	-	-			
	(E)-2-Hexen-1-ol	Faint scent	0–2	5.81 ± 0.19 a	14.27 ± 6.87 a	2.13 ± 0.58 c	4.42 ± 0.54 b	24.48 ± 19.42 a	2.99 ± 0.43 bc	5.27 ± 0.85 a	ns	ns	*
			4–6		2.23 ± 0.19 c	2.37 ± 0.16 c	2.81 ± 0.29 c	5.15 ± 2.75 abc	3.22 ± 0.36 abc	3.14 ± 0.39 bc			
			8–10		4.29 ± 0.52 b	4.55 ± 0.42 a	2.13 ± 0.27 c	6.52 ± 3.70 abc	4.86 ± 0.68 ab	2.89 ± 0.46 bc			
			20		2.39 ± 0.75 c	3.87 ± 0.32 b	5.39 ± 0.91 a	6.50 ± 0.79 abc	-	-			
	(E)-3-Hexen-1-ol	Faint scent	0–2	0.48 ± 0.17 c	1.26 ± 0.48 ab	-	0.22 ± 0.24 cd	0.57 ± 0.24 bc	-	1.17 ± 0.13 a	ns	ns	*
			4–6		0.13 ± 0.14 d	0.76 ± 0.14 b	0.42 ± 0.43 bcd	2.59 ± 1.53 a	0.32 ± 0.73 abcd	0.28 ± 0.12 cd			
			8–10		0.17 ± 0.24 cd	0.86 ± 0.16 b	0.68 ± 0.13 bc	0.17 ± 0.28 cd	0.37 ± 0.24 cd	0.47 ± 0.25 bcd			
			20		0.39 ± 0.91 abcd	0.40 ± 0.81 abcd	0.42 ± 0.44 bcd	-	-	-			
Aldehydes	Furfural	Bitter almond aroma	0–2	-	0.17 ± 0.80 bc	0.26 ± 0.25 c	0.28 ± 0.84 c	0.18 ± 0.18 c	0.46 ± 0.49 c	1.16 ± 0.17 c	*	ns	*
			4–6		0.56 ± 0.80 c	-	0.14 ± 0.16 c	-	-	2.69 ± 0.32 a			
			8–10		0.33 ± 0.34 c	1.92 ± 0.44 b	1.54 ± 0.20 bc	0.87 ± 0.38 c	0.54 ± 0.12 c	0.25 ± 023 c			
			20		0.90 ± 0.28 c	0.47 ± 0.82 c	0.57 ± 0.13 c	0.68 ± 0.32 c	-	-			
	Heptanal	Strong unpleasant fat odor	0–2	0.15 ± 0.12 d	0.62 ± 0.21 ab	0.19 ± 0.27 c	0.19 ± 0.27 d	0.37 ± 0.35 abcd	0.11 ± 0.13 d	0.58 ± 0.95 abcd	ns	ns	*
			4–6		0.70 ± 0.11 ab	0.68 ± 0.14 ab	0.49 ± 0.11 bc	0.18 ± 0.11 d	0.65 ± 0.97 abcd	-			
			8–10		0.40 ± 0.13 c	0.12 ± 0.20 d	0.12 ± 0.12 d	0.20 ± 0.11 d	0.64 ± 0.24 ab	0.97 ± 0.16 a			
			20		0.92 ± 0.20 a	0.74 ± 0.88 abcd	0.96 ± 0.16 ab	0.18 ± 0.54 d	-	-			
	Benzaldehyde	Almond aroma	0–2	0.48 ± 0.35 ab	2.66 ± 0.95 a	0.73 ± 0.56 ab	0.70 ± 0.17 a	3.72 ± 3.22 a	0.52 ± 0.29 ab	0.54 ± 0.76 ab	ns	ns	*
			4–6		0.34 ± 0.43 ab	0.20 ± 0.26 b	0.77 ± 0.25 a	0.54 ± 0.29 ab	1.86 ± 0.15 a	0.44 ± 0.24 ab			
			8–10		0.58 ± 0.73 ab	1.35 ± 0.27 a	1.81 ± 0.29 a	0.89 ± 0.57 ab	0.36 ± 0.44 ab	1.37 ± 0.46 a			
			20		0.53 ± 0.12 ab	0.17 ± 0.28 b	0.55 ± 0.45 ab	1.53 ± 0.39 a	-	-			
	Octanal	Strong fruity aroma	0–2	0.16 ± 0.12 c	0.22 ± 0.85 abc	0.95 ± 0.21 a	0.58 ± 0.73 abc	0.38 ± 0.35 abc	0.34 ± 0.22 bc	0.15 ± 0.28 bc	ns	ns	*
			4–6		0.57 ± 0.12 b	0.43 ± 0.67 abc	0.57 ± 0.82 abc	0.16 ± 0.71 abc	0.95 ± 0.22 a	0.17 ± 0.29 bc			
			8–10		0.14 ± 0.86 abc	0.56 ± 0.19 ab	0.75 ± 0.87 abc	-	-	-			
			20		-	-	-	-	-	-			
	Nonanal	Rose and citrus aromas; strong oily aroma	0–2	0.39 ± 0.75 a	1.13 ± 0.43 a	0.24 ± 0.90 a	0.31 ± 0.34 a	1.72 ± 1.58 a	0.16 ± 0.76 a	0.13 ± 0.13 a	ns	ns	ns
			4–6		0.17 ± 0.13 a	0.36 ± 0.25 a	0.73 ± 0.54 a	0.59 ± 0.36 a	0.15 ± 0.28 a	-			
			8–10		0.14 ± 0.17 a	0.38 ± 0.39 a	0.34 ± 0.44 a	0.49 ± 0.22 a	0.32 ± 0.66 a	0.38 ± 0.27 a			
			20		0.14 ± 0.30 a	0.15 ± 0.29 a	0.23 ± 0.49 a	0.51 ± 0.47 a	-	-			
	(E)-2-Nonenal	Cucumber fragrance	0–2	0.34 ± 0.42 ab	0.83 ± 0.37 a	0.57 ± 0.16 a	0.24 ± 0.57 ab	0.18 ± 0.94 ab	0.13 ± 0.16 b	-	ns	ns	*
			4–6		0.23 ± 0.39 ab	0.48 ± 0.41 ab	0.37 ± 0.68 ab	0.43 ± 0.23 ab	-	-			
			8–10		0.39 ± 0.59 ab	0.29 ± 0.19 ab	0.43 ± 0.57 ab	0.51 ± 0.31 ab	0.53 ± 0.66 ab	-			
			20		0.18 ± 0.53 ab	-	-	-	-	-			
	Decanal	Strong aldehyde aroma	0–2	0.51 ± 0.56 a	0.13 ± 0.53 a	0.83 ± 0.12 a	0.82 ± 0.28 a	0.22 ± 0.19 a	0.27 ± 0.35 a	0.19 ± 0.35 a	ns	ns	ns
			4–6		0.12 ± 0.17 a	0.13 ± 0.14 a	0.14 ± 0.22 a	0.19 ± 0.14 a	0.88 ± 0.19 a	-			
			8–10		0.14 ± 0.50 a	0.19 ± 0.23 a	0.17 ± 0.12 a	0.88 ± 0.63 a	0.26 ± 0.33 a	0.16 ± 0.12 a			
			20		0.15 ± 0.96 a	0.16 ± 0.29 a	0.10 ± 0.94 a	-	-	-			

Table 1. *Cont.*

Category	Compound	Aroma Character	Temperature Treatment (°C)	0 d	3 d	5 d	7 d	10 d	15 d	20 d	Significances		
											T	D	T × D
	1-Cyclohexene-1-carboxaldehyde, 2,6,6-trimethyl	Fruit and faint scent	0–2	0.18 ± 0.98 ab	0.30 ± 0.14 b	0.20 ± 0.59 a	0.13 ± 0.25 a	0.47 ± 0.38 ab	0.16 ± 0.47 b	0.76 ± 0.16 b	*	ns	*
			4–6		0.12 ± 0.13 b	0.13 ± 0.13 b	0.15 ± 0.32 a	0.34 ± 0.22 ab	0.19 ± 0.29 b	-			
			8–10		0.44 ± 0.35 b	1.17 ± 0.18 a	0.24 ± 0.32 a	0.25 ± 0.17 b	0.61 ± 0.25 b	0.19 ± 0.23 b			
			20		0.22 ± 0.29 b	0.38 ± 0.91 ab	0.43 ± 0.84 ab	0.32 ± 0.58 b	-	-			
	2-Hexenal	Fruit aroma and green leaf fragrance	0–2	2.71 ± 0.27 c	6.78 ± 2.49 b	2.74 ± 0.81 c	2.24 ± 0.41 c	2.74 ± 18.48 abcde	1.86 ± 0.19 c	6.78 ± 1.14 b	*	ns	**
			4–6		1.95 ± 0.15 c	1.88 ± 0.36 c	1.52 ± 0.15 c	3.14 ± 1.75 bc	1.99 ± 0.26 c	1.30 ± 0.14 d			
			8–10		4.61 ± 0.29 b	1.56 ± 0.66 cde	2.25 ± 0.40 c	4.62 ± 1.94 bc	15.27 ± 2.42 a	2.93 ± 0.23 c			
			20		1.84 ± 0.23 c	0.87 ± 0.15 e	2.00 ± 0.40 c	2.17 ± 0.54 b	-	-			
	(E,E)-2,4-hexadienal	Green plant scent	0–2	0.34 ± 0.67 ab	0.62 ± 0.25 a	0.18 ± 0.23 b	0.14 ± 0.44 b	0.69 ± 0.87 ab	0.19 ± 0.77 ab	0.62 ± 0.86 ab	*	ns	*
			4–6		0.84 ± 0.12 a	0.11 ± 0.12 b	0.14 ± 0.16 b	0.14 ± 0.67 ab	0.17 ± 0.33 b	0.60 ± 0.15 ab			
			8–10		0.18 ± 0.2 b	0.34 ± 0.11 b	0.99 ± 0.29 a	0.17 ± 0.12 b	0.17 ± 0.21 b	0.59 ± 0.79 ab			
			20		0.27 ± 0.66 ab	0.22 ± 0.60 ab	-	-	-	-			
Esters	cis-3-hexenyl acetate	Intense banana aroma	0–2	0.32 ± 0.56 ab	0.14 ± 0.42 b	0.33 ± 0.44 ab	0.46 ± 0.86 ab	0.41 ± 0.39 b	0.23 ± 0.50 a	0.56 ± 0.29 ab	ns	ns	*
			4–6		0.19 ± 0.37 ab	0.12 ± 0.30 b	0.20 ± 0.32 b	0.34 ± 0.18 b	0.12 ± 0.38 b	0.13 ± 0.13 b			
			8–10		0.31 ± 0.12 b	0.86 ± 0.11 a	0.81 ± 0.28 a	0.39 ± 0.28 ab	0.12 ± 0.15 b	0.49 ± 0.33 ab			
			20		0.47 ± 0.67 ab	0.23 ± 0.82 ab	0.84 ± 0.11 a	1.42 ± 0.34 a	-	-			
	Acetic acid, hexyl ester	Fruit and faint scent	0–2	0.56 ± 0.80 c	0.33 ± 0.93 c	0.18 ± 0.43 c	0.19 ± 0.50 c	0.96 ± 0.70 c	0.94 ± 0.35 c	0.93 ± 0.22 c	*	*	*
			4–6		0.14 ± 0.27 c	0.43 ± 0.44 c	0.28 ± 0.16 c	0.16 ± 0.17 c	0.51 ± 0.74 c	-			
			8–10		0.34 ± 0.43 c	0.86 ± 0.11 c	0.34 ± 0.32 c	0.23 ± 0.12 c	0.13 ± 0.16 c	0.48 ± 0.32 c			
			20		0.43 ± 0.12 c	0.63 ± 0.95 c	8.64 ± 0.82 b	35.22 ± 6.58 a	-	-			
	Butanoic acid, 3-hexenyl ester	The faint scent of fruits	0–2	0.12 ± 0.29 b	0.31 ± 0.13 b	0.17 ± 0.13 b	0.11 ± 0.34 b	0.34 ± 0.33 b	0.13 ± 0.19 b	-	*	ns	*
			4–6		0.83 ± 0.13 a	0.68 ± 0.53 ab	0.18 ± 0.19 b	0.32 ± 0.19 b	0.15 ± 0.18 b	0.43 ± 0.53 ab			
			8–10		0.15 ± 0.99 ab	0.25 ± 0.53 ab	0.21 ± 0.42 b	0.29 ± 0.14 b	0.88 ± 0.11 a	0.34 ± 0.27 b			
			20		0.24 ± 0.67 ab	0.36 ± 0.94 ab	0.43 ± 0.68 ab	0.43 ± 0.19 ab	-	-			
	Butanoic acid, hexyl ester	The sweetness of fruits	0–2	0.16 ± 0.23 d	-	-	-	-	-	-	*	*	*
			4–6		0.13 ± 0.53 d	0.65 ± 0.55 d	0.76 ± 0.14 bd	-	0.66 ± 0.94 d	-			
			8–10		0.27 ± 0.34 d	5.54 ± 0.58 b	18.75 ± 6.33 a	4.58 ± 8.80 abcd	2.99 ± 0.46 c	6.67 ± 0.82 b			
			20		-	-	-	-	-	-			
Acids	Acetic acid	Strong pungent aroma	0–2	-	0.52 ± 0.19 a	-	-	0.62 ± 0.59 a	-	-	ns	ns	ns
			4–6		0.57 ± 0.58 a	-	0.22 ± 0.16 a	-	0.13 ± 0.27 a	0.53 ± 0.19 a			
			8–10		0.14 ± 0.20 a	0.17 ± 0.45 a	-	-	0.28 ± 0.62 a	-			
			20		0.77 ± 0.13 a	-	0.19 ± 0.22 a	0.33 ± 0.45 a	-	-			
	Benzoic acid	Slight smell of benzoin	0–2	-	0.13 ± 0.39 b	0.19 ± 0.26 b	-	0.45 ± 0.40 b	-	0.57 ± 0.92 ab	*	*	*
			4–6		-	0.46 ± 0.60 ab	0.52 ± 0.39 b	-	-	-			
			8–10		0.50 ± 0.27 b	0.57 ± 0.11 b	-	-	1.23 ± 0.25 a	-			
			20		0.53 ± 0.61 ab	0.40 ± 0.36 b	0.57 ± 0.37 ab	0.25 ± 0.34 b	-	-			
	Nonanoic acid	Light fat fragrance	0–2	-	-	0.18 ± 0.14 b	0.17 ± 0.35 ab	-	-	-	ns	ns	*
			4–6		0.24 ± 0.21 ab	0.81 ± 0.49 a	0.35 ± 0.59 ab	0.27 ± 0.16 ab	0.19 ± 0.25 ab	0.66 ± 0.13 a			
			8–10		0.18 ± 0.26 ab	0.30 ± 0.44 ab	0.38 ± 0.81 ab	-	0.22 ± 0.39 ab	0.17 ± 0.65 ab			
			20		0.50 ± 0.19 a	-	0.36 ± 0.23 ab	0.15 ± 0.25 ab	-	-			
	Hexanoic acid	Smells like sheep	0–2	-	-	-	-	-	-	-	-	-	-
			4–6		-	-	-	-	-	-			
			8–10		-	-	0.46 ± 0.58 a	-	0.27 ± 0.33 a	0.55 ± 0.31 a			
			20		-	-	0.27 ± 0.12 a	0.18 ± 0.15 a	-	-			

Table 1. *Cont.*

Category	Compound	Aroma Character	Temperature Treatment (°C)	0 d	3 d	5 d	7 d	10 d	15 d	20 d	Significances		
											T	D	T × D
Ketones	2-Butanone, 4-(2,6,6-trimethyl-1-cyclohexen-1-yl)	Woody, floral, and fruity aromas	0–2	-	0.14 ± 0.73 a	0.45 ± 0.83 a	0.49 ± 0.30 a	0.21 ± 0.20 a	-	-	-	-	-
			4–6		0.40 ± 0.39 a	0.37 ± 0.56 a	0.57 ± 0.43 a	-	-	-			
			8–10		-	-	-	-	-	-			
			20		-	-	-	-	-	-			
	5,9-Undecadien-2-one, 6,10-dimethyl	Fruit, wax, wood, and faint aromas	0–2	-	-	-	-	-	-	-	-	-	-
			4–6		0.79 ± 0.72 a		0.15 ± 0.12 a	-	-	-			
			8–10		0.17 ± 0.32 a	0.24 ± 0.32 a	0.18 ± 0.27 a	-	-	-			
			20		0.16 ± 0.16 a	-	0.18 ± 0.11 a	0.27 ± 0.34 a	-	-			
	3-Buten-2-one, 4-(2,6,6-trimethyl-1-cyclohexen-1-yl)	Wood aroma	0–2	0.28 ± 0.29 a	0.42 ± 0.14 a	0.24 ± 0.34 a	1.15 ± 14.31 a	0.83 ± 0.80 a	-	0.49 ± 0.14 a	ns	ns	ns
			4–6		0.17 ± 0.46 a	0.18 ± 0.39 a	0.24 ± 0.11 a	0.49 ± 0.30 a	0.20 ± 0.26 a	0.99 ± 0.17 a			
			8–10		0.65 ± 0.28 a	0.41 ± 0.40 a	0.42 ± 0.85 a	0.39 ± 0.24 a	0.45 ± 0.14 a	0.14 ± 0.70 a			
			20		0.38 ± 0.73 a	-	0.69 ± 0.69 a	0.36 ± 0.82 a	-	-			
Alkanes	7-Oxabicyclo [4.1.0] heptane	No fragrance	0–2	0.81 ± 0.58 a	0.34 ± 0.82 a	0.22 ± 0.80 a	0.27 ± 0.36 a	1.65 ± 1.45 a	0.33 ± 0.32 a	0.55 ± 0.78 a	ns	ns	ns
			4–6		0.42 ± 0.15 a	0.23 ± 0.16 a	0.27 ± 0.11 a	0.33 ± 0.20 a	0.15 ± 0.22 a	0.84 ± 0.19 a			
			8–10		0.80 ± 0.24 a	0.86 ± 0.11 a	0.49 ± 0.87 a	0.68 ± 0.29 a	0.19 ± 0.40 a	0.73 ± 0.52 a			
			20		-	0.99 ± 0.12 a	0.76 ± 0.21 a	0.13 ± 0.22 a	-	-			
Aromatic	o-Xylene	Smells like toluene	0–2	0.58 ± 0.19 a	0.13 ± 0.59 a	0.58 ± 0.86 a	0.48 ± 0.13 a	0.47 ± 0.39 a	0.52 ± 0.65 a	-	ns	ns	ns
			4–6		0.12 ± 0.12 a	0.35 ± 0.40 a	-	-	-	-			
			8–10		0.73 ± 0.26 a	-	0.14 ± 0.29 a	0.65 ± 0.48 a	0.13 ± 0.16 a	0.44 ± 0.12 a			
			20		0.43 ± 0.20 a	0.32 ± 0.84 a	0.41 ± 0.11 a	0.64 ± 0.23 a	-	-			
Terpenes	Limonene	Smells like lemon	0–2	0.26 ± 0.31 a	0.59 ± 0.24 a	0.41 ± 0.16 a	0.26 ± 0.40 a	2.17 ± 1.83 a	0.36 ± 0.43 a	1.27 ± 0.34 a	ns	ns	ns
			4–6		0.46 ± 0.43 a	0.21 ± 0.24 a	-	0.29 ± 0.15 a	-	0.43 ± 0.65 a			
			8–10		0.33 ± 0.27 a	0.59 ± 0.50 a	0.27 ± 0.24 a	1.22 ± 0.69 a	-	0.16 ± 0.62 a			
			20		0.12 ± 0.25 a	0.35 ± 0.43 a	0.58 ± 0.74 a	0.31 ± 0.24 a	-	-			
	linalool	Lily of the valley aroma	0–2	-	0.26 ± 0.72 b	0.14 ± 0.12 b	0.52 ± 0.76 b	0.16 ± 0.95 b	-	1.49 ± 0.17 a	*	ns	*
			4–6		0.93 ± 0.86 ab	0.43 ± 0.44 b	0.21 ± 0.53 b	0.14 ± 0.73 b	-	0.59 ± 0.13 b			
			8–10		0.82 ± 0.59 ab	0.46 ± 0.65 b	1.27 ± 0.66 ab	-	0.68 ± 0.14 b	0.68 ± 0.94 ab			
			20		0.21 ± 0.51 b	0.62 ± 0.36 b	0.36 ± 0.22 b	0.16 ± 0.34 b	-	-			
Heterocyclic compound	2-Furancarboxaldehyde, 5-(hydroxymethyl)	Chamomile fragrance	0–2	-	-	-	-	-	-	1.26 ± 0.67 c	-	-	-
			4–6		-	-	0.12 ± 0.18 d	-	-	-			
			8–10		-	6.43 ± 0.32 a	-	-	1.14 ± 0.18 c	-			
			20		5.92 ± 1.17 b	1.48 ± 0.94 c	0.72 ± 0.46 c	0.28 ± 0.25 c	-	-			

Principal Component Analysis (PCA) was conducted on six types of aroma compounds, i.e., alcohols, aldehydes, esters, acids, ketones, and aromatics, identified in all four treatments (Figure 3A). Factors with an Eigen value of >1 were selected for factor extraction. The cumulative variance contribution rates of the first two principal components were 59.20%, and the variance contribution rates of PC1 and PC2 were 39.72% and 19.48%, respectively. As shown in Figure 3, PC1 mainly reflected information on aroma substances, including aldehydes, terpenes, alcohols, ketones, and acids. Esters were negatively correlated with PC1. However, PC2 reflected information about esters, acids, ketones, aldehydes, and alcohols. Terpenes were negatively correlated with PC2. Overall, this indicated that alcohols, aldehydes, ketones, and acids likely contributed to the overall aroma.

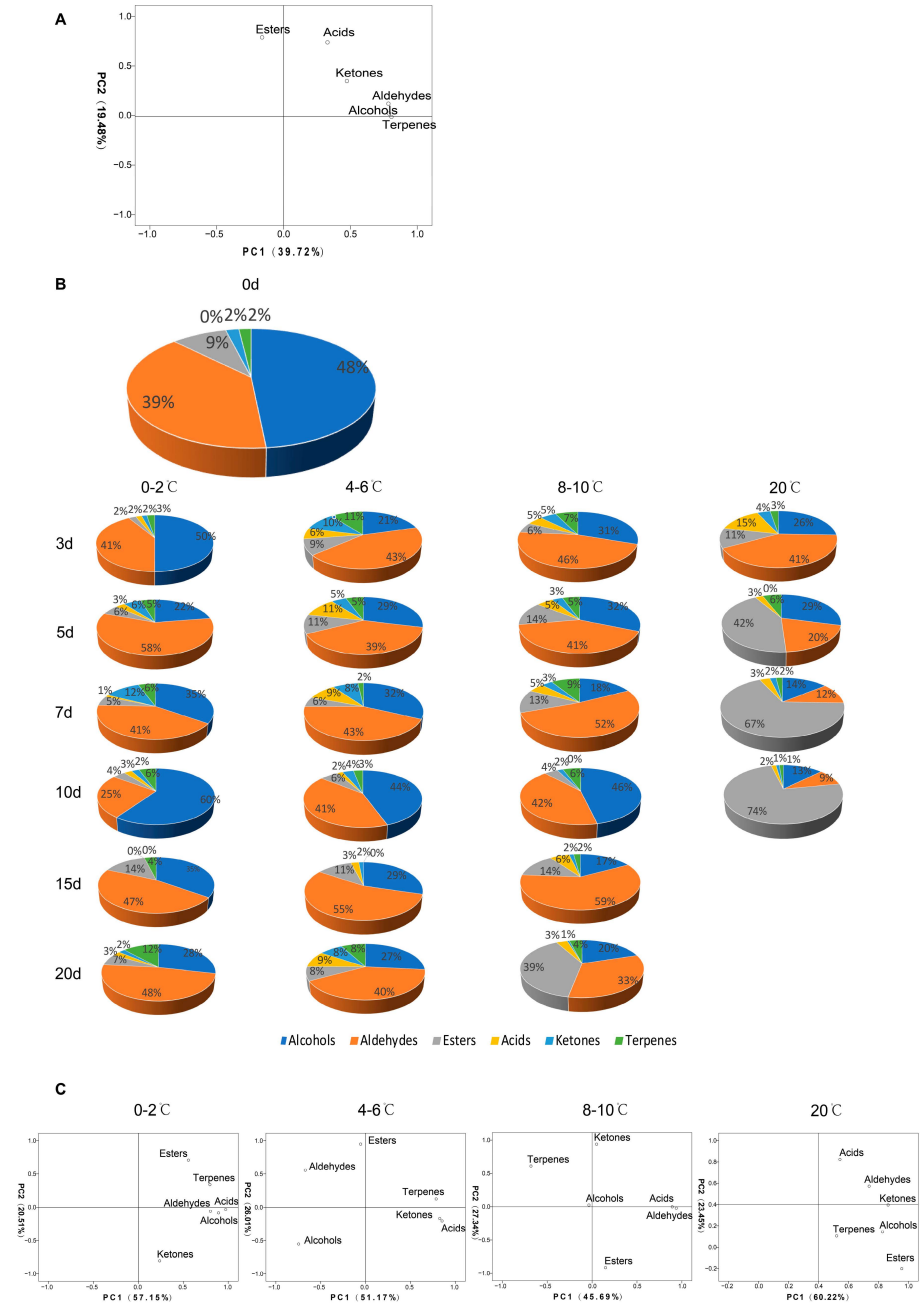

Figure 3. PCA analysis of total aroa substances (**A**). Changes in the content of aroma compounds in plums under different temperature conditions during storage (**B**). PCA analysis of aroma substances under different temperatures (**C**).

Furthermore, we visualized changes in the six types of aroma compounds identified in all four treatments during different temperatures of storage. The results showed that under various low-temperature treatments, the contribution of alcohols, aldehydes, ketones, and acids to the overall aroma highly varies, further supporting that the accumulation of aroma substances was significantly affected by storage temperature in 'Wushancuili' plum (Figure 3B). These changes were supported by the PCA analysis conducted on each temperature treatment (Figure 3C). It is evident that alcohols, aldehydes, ketones, and acids, which make a greater contribution to the overall aroma profile, also exhibit a higher proportion of total aroma compounds under storage conditions of 0–2 °C. Moreover, the PCA analysis of aroma substances at 0–2 °C conditions exhibited a higher degree of similarity to the overall aroma substance analysis, indicating a vital affection of 0–2 °C storage on the composition of aroma compounds.

3.4. Changes in Major Aroma Components during Storage at Different Temperatures

Based on the results of the PCA analysis, we then analyzed the changes in ketones, acids, alcohols, and aldehydes in response to different temperatures during storage. (E)-2-hexen-1-ol was the major alcohol present in substantial amounts in the samples. This compound has been associated with a faint scent [20]. By contrast, of all alcohols, the content of (E) -2-hexen-1-ol remained at a higher and more stable concentration. Following low-temperature treatment at 0–2 °C, there was a significant increase in the content of (E)-2-Hexen-1-ol in the sample compared to day 0. However, under other low-temperature treatments, the content of (E)-2-Hexen-1-ol decreased to varying extents. At 4–6 °C and 20 °C, the content of (E) -2-Hexen-1-ol showed an initial increase followed by a decrease. However, at 0–2 °C and 8–10 °C, (E) -2-hexen-1-ol was more variable, increasing rapidly, then decreasing, increasing again, and then decreasing after 15–20 days. Nevertheless, the total alcohol content in fruit stored at 0–2 °C was significantly higher than that in other treatments.

The aldehyde present in high amounts was 2-Hexenal, and this compound contributes to fruit aroma and green leaf fragrance [21]. Under conditions of 4–6 °C and 20 °C, 2-Hexenal was present at a low level, and there were insignificant changes during storage. The content of 2-Hexenal in the samples increased after low-temperature treatment at 0–2 °C and 8–10 °C compared to the 0th day, with the content at 0–2 °C on the 3rd day reaching more than 2.5 times that of the 0th day. Then, at 0–2 °C and 8–10 °C, there was an overall tendency to fluctuate, first increasing, decreasing, increasing again, and then decreasing towards the end of storage. Notably, during the late stage of storage at 0–2 °C storage, aldehyde content was significantly higher compared to other treatments, indicating that 0–2 °C storage temperature was more favorable for maintaining aldehydes in 'Wushancuili' fruit.

In fruit stored at 0–2 °C, ketone aroma compounds initially increased and then decreased, reaching their peak value on day 7, which was significantly higher than that observed at other temperatures. At 4–6 °C, an intermittent rise and fall pattern was observed. At both 8–10 °C and 20 °C, there was an overall increasing trend followed by a decrease in ketone aroma compound levels towards the end of storage. The peak value appeared later at 0–2 °C compared to 4–6 °C and was much higher than at other storage temperatures. The changes in levels of acid aroma compounds under various storage conditions were not significant. Even so, 0–2 °C seemed beneficial for slowing down the decrease of acid aroma compounds in the 'Wushancuili' plum. In summary, storage at 0–2 °C seems to be conducive to maintaining the content of the main aroma compounds in 'Wushancuili', thereby facilitating the preservation of flavor quality.

4. Discussion

4.1. Relationship between Fruit Flavor Quality and Soluble Sugars, Organic Acids, and Aroma Composition

The presence of soluble sugars, organic acids, and aroma components serves as crucial indicators of a fruit's inherent quality and significantly influences its taste and fla-

vor [22]. Soluble sugars determine sweetness, while organic acids contribute to sourness. Together with aromas perceived by the olfactory senses, they collectively shape the overall flavor profile of fruits [23]. Among various types of soluble sugars, fructose exhibits the highest level of sweetness. It is approximately 2.34 times sweeter than glucose and 1.73 times sweeter than sucrose. In most apples and pears, fructose is the primary soluble sugar, followed by glucose and sucrose [24,25]. However, 'Wushancuili' plum displays a different composition during postharvest storage, where glucose becomes the primary component, followed by fructose. In addition, the predominant organic acid components in the plums of 'Huang guan' and 'Black Amber' were malic acid, followed by tartaric acid [23], which was basically consistent with the findings in this study. Quinic acid and malic acid were the main organic acids in 'Wushancuili' fruit stored at 0–2 °C. Different plum varieties possess distinct aroma characteristics. Aldehydes were the dominant volatiles in *P. domestica* and *P. spinosa*, while esters were the major volatiles in the fruit of *P. ussuriensis*, *P. salicina*, and its hybrids. Regarding terpenoids and alcohols, they were relatively high in several *P. salicina* cultivars, *P. salicina* hybrids, and *P. spinosa*, and in *P. cerasifera*, respectively [26]. Consistently, it was demonstrated that alcohols, aldehydes, ketones, and acids were the major aroma substances during the postharvest storage of the 'Wushancuili' plum.

4.2. Effect of Temperature on Soluble Sugar, Organic Acid, and Aroma Composition

In a previous study, it was indicated that lower storage temperatures for 'Qingcuili' result in a slower accumulation of soluble sugars and a reduction in titratable acid [27]. By contrast, our results showed that soluble sugar content under low-temperature storage, particularly at 0–2 °C, was significantly higher than that under room-temperature storage conditions. However, it is noted that lower storage temperatures do not necessarily correlate with higher soluble sugar content. The discrepancy in changes in sugars may be attributed to the difference in cultivar or other experimental details. Even so, organic acid content exhibited a decreasing trend under low-temperature storage at 0–2 °C but remained higher during the early stages compared to other temperature conditions. This suggested that lower temperatures would slow down the reduction of titratable acid. However, tartaric acid and oxalic acid accounted for an extremely low ratio to total acid content during storage. Interestingly, during postharvest storage, the oxalic acid level only exhibited a gradual increase in the first 10 days under 8–10 °C. The temperature-dependent accumulation may be distinctive for oxalic acid. Changes in the content of fruit aroma compounds may be attributed to the activity of enzymes involved in aroma synthesis or metabolism, which may be inhibited under low-temperature storage conditions. In tomato, changes in DNA methylation reduce the expression of genes involved in the generation of flavor volatiles [28]. Under normal-temperature storage conditions, fruit's aldehyde contents decreased while alcohol and ester contents increased [29]. The production of esters was inhibited during low-temperature storage, which was consistent with the findings of this study. However, under low-temperature storage at 0–2 °C, the alcohol content in 'Wushancuili' was higher than that under normal-temperature storage. Although esters are important for plum fruit aroma, high levels can be detrimental to fresh plum fruit preservation. The combined effect of alcohols and aldehydes is the main contributor to plum fruit fragrance. Low-temperature storage at 0–2 °C promoted the accumulation of alcohols and aldehydes, which may help maintain fresh plums' flavor quality [30,31]. In addition, the results of PCA analysis indicated that ketones and acids made a significant contribution to aroma and gave rise to distinctive aromas in fruits. Moreover, the preservation of ketones and acids was enhanced when stored in a low-temperature range of 0–2 °C.

4.3. Effect of Temperature on Fruit Flavor Quality

Our previous study indicated that 0–2 °C treatment not only effectively delayed the ethylene release but also reduced the ethylene peak [19]. Wang et al. indicated that low temperatures could inhibit the ethylene release in apples during postharvest storage.

In terms of fruit energy metabolism level and quality, it was indicated that 2 °C storage exhibited better effects compared to 0 °C [31]. Moreover, Zhu et al. revealed that ethylene release in peach fruits decreases under low-temperature treatment, thereby delaying the fruit softening process [32]. Moreover, the present study revealed that 'Wushancuili' plums exhibited a more stable level of soluble sugars and organic acid when stored at 0–2 °C. Thus, this temperature is beneficial for preserving the flavor quality of plum fruits. By contrast, other higher-temperature storage may not efficiently prevent the release of ethylene and fruit respiration, which is not conducive to the maintenance of fruit quality. Aroma substances, such as 2-hexenal and (E)-3-hexen-1-ol [33,34], related to non-decay were more abundant at 0–2 °C, which was likely associated with the decrease in ethylene release and fruit energy metabolism during postharvest storage.

5. Conclusions

To provide scientific guidance for industrial application in 'Wushancuili' plum, we explored the effect of different storage temperatures of 0–2 °C, 4–6 °C, 8–10 °C, and 20 °C on flavor quality during postharvest storage. The key parameters of flavor quality, including soluble sugars, organic acids, and aroma compounds, were analyzed. Our results strongly indicated that 0–2 °C was most effective for preserving the postharvest flavor quality of 'Wushancuili' plum.

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