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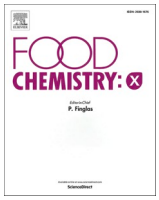

Combined ultraviolet-C radiation and L-cysteine treatment improves the post-harvest quality and volatile compounds of edible Lanzhou lily bulbs (*Lilium davidii* var. *unicolor*) by regulating reactive oxygen species metabolism

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ABSTRACT

Lanzhou lily bulbs (*Lilium davidii* var. *unicolor*) are Chinese traditional edible fruits; however, industrial benefits are limited owing to ineffective post-harvest preservation technology. This study investigated the effect of 4.5 kJ/m^2 ultraviolet (UV)-C radiation and 2.0 g/L L-cysteine (L-cys) treatment on storage quality and reactive oxygen species (ROS) metabolism in lily bulbs. The combined UV-C/L-cys treatment inhibited the increase in decay rate, weight loss, ΔE* and reducing sugar content; delayed the decrease of firmness and starch content; retained aromatic volatile compounds; and reduced pungent compounds. UV-C/L-cys treatment reduced H_2O_2 content, $O_2^{\cdot-}$ production rate, lipoxygenase activity and malondialdehyde content by maintaining high ROS-scavenging enzymes (superoxide dismutase and catalase) activities and substances (total phenolic and ascorbic acid) levels, thereby protecting mitochondrial structure. Mantel test indicated that post-harvest quality and volatile compounds were closely related to ROS metabolism. Hence, UV-C/L-cys treatment can efficiently delay lily bulb senescence by reducing ROS accumulation during storage.

1. Introduction

Lanzhou lily (*Lilium davidii* var. *unicolor*), a variety of L. *davidii* Duchartre, is commonly referred to the "only sweet lily" in China. Due to its sweet taste and unique flavor, it is favored by Chinese consumers and is commonly used in home cooking and the food industry (Huang et al., 2021). The Lanzhou lily bulb contains various nutrients such as starch, proteins, and vitamins, along with several biologically active substances, including polysaccharides, alkaloids, and steroidal saponins (Li, Wang, Zhang, et al., 2021). Recent studies reported that Lanzhou lily bulb has antitumor, anti-inflammatory, and antioxidation activities (Li et al., 2020; Wei et al., 2022). However, due to the high respiration rate, high water content, and photosensitivity, the quality of lily bulbs rapidly deteriorates during storage, mainly characterized by water loss, browning, purplification, and loss of nutrients and flavor (Huang et al., 2021). The decline of post-harvest quality has seriously affected the industrial significance for this lily variety, representing an urgent problem to be solved. Previous studies have demonstrated that the storage quality decline of lily bulbs is mainly due to the aging process of the fruit under abiotic stress, which is regulated by disruptions in ROS metabolism (Jiang et al., 2022).

The most common ROS generated during the storage period of fruits and vegetables include hydrogen peroxide (H_2O_2) and superoxide anion ($O_2^{\cdot-}$) (Yu et al., 2022). Excessive ROS generation can induce malondialdehyde (MDA) production, which accelerates the lipid peroxidation of cell membranes. Moreover, excessive ROS in mitochondria can lead to oxidative damage of mitochondrial proteins, eventually resulting in the loss of function and death of the mitochondria (Chu et al., 2018). Many

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studies have indicated that dysregulation of ROS metabolism can accelerate cellular senescence and affect the storage quality of post-harvest fruits such as litchi, pummelo, and longan (Jiang et al., 2018; Lin et al., 2020; Nie et al., 2020). As a response mechanism to resist the harm caused by excessive ROS production, post-harvest fruits enhance the activities and levels ROS-scavenging substances (e.g., total phenolics, ascorbic acid, and carotenoids) and enzymes [e.g., superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase] to eliminate excessive ROS and reduce oxidative damage in cells (Wang et al., 2020). For instance, in fresh-cut pitaya fruit, the initial storage conditions stimulate the production of ROS, resulting in an increase in the activities of antioxidant enzymes, including CAT, SOD, and glutathione reductase, to maintain the ROS balance (Li, Long, et al., 2017). This natural mechanism could provide a strategy for the development of novel technologies to delay the senescence in post-harvest lily bulbs during storage by manipulating the common regulatory ROS production-scavenging system.

Ultraviolet (UV)-C (short wavelength range of 200–280 nm) radiation is a low-cost and environmentally friendly physical technology that has been applied in post-harvest food processing to prolong the storage period. Application of UV-C radiation can effectively control the growth of surface bacteria on fruits by modifying the synthesis of pyrimidine dimers to damage the cellular DNA of most microorganisms, and is thus commonly employed for disinfection purposes (Martínez-Sánchez et al., 2019). Furthermore, UV-C treatment can function on its own or in combination with other processes to promote the generation and accumulation of ROS-scavenging substances and trigger the activities ROS-scavenging enzymes in fresh produce at the post-harvest stage (He et al., 2024). Huang et al. (2017) reported that 4.5 kJ/m^2 UV-C radiation increased the total phenolic content and promoted peroxidase (POD) activity, thereby stimulating the plant defense mechanism to abiotic stress, resulting in the enhancement of antioxidant activity in lily bulbs.

More recently, UV-C radiation has been combined with the treatment of post-harvest fruits and vegetables with edible amino acids that have effects in maintaining freshness and are classified as “generally recognized as safe” substances (Sharma et al., 2024). L-cys is a sulfur-containing amino acid that plays a role in the biosynthesis of fundamental biomolecules and defensive chemicals and is essential for both the primary and secondary metabolism of plants (Wang et al., 2022). Moreover, L-cys is a precursor to the formation of hydrogen sulfide, a crucial signaling molecule in numerous metabolic processes that prevents a variety of post-harvest commodities from ripening and aging. Therefore, L-cys has also been applied to enhance the quality of post-harvest fruits and vegetables in recent years. For example, L-cys immersion treatment was found to improve the capacity of antioxidant enzymes to scavenge ROS in lotus root slices and increased the total phenolic, ascorbic acid, and total glutathione contents in goji fruit (Bata Gouda et al., 2021; Wang et al., 2022).

Therefore, we hypothesized that combined UV-C and L-cys treatment would have a synergistic effect in improving the post-harvest quality of Lanzhou lily bulbs during low-temperature storage. This hypothesis was tested by examining the changes in quality indicators (decay rate, weight loss, firmness, color change); contents of starch, reducing sugar, total phenolics, ascorbic acid, and bioactive substances; antioxidant activity; and volatile aroma profiles under treatment with or without UV-C and/or L-cys during storage. We further explored the probable mechanisms by which UV-C and L-cys exert their protective effects with regard to ROS metabolism. These findings can provide methodological guidance for the post-harvest processing of Lanzhou lily bulbs to retain quality during storage.

2. Material and methods

2.1. Experimental material and treatments

Lanzhou lily bulbs (*Lilium davidii* var. *unicolor*) were obtained from the National Lily Germplasm Bank at Beijing Academy of Agricultural and Forestry Sciences; the bulbs were delivered to the laboratory within 12 h and maintained at 4 °C during transport. The whole form of bulbs that were uniform in size (3–5 cm in length, 2–4 cm in width, 45–50 g) and lacked signs of disease or mechanical damage were selected and washed with flowing water after removing the fibrous roots and outermost scales.

UV-C treatment was implemented by a UV-C lamp bank with a peak emission at 254 nm (TUV, 30 W, Philips), which was hung horizontally over the radiation vessel at a distance of 15 cm. The UV-C intensity at this distance was measured to be 0.828 mW/cm^2 using a UV light meter (LS125, Linshang Technology Co., Ltd., Guangdong, China). To guarantee consistent illumination, the bulbs were gently turned 180° horizontally throughout the irradiation period. The radiation UV-C dosage was calculated by following equations:

$$U = \frac{E \times t}{100} \quad (1)$$

where U represents the dose of ultraviolet radiation (kJ/m^2); E is the radiation intensity (mW/cm^2); and t corresponds to the exposure time (s) of the bulbs to ultraviolet light.

Preliminary studies were performed to examine the effects of various irradiation dosages of 3.0, 3.5, 4.0, 4.5, and 5.0 kJ/m^2, corresponding to radiation times of 362, 423, 483, 543, 603 s. L-cys treatment was applied by immersing the bulbs in an L-cys solution for 15 min. 0.5, 1.0, 1.5, 2.0, and 2.5 g/L L-cys concentrations was used. Bulbs were first subjected to UV-C irradiation at 4.5 kJ/m^2, and then soaked in a 0.2 g/L L-cys solution for 15 min to implement a combination of UV-C/L-cys treatment.

A total of 1200 bulbs were randomly divided into four treatment groups (control (untreated), UV-C only, L-cys only, and combined UV-C/L-cys treatment) and were then preserved for 50 days at 2 ± 0.5 °C and 90 % relative humidity.

2.2. Sampling procedure

Bulb samples were collected for the evaluation of quality indicators; the contents of starch, reducing sugar, total phenolics, and ascorbic acid; antioxidant activity; and ROS production every 10 days. During each sampling, 50 lily bulbs were taken from each treatment group, of which 10 bulbs were used for decay rate measurement, 10 bulbs were used for weight loss rate measurement, 10 bulbs were used for firmness measurement, 10 bulbs were used for ΔE measurement. The remaining 10 bulbs were mixed and used for other experiments. Liquid nitrogen was used to quickly freeze fresh samples, which were then stored at −80 °C until use. All analyses were performed in at least triplicate.

2.3. Measurement of quality parameters

All samples were stored at 2 ± 0.5 °C and 90 % relative humidity for 50 days to measure decay rate, weight loss, firmness, and ΔE every 10 days. The decay rate was calculated as the proportion of the number of rotten bulbs to the total number of bulbs. The Lanzhou lily bulbs were divided into the following 4 levels according to the degree of rot on the fruit: Grade 0, no mildew and decay; Grade 1, there are small brown spots and disease spots, and the decayed area is less than 10 %; Grade 2, the rotten area accounts for about 10–30 % of the fruit; Grade 3, the rotten area accounts for approximately more than 30 % of the fruit. Weight loss was evaluated by weighing the lily bulbs before and after the storage period and was expressed as the percentage of weight loss compared to the initial weight. Firmness (N) was assessed at three even points in each fruit using a handheld penetrometer (GY-4, Top Instrument Co.,Ltd., Zhejiang, China); The color of the lily bulb surface was determined by an NF55 chromameter (Nippon Denshoku, Japan). The L*, a*, and b* values were obtained at three positions on each surface in lily bulbs and the average readings were used to determine the

difference in color ($\Delta E^* = \sqrt{\Delta L^* + \Delta a^* + \Delta b^*}$) between initial and stored samples.

2.4. Measurement of starch, reducing sugar, and total phenolic ascorbic acid contents

The starch content was evaluated using the colorimetric anthrone method reported by Huang et al. (2017) with some modifications. A 0.5 g sample of each lily bulb was homogenized in an ethanol solution (5 mL, 80 %) and centrifuged at 3500*g* for 10 min. After discarding the supernatant, 2 mL of distilled water was added to the precipitate and boiled in a water bath for 15 min. Subsequently, 2 mL of 9.2 mol/L perchloric acid was added, followed by centrifugation for 10 min at 4000*g*. A spectrophotometer (FastTrack, Mettler Toledo International Trade Co., Ltd., Shanghai, China) was used to measure the absorbance at 620 nm. A calibration curve was constructed using standard starch solutions. The results were expressed in units of grams per kilogram.

The reducing sugar content was determined by the 3,5-dinitrosalicylic acid (DNS) method. The sample (2.0 g) was homogenized in 40 mL of distilled water for 20 min at 50 °C and the mixture was filtered. The supernatant and DNS reagent were mixed at a 1:1 ratio. The mixed solutions were boiled in a boiling water bath for 5 min. The FastTrack spectrophotometer was then used to measure the absorbance at 540 nm; the results were expressed in units of grams per kilogram.

The total phenol content was determined using a slight modification of the method developed by Huang et al. (2021). In brief, 2.0 g frozen samples were added to 1.0 mL of Folin phenol reagent and 2.0 mL 15 % Na_2CO_3 solution. The solution was mixed completely and left to stand for 2 h. The absorbance value was then measured at 760 nm. Total phenol content was expressed as grams of gallic acid per kilogram of bulb fresh weight basis.

The ascorbic acid content was determined using an adapted and validated method (Li et al., 2022). Briefly, frozen samples (5.0 g from 15 fruits) were added to 10 mL of oxalic acid solution for homogenization in an ice bath. The homogenate was extracted for 30 min and filtered. Subsequently, 10 mL of the supernatant was titrated with 2,6-dichlorophenol indophenol solution until the color turned red; 20 g/L oxalic acid served as the blank control.

2.5. Analysis of volatile compounds

A gas chromatography (GC)-ion mobility spectrometry (IMS) instrument (G.A.S., Dortmund, Germany) with a syringe and an automated headspace sampler unit was used to analyze the volatile fractions. The homogenized frozen tissue powders (4.0 g from 15 fruits) were transferred into a 20-mL headspace bottle. The extracted headspace air had a volume of 500 L and the temperature of the syringe was 45 °C. Pre-separation of the volatile organic compounds was performed by the gas chromatographic column (MXT-5, 15 m, 0.53 mm) and coupled to IMS. The column temperature was 40 °C and the carrier gas was 99.99 % pure nitrogen. All analyses were carried out in triplicates. The volatile compounds were identified based on comparison of the retention index and the drift time of the standard chemicals in the GC-IMS library.

2.6. Determination of H_2O_2 and $O_2^{\cdot-}$

The H_2O_2 content was assayed by a Hydrogen Peroxide assay kit (Beijing Solarbio Science & Technology Co., Ltd., China) according to the manufacturer instructions. Frozen tissues (1.0 g from 15 fruits) were homogenized with 10 mL of ice-cold acetone and then the absorbance was measured at 405 nm. The calculations were based on H_2O_2 as a reference point and the results are expressed as mmol/kg on a fresh weight basis.

The $O_2^{\cdot-}$ production rate was calculated using the method reported by Sun et al. (2018), with slight adjustments. Frozen tissues (1.0 g from 15 fruits) were homogenized with 5 mL of phosphate buffer (50 mM, pH 7.8) and centrifuged at 12,000*g* for 20 min. Subsequently, 1.0 mL of supernatant was mixed with 0.9 mL of phosphate buffer (50 mM, pH 8.0) and 0.1 mL of 10 mM hydroxylammonium chloride. After incubating at 25 °C for 60 min, 1.0 mL of 17 mM 4-aminobenzenesulfonic acid and 0.1 mL of 70 mM of α-naphthyl amine were added to the mixture and incubated at 25 °C for 20 min. The absorbance was measured at 530 nm by a FastTrack UV spectrophotometer.

2.7. Measurement of MDA content and lipoxygenase (LOX) activity

The MDA content in the lily bulbs was measured using an adapted and validated method (Li, Cheng, et al., 2017; Li, Long, et al., 2017). After dissolving in 1 mL of 10 % pre-cooled trichloroacetic acid, 1.0 *g* of frozen tissues were centrifuged at 12,000*g* for 15 min at 4 °C. The supernatant liquid was diluted twice and mixed with 0.67 % thiobarbituric acid, heated for 20 min in a boiling water bath, and then centrifuged at 12,000 ×*g* for 15 min after cooling in an ice bath. The supernatant was collected and the absorbance was read at wavelengths of 450 nm, 532 nm, and 600 nm, respectively. The MDA content was expressed as μmol/kg.

LOX activity was assay by the method described by Luo et al. (2021). After homogenizing 5.0 g of frozen lily bulb samples in 5 mL of 0.1 M phosphate-buffered saline (PBS; pH 6.8), the mixture was centrifuged at 8300 ×*g* for 30 min at 4 °C. One unit of LOX activity was defined as the amount of enzyme that increases absorbance by 0.01 per minute at 450 nm. The result was expressed as U/g.

2.8. Measurement of ROS-scavenging enzyme activities

SOD activity was determined by the method described by Wang et al. (2020). In brief, 5.0 g frozen samples were homogenized with 5 mL of 100 mmol/L PBS (pH 7.8). The SOD activity was then determined at 560 nm by the nitroblue tetrazolium (NBT) method. One unit of SOD activity was defined as the amount of enzyme responsible for 50 % inhibition of NBT. The enzyme activity was expressed as U/g.

CAT activity was measured using the method described Jiang et al. (2022). In brief, 28 mL of 50 mM PBS (pH 7.0), 15 mM hydrogen peroxide, and 2 mL of the enzyme sample obtained as described above were combined. The mixture was heated in a water bath for 10 min at 30 °C and then the reaction was stopped by adding 20 mL of 10 % sulfuric acid. One unit of CAT activity was defined as a 0.01 change in absorbance per minute at 240 nm. The enzyme activity was expressed as U/g.

2.9. Measurement of 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonate) (ABTS) scavenging activity

The ABTS scavenging activity was evaluated according to Qiu et al. (2022) with slight modifications. The homogenized samples (0.1 g) were blended with 9.9 mL of ABTS solution obtained by the reaction of an aqueous 3.84 g/L ABTS solution and an equal volume of 0.66 g/L potassium persulfate solution. The FastTrack UV spectrophotometer was used to determine the absorbance at 734 nm.

2.10. Transmission electron microscopy (TEM) observations

The ultrastructure of the lily bulb was determined using a transmission electron microscope (H-7650, Hitachi, Japan). After pre-fixing the frozen samples in 2.5 % glutaraldehyde for 12 h, they were washed in 0.1 M phosphate buffer (pH 7.0). The pre-fixed samples were then fixed in 1 % osmic acid for 1 h before being dehydrated through a graded ethanol series of 30 %, 50 %, 70 %, 80 %, 90 %, and 95 % for 15 min, followed by a 20-min wash with 100 % acetone. The sample was mixed with a Spurr resin mixture comprising resin and acetone at a 1:3 ratio overnight. Subsequently, the specimen was sectioned in an

ultratome (EM UC7, Leica, Germany). Sections were stained for 5–10 min with uranyl acetate and alkaline lead citrate, respectively, and observed with TEM.

2.11. Statistical analysis

Each experiment was performed at least three times and all results are presented as the mean ± standard deviation. Measurement values among groups were statistically evaluated using one-way analysis of variance followed by Duncan's multiple-range test with the SPSS 24 statistical software program (SPSS Inc., Chicago, IL, USA). $P < 0.05$ was regarded as a statistically significant difference in all experiments. "Fingerprint" Gallery Plots and principal component analysis (PCA) of lily bulbs volatile compounds profiles were analyzed by the software of Laboratory Analytical Viewer (LAV) and the Reporter, PCA and Gallery plug-ins of GC-IMS Library Search equipped with the GC-IMS instrument (G.A.S., Dortmund, Germany). The Mantel test analysis was performed using the ChiPlot tools at https://www.chiplot.online.

3. Results and discussion

3.1. Determination of UV-C dose and L-cys concentration

ΔE was used to screen for the optimal dosage of UV-C and concentration of L-cys. As shown in Fig. S1 A, the optimal radiation dose of UV-C was 4.5 kJ/m^2, and the excessively high UV-C dose (5.0 kJ/m^2) resulted in higher color changes of Lanzhou lily bulbs. Similar to Gómez et al. (2010), excessive UV-C doses also exacerbated browning of cut-apple. Fig. S1B shows that 2.0 g/L was the optimal L-cys concentration. According to preliminary experiments, 4.5 kJ/m^2 UV-C and 2.0 g/L L-cys were selected.

3.2. Decay rate, weight loss, firmness, and color properties

Decay rate is the major index of post-harvest quality evaluation in lily bulbs, which can reflect the degree of infection and damage of the bulbs by external pathogenic microorganisms. The decay rate of all experimental groups increased steadily with increasing storage time (Fig. 1A). The occurrence of decay in the UV-C-treated group was delayed by 10 days compared to that of the untreated control group (CK group), and decay in the L-cys-treated and UV-C/L-cys-treated groups was delayed by 20 days. At the end of the storage period (50 days), the

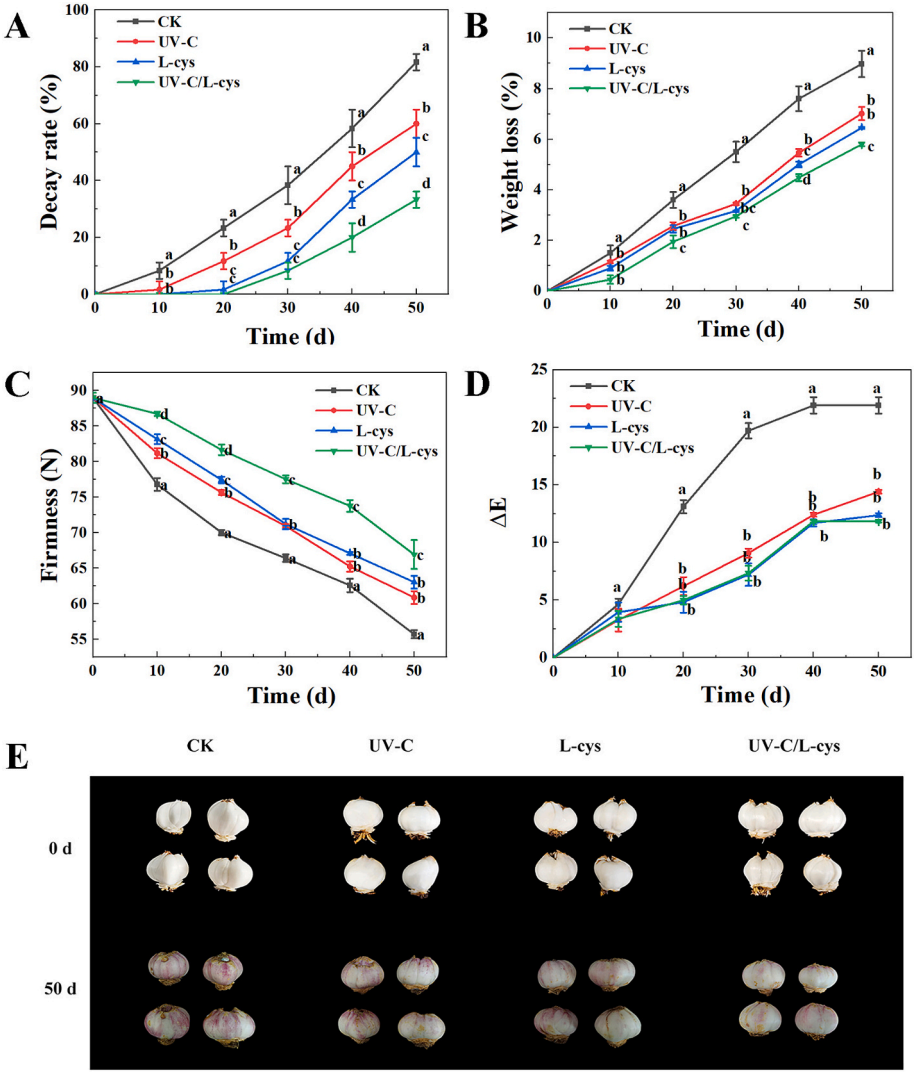

Fig. 1. Decay rate (A), weight loss (B), firmness (C), color change (ΔE) (D), and appearance (E) of Lanzhou lily bulbs with various post-harvest treatments and stored at 2 ± 0.5 °C for 50 days. Values are expressed as the mean ± SD of three independent determinations. Different letters indicate significant differences ($P < 0.05$).

decay rate in the UV-C-treated, L-cys-treated, and UV-C/L-cys-treated groups was 60.00 ± 5.00 %, 50.00 ± 5.00 %, and 33.33 ± 2.89 %, respectively, while that of the control group was 81.67 ± 2.89 % (all $P < 0.05$). These results showed that the combined UV-C/L-cys treatment can inhibit the decay and deterioration of lily bulbs, which may be related to increasing the activity of antioxidant enzymes and antioxidant substances, thereby improving the resistance of Lanzhou lily bulbs to microbial infection. As proposed by Zhang, Jiang, et al. (2021), UV-C treatment can promote the antioxidant system of nectarine, stimulate the phenylpropane metabolism pathway, and enhance anthocyanin synthesis, thereby reducing the lesion diameter and decay index of nectarine during storage.

Weight loss is a crucial factor in determining the edible quality of harvested lily bulbs. Generally, the weight loss of fruits and vegetables affects their appearance, texture, flavor, and nutrition, and further accelerates their deterioration during storage (Asgarian et al., 2022). As shown in Fig. 1B, in both the CK and treatment groups, the weight loss of lily bulbs increased over storage time, which was primarily due to a higher rate of transpiration and respiration. After storage for 50 days, the minimum weight loss was seen in the UV-C/L-cys-treated group (5.80 ± 0.37 %), followed by the L-cys-treated group (6.45 ± 0.08 %), UV-C-treated group (7.01 ± 0.26 %), and CK group (8.98 ± 0.52 %). This may be due to the fact that UV-C/L-cys treatment can reduce ROS production, reduce membrane lipid peroxidation, and protect cell membranes from damage, thereby maintaining the cell structure to consequently reduce water loss. These results indicated that the combined UV-C/L-cys treatment could prevent the water and mass loss of lily bulbs, suggesting a potential method to maintain the weight of lily bulbs during storage. However, high doses of UV-C can cause oxidative stress on lily bulbs, leading to negative effects on their quality (Gómez et al., 2015). Hence, it was necessary to avoid high UV-C doses in practical applications.

Firmness is a key parameter reflecting the ripeness and softening degree of fruit and can also affect the acceptability of consumers to fruit (Cheng et al., 2024). The effects of various treatments on the firmness of lily bulbs during storage are shown in Fig. 1C. The firmness of the CK group decreased with an increase in storage time, reaching a minimum of 55.72 ± 0.58 N at 50 days. The firmness values of the UV-C and L-cys groups were higher than that of the control group, but were significantly ($P < 0.05$) lower than that of the UV-C/L-cys treatment group (66.94 ± 2.03 N), which might be related to the decrease of the starch decomposition and prevention of cell wall degradation in the UV-C/L-cys treatment group (Gómez et al., 2011).

The surface color of a fruit or vegetable is one of the main criteria reflecting a consumer's purchase decision. As shown in Fig. 1D-E, the ΔE value increased sharply during storage and then peaked at 40 days in the control group, corresponding to a result of 21.90 ± 0.71. During the 50 days of storage, ΔE values in all treatment groups remained at low levels without a significant difference between single treatments and the composite treatment ($P > 0.05$). These results showed that both UV-C radiation and L-cys treatment can maintain the initial color of Lanzhou lily according to the reduced ΔE value, resulting in a better appearance and enhanced commercial value. This may be due to the fact that UV-C/L-cys treatment can better maintain the structure of cells, thereby reducing the contact of polyphenol oxidase and POD with enzymatic browning substrates to delay enzymatic browning. Wang et al. (2022) also found that 0.05 % cysteine treatment increased the L value to maintain a better appearance of goji fruit compared to the control group during storage from 4 to 6 days.

3.3. Starch, reducing sugar, total phenolic, and ascorbic acid contents

Lily bulb is a fruit rich in starch, which serves as the primary source of energy for vegetables and fruits. During storage, starch can be converted into monosaccharides, providing energy for the respiration of lily bulbs. As shown in Fig. 2A, the starch content of the bulbs decreased steadily over the course of storage, which indicates that the starch was easily hydrolyzed and converted into soluble sugars by α-amylase and β-amylase, resulting in a sweeter flavor and softer texture of the bulbs during senescence. The starch content of the CK group decreased from an initial value of 78.12 ± 0.24 g/kg to 41.72 ± 1.02 g/kg at 50 days of storage. However, the starch content of the UV-C-treated, L-cys-treated,

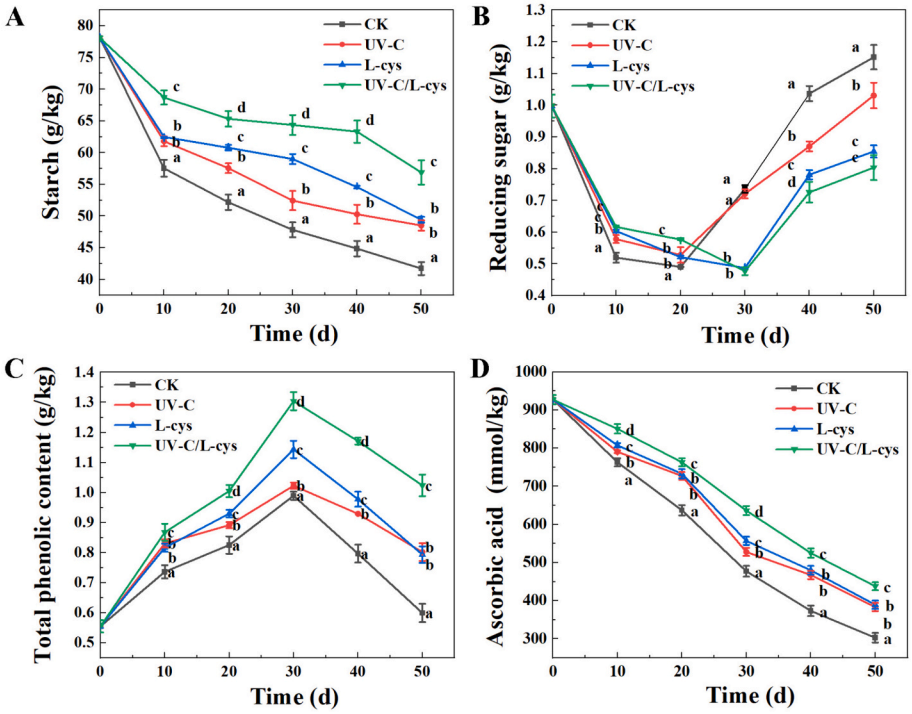

Fig. 2. Starch (A), reducing sugar (B), total phenolic (C), and ascorbic acid (D) contents of Lanzhou lily bulbs with various post-harvest treatments and stored at 2 ± 0.5 °C for 50 days. Values are expressed as the mean ± SD of three independent determinations. Different letters indicate significant differences (P < 0.05).

and UV-C/L-cys-treated groups was 48.52 ± 0.82 g/kg, 49.41 ± 0.47 g/kg, and 56.87 ± 1.91 g/kg, respectively, at the end of the storage period, demonstrating that these treatments significantly delayed starch degradation ($P < 0.05$). These findings suggest that the UV-C/L-cys treatment was more conducive to delaying starch conversion to sugars than either the UV-C or L-cys treatment alone, resulting in a slower rate of senescence and softening of the lily bulbs, which was consistent with the observed change of firmness under the different treatments. Similarly, a previous study showed that treatment with oxygen-modified atmosphere packaging combined with solid particles of plant essential oils could delay the hydrolyzation of starch in fresh-cut lily bulbs by inhibiting α-amylase and β-amylase activities (Jiang et al., 2022).

Reducing sugars are crucial for maintaining plant structure and metabolism at the organism and cellular levels, and can also help plants mount a defensive response to stressful environmental conditions. The content of reducing sugars initially decreased and then increased throughout the storage period in all groups during the storage. (Fig. 2B). On the 20th day of storage, the reducing sugar content in the CK group was 0.49 ± 0.01 g/kg, significantly lower than UV-C-treated group (0.53 ± 0.02 g/kg), L-cys-treated group (0.52 ± 0.01 g/kg), UV-C/L-cys-treated group (0.58 ± 0.01 g/kg) ($P < 0.05$). The initial decreasing trend might be due to the continuous consumption of reducing sugar in the different stages of storage to maintain the normal physiological activities of plants, whereas the increase in the later stage of storage may be related to the enhancement of starch degradation. The L-cys and UV-C/L-cys treatments could effectively delay this trend, in which the level of reducing sugars started to increase at 30 days of storage, whereas the increase was observed at 20 days of storage for the control and UV-C-treated bulbs. The reducing sugar content in the CK group increased and reached a peaked value of 1.15 ± 0.04 % at 50 days of storage. All treatments reduced the rate of the accumulation of reducing sugars and the UV-C/L-cys treatment had the best effect in maintaining a relatively stable level of reducing sugar. This finding was consistent with the change of starch content, indicating that UV-C/L-cys treatment can delay the degradation of starch and consequently the consumption and accumulation of reducing sugars.

Phenolic compounds and ascorbic acid are regarded as members of the non-enzymatic antioxidant system, which can effectively scavenge ROS and protect against oxidative damage (Fang et al., 2021). Phenolic compounds are also common substrates for enzymatic browning. Monophenols are hydroxylated to form bisphenols under the catalysis of browning enzymes such as polyphenol oxidase and then are further condensed to form quinones, leading to browning. As depicted in Fig. 2C, the total phenolic content in all groups showed an increasing trend from 0 to 30 days of storage. On the 30th day of storage, the phenolic compounds content in the CK group was 0.99 ± 0.01 g/kg, significantly lower than UV-C-treated group (1.02 ± 0.01 g/kg), L-cys-treated group (1.14 ± 0.03 g/kg), UV-C/L-cys-treated group (1.30 ± 0.03 g/kg) ($P < 0.05$), which suggests that the non-enzymatic ROS-scavenging system was activated due to the accumulation of ROS with extension of the storage period. After 30 days of storage, the total phenolics content in the CK group decreased sharply; although the phenolics content also decreased over time in the treatment groups, the decrease rate was the lowest in the UV-C/L-cys-treated group, which might be related to the oxidation of phenols to quinones in the later stage of storage. These results showed that UV-C/L-cys treatment could enhance the content of total phenolics to help post-harvest lily bulbs resist or delay senescence. This finding was in line with the results of Li, Wang, Fang, et al. (2021) in post-harvest shiitake mushrooms, in which treatment of a water-based phase-change coolant increased the total phenolic content to extend the shelf-life of the mushrooms.

Ascorbic acid serves as an important index for fruit anti-aging and fruit quality evaluation. Fig. 2D displays the effects of different treatments on the ascorbic acid content of lily bulbs, exhibiting a downward trend for all treatment groups; nevertheless, the ascorbic acid content in the UV-C/L-cys treatment group was significantly ($P < 0.05$) higher than that of the other groups after storage for 50 days. These results indicated that UV-C/L-cys treatment could effectively delay the decrease of ascorbic acid content, thereby preserving the antioxidant capacity of lily bulbs during storage. Li et al. (2022) reported that a coating treatment of 1-methylcyclopropene and tea polyphenols could effectively delay the decrease of ascorbate and glutathione contents during storage, thereby maintaining the post-harvest quality of bracken.

3.4. Volatile compounds

Complex changes of volatile compounds occur during storage, which results in the variation of food flavor that in turn affects consumers' eating experience. In general, the biosynthesis and degradation of volatile compounds can be affected by many factors, including fruit senescence, post-harvest treatments, and storage conditions, in fruits and vegetables. As a novel analytic technology of volatile compounds, headspace GC-IMS has the advantages of no requirement of pretreatment before detection and a low detection limit, and has thus frequently been used to examine volatile substances in foods, including bacon, fruits and vegetables (Guo et al., 2022; Zhang, Zhang, et al., 2021). Therefore, we used this method to compare the volatile profiles in lily bulbs with different treatments and at different stages of storage. Based on reference to the GC-IMS library, a total of 36 volatile compounds were identified, including 13 aldehydes, 9 esters, 4 ketones, 3 alcohols, 2 furans, and 5 other types of compounds (Table. 1). The compound name, CAS number, molecular formula, molecular weight, retention index, retention time, and drift time of the identified metabolites are listed in Table 1. Fingerprints were generated by Gallery Plot to compare the contents of each volatile compound between bulbs in different treatment groups during the 50-day storage period. In the fingerprint map shown in Fig. 3A, each row and column denote a sample and a substance, respectively. Volatile substances are also displayed in the cells at different stages of storage from 0 to 50 days. A bright color in the map indicates a higher content of each substance. Higher contents of acetic acid ethyl ester-M, (E)-2-hexenyl acetate-M, ethyl pentanoate, (E)-2-hexenal-M, nonanal, octanal, 3-methylbutan-1-ol-D, and 2-heptanone were detected in the UV-C/L-cys group than in the CK, UV-C, and L-cys groups after storage for 50 days. Most of these substances are considered aromatic volatile compounds and are thus responsible for the typical fruity aroma, contributing to the fresh bulb flavor, suggesting that the UV-C/L-cys treatment could either help release these aromatic volatile compounds or protect them against degradation. Similarly, a previous study showed that low-temperature treatment prevented the loss of aromatic esters in 'Nanguo' pears (Zhou et al., 2015). During storage, the CK group produced certain pungent substances such as 3-methylbutanal, 2-methylpropanal, (E)-2-pentenal, 1-penten-3-one-M, and tetrahydrofurane-M, whereas the UV-C/L-cys treatment inhibited the production of these substances. A similar finding was reported for honey peach packaged with different preservation methods (Leng et al., 2021). In addition, the contents of some aromatic substances, including styrene, 2,3-butanediol, 3-methylbutan-1-ol-M, ethyl butyrate, 3-hydroxybutan-2-one, and 1-penten-3-one-D, increased at 30 days and decreased at 50 days of storage in all groups, which is attributed to the emergence of the post-ripening phenomenon. Similar results were found in jujube fruits in which the relative proportions of ethyl propanoate, ethyl isobutanoate, and propyl acetate were lower at 0–30 days of storage and increased after 45 days of storage (Yang et al., 2019).

Principal component analysis (PCA) is a multivariate statistical analysis technique that is widely used to compare samples and assess their similarity and differences based on the contribution rates of the principal component (PC) factors to the total variation. We used PCA to identify variations in the aroma profiles of lily bulb samples. The contribution rates of the first and second PCs were 47 % and 26 %, respectively, as shown in Fig. 3B. The PCA results clearly demonstrated that the distribution map can distinguish between various treatment samples during storage in a relatively independent space. Bulb samples

Table 1
Headspace gas chromatography-ion mobility spectrometry integration parameters of volatile compounds identified in Lanzhou lily bulbs. MW: Molecular weight, RI: the retention index, Rt: the retention time, Dt: the drift time.

	Compound	CAS	Formula	MW	RI	Rt [*sec*]	Dt [*a.u.*]
Pungent compounds	3-methylbutanal	C590863	C5H10O	86.1	649.3	151.675	1.39684
	2-methylpropanal	C78842	C4H8O	72.1	559.8	128.201	1.27857
	(*E*)-2-pentenal	C1576870	C5H8O	84.1	750.7	185.269	1.36823
	1-penten-3-one-M	C1629589	C5H8O	84.1	677.7	159.991	1.07622
	Tetrahydrofurane-M	C109999	C4H8O	72.1	626.4	145.277	1.06238
	Tetrahydrofurane-D	C109999	C4H8O	72.1	619.4	143.391	1.22845
Postripeness aromatic compounds	Styrene	C100425	C8H8	104.2	886.9	253.526	1.43996
	2,3-Butanediol	C513859	C4H10O2	90.1	803.2	207.529	1.36685
	3-methylbutan-1-ol-M	C123513	C5H12O	88.1	730.3	177.724	1.1122
	Ethyl butyrate	C105544	C6H12O2	116.2	814	212.972	1.21156
	3-hydroxybutan-2-one	C513860	C4H8O2	88.1	721.9	174.705	1.32395
	1-penten-3-one-D	C1629589	C5H8O	84.1	683	161.58	1.32535
Aromatic volatile compounds	(E)-2-Hexenyl acetate-M	C2497189	C8H14O2	142.2	1014.9	361.043	1.38889
	(E)-2-Hexenyl acetate-D	C2497189	C8H14O2	142.2	1014.9	361.043	1.89228
	acetic acid ethyl ester-M	C141786	C4H8O2	88.1	610.9	141.127	1.09421
	acetic acid ethyl ester-D	C141786	C4H8O2	88.1	604	139.312	1.33578
	Ethyl pentanoate	C539822	C7H14O2	130.2	894.1	258.042	1.67518
	(E)-2-hexenal-M	C6728263	C6H10O	98.1	871.3	244.244	1.1817
	Nonanal	C124196	C9H18O	142.2	1107.1	487.896	1.4706
	Octanal	C124130	C8H16O	128.2	1026.5	374.966	1.82078
	Heptanal	C111717	C7H14O	114.2	886.9	253.526	1.32469
	Limonene	C138863	C10H16	136.2	1035.2	385.795	1.29697
	p-Cymene	C99876	C10H14	134.2	1027.7	376.512	1.72302
	Hexanenitrile	C628739	C6H11N	97.2	888.2	254.299	1.57565
	2-heptanone	C110430	C7H14O	114.2	889.5	255.073	1.63694
	3-methylbutan-1-ol-D	C123513	C5H12O	88.1	739.6	181.119	1.24506
	(E)-2-nonenal	C18829566	C9H16O	140.2	1168.9	597.059	1.41067
	2-pentyl furan	C3777693	C9H14O	138.2	989.9	333.97	1.25465
	(E)-2-hexenal-D	C6728263	C6H10O	98.1	852.4	233.415	1.52459
Other volatile compounds	Hexanal-M	C66251	C6H12O	100.2	812.9	212.434	1.25752
	Hexanal-D	C66251	C6H12O	100.2	798.6	205.265	1.55922
	Isopropyl acetate	C108214	C5H10O2	102.1	662.4	155.464	1.1551
	methyl acetate	C79209	C3H6O2	74.1	567.3	130.043	1.20028
	Mesityl oxide	C141797	C6H10O	98.1	790.8	201.478	1.45646
	(E)-hept-2-enal	C18829555	C7H12O	112.2	952.1	301.639	1.25696
	(E)-2-octenal	C2548870	C8H14O	126.2	1058.1	415.697	1.33031

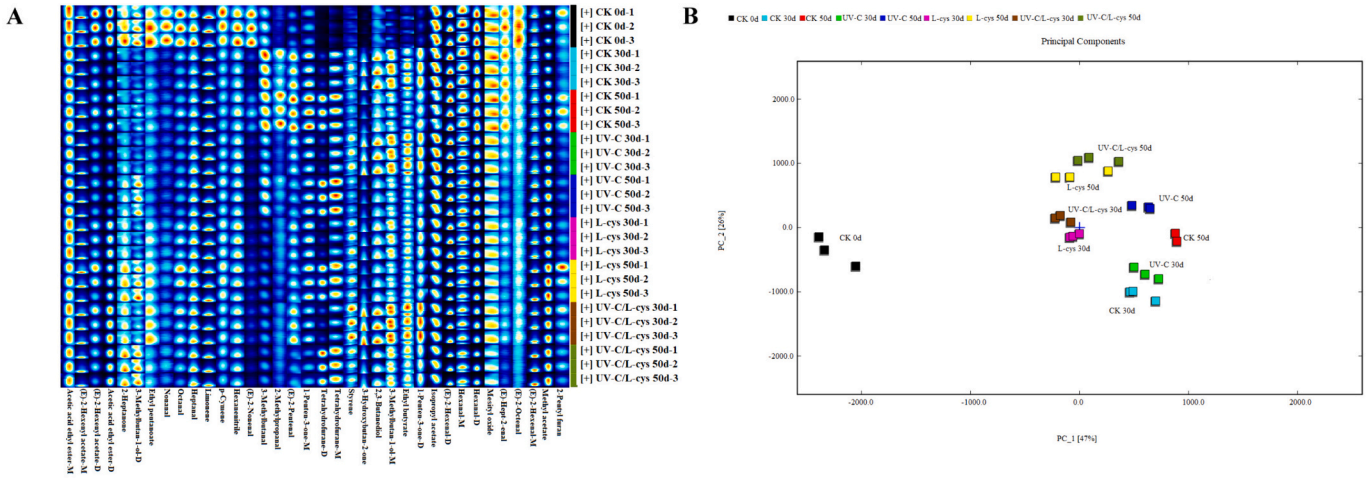

Fig. 3. Fingerprint gallery plot of the volatile compounds in Lanzhou lily bulbs with various post-harvest treatments and stored at 2 ± 0.5 °C for 50 days (A). Principal component analysis based on the signal intensity of volatile compounds detected at different storage stages in Lanzhou lily bulbs (B).

with similar aroma profiles clustered more closely together in the plot (Song et al., 2021). Compared with the position of the CK group, the samples of the UV-C, L-cys, and UV-C/L-cys treatment groups were closer on the plot at 30 and 50 days of storage, indicating that the three treatments had an effect of maintaining the freshness of the bulbs. In addition, the UV-C/L-cys treatment samples clustering closer together among the three treatment groups. These results indicated that the combined UV-C/L-cys treatment could maintain a good flavor profile of lily bulbs by regulating the synthesis and release of volatile compounds.

3.5. ROS metabolism

3.5.1. H_2O_2 content and $O_2^{\cdot-}$ production rate

A previous study reported a strong correlation between fruit senescence and the production of ROS such as H_2O_2 and $O_2^{\cdot-}$, which are considered by-products of normal cell metabolism (Xia et al., 2016).

H_2O_2 is not only a key ROS but is also a hub for the mutual transformation of ROS. On the one hand, H_2O_2 can directly or indirectly oxidize biological macromolecules such as nucleic acids and proteins in cells, causing damage to cell membranes and thereby accelerating cell aging and disintegration. On the other hand, H_2O_2 is also a key regulator in many oxidative stress reactions. As displayed in Fig. 4A, the H_2O_2 content of lily bulbs in all groups rose gradually throughout the storage period. In the CK group, the H_2O_2 content increased sharply during storage, especially from 40 to 50 days; however, the UV-C, L-cys, and UV-C/L-cys treatments could significantly delay this increasing trend ($P < 0.05$). These results indicated that UV-C/L-cysteine treatment can reduce the accumulation of H_2O_2, which may be related to the increase in the contents of total phenolics and ascorbic acid. Similarly, a previous study showed that treatment of L-cys hydrochloride inhibited the increase in H_2O_2 content during the late stage of storage to delay the senescence of harvested longan (Li et al., 2018).

$O_2^{\cdot-}$ is a crucial indicator for the detection of ROS. Excessive accumulation of $O_2^{\cdot-}$ can cause damage to cell membranes and biological macromolecules, leading to abnormal metabolism of cells and tissues, ultimately resulting in the aging of fruits and vegetables. As indicated in Fig. 4B, the $O_2^{\cdot-}$ generation rate of the control lily bulbs showed an increasing trend with extended storage time. Although the UV-C and L-cys treatment groups fluctuated with an overall rising trend, these treatments significantly inhibited the formation of the $O_2^{\cdot-}$. At 50 days of storge, the $O_2^{\cdot-}$ generation rate of the UV-C/L-cys treatment group was 5.62 ± 0.28 mmol/min/kg and was reduced by 44 % compared with that of the CK group. These results revealed that the combined UV-C/L-cys treatment can delay the senescence and deterioration of lily bulbs by reducing the H_2O_2 content and $O_2^{\cdot-}$ generation rate, thereby suppressing the accumulation of ROS.

3.5.2. MDA content and LOX activity

ROS production can increase permeability of the cell membrane and cause the phospholipids in the cell membrane to hydrolyze, leading to peroxidation and degradation of the membrane. As the primary components of the cell membrane, membrane lipids can be catalyzed by the enzyme LOX to produce small hydrocarbon fragment. MDA is the final product of membrane lipid peroxidation and is used as a gauge of the degree of cell membrane damage (Lin et al., 2020). As shown in Fig. 4C, D, the MDA content and LOX activity both increased gradually during storage time in the CK group and in the three treatment groups. However, the CK group had a higher MDA content and LOX activity, which is in accordance with the higher H_2O_2 content and $O_2^{\cdot-}$ generation rate. In contrast, the UV-C, L-cys, and UV-C/L-cys treatments delayed the upward trend of MDA content and LOX activity ($P < 0.05$), suggesting that UV-C/L-cys treatment can delay the peroxidation of membrane lipids by reducing LOX enzyme activity and MDA production, thus protecting the cell membrane structure of lily bulbs and facilitating their preservation during cold storage. Our findings are in line with earlier research by Li, Cheng, et al. (2017), who discovered a positive correlation between ROS levels and the LOX activity and MDA content during the storage of "Huangguan" pears.

3.5.3. ROS-scavenging enzyme activities

When fruits and vegetables face abiotic stresses, the dynamic equilibrium of intracellular ROS production and scavenging is disrupted, causing damage to proteins, nucleic acids, and cell structures. Fruits and vegetables need antioxidant enzymes to protect against various stresses by maintaining the antioxidant system. SOD and CAT are two typical antioxidant enzymes. SOD can scavenge superoxide radicals in biological cells to generate H_2O_2 and oxygen, and then the produced H_2O_2 is further catalyzed by CAT to produce oxygen and H_2O. Fig. 5A illustrates

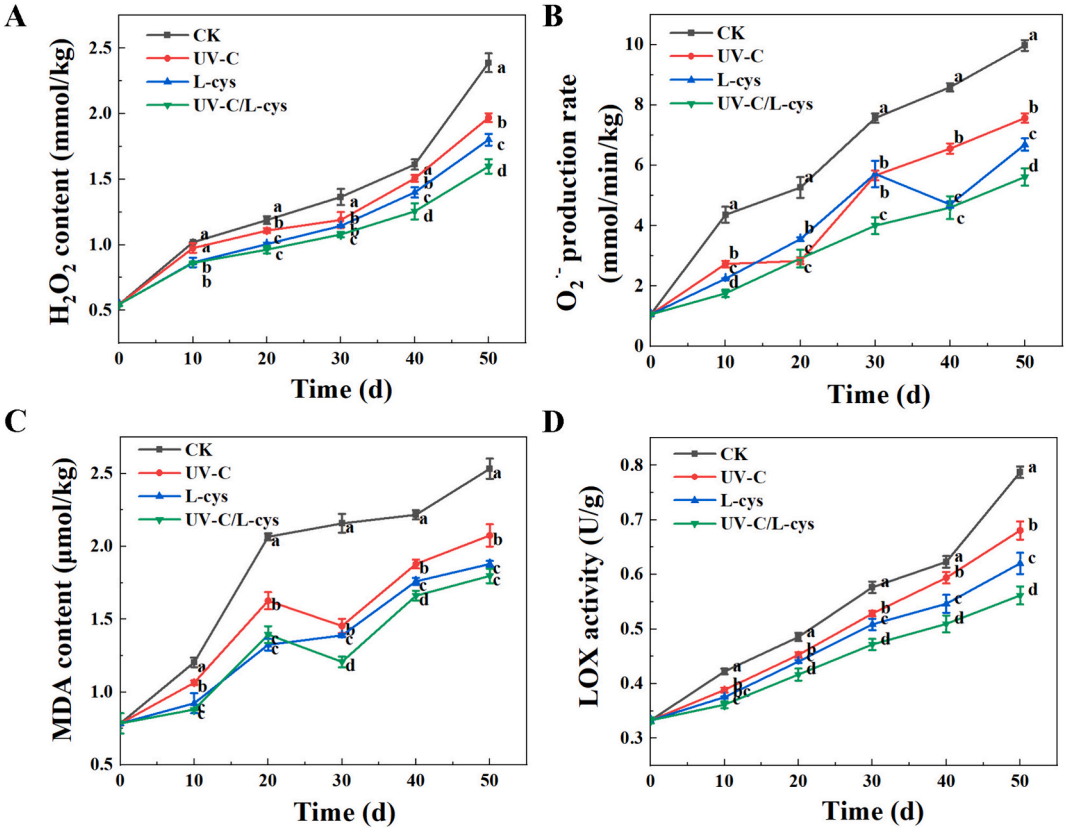

Fig. 4. H_2O_2 content (A), $O_2^{\cdot-}$ production rate (B), malondialdehyde (MDA) content (C), and lipoxygenase (LOX) activity (D) of Lanzhou lily bulbs with various post-harvest treatments and stored at 2 ± 0.5 °C for 50 days. Values are expressed as the mean ± SD of three independent determinations. Different letters indicate significant differences ($P < 0.05$).

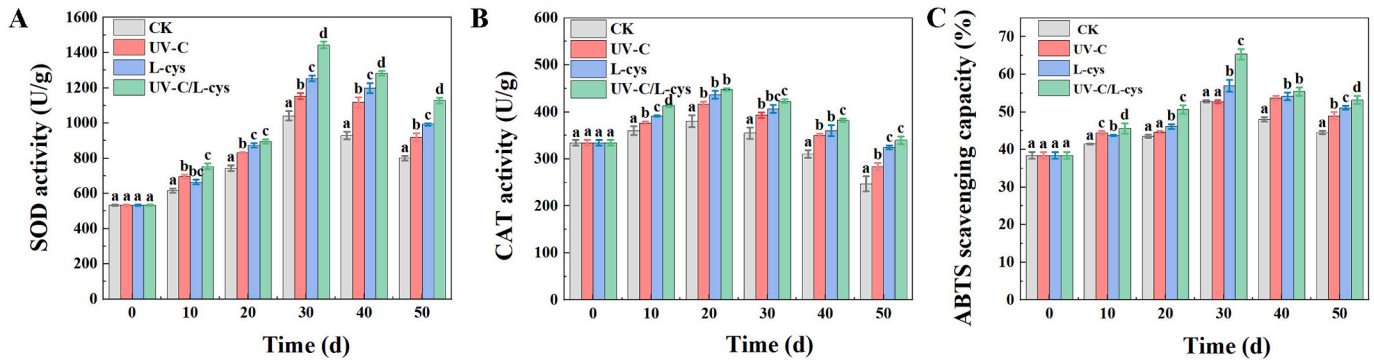

Fig. 5. Superoxidase (SOD) activity (A), catalase (CAT) activity (B), and ABTS radical-scavenging capacity (C) of Lanzhou lily bulbs with various post-harvest treatments and stored at 2 ± 0.5 °C for 50 days. Values are expressed as the mean ± SD of three independent determinations. Different letters indicate significant differences ($P < 0.05$).

that the SOD activity of lily bulbs gradually increased from 0 to 20 days of storage before rapidly increasing in the following 10 days and then rapidly decreasing from 30 days to the end of storage. This indicates that upon the accumulation of ROS, the activities of SOD and CAT enzymes increased to remove excessive ROS. With the extension of storage time, the cell aging phenomenon continued to progress, and the activity of the antioxidant enzymes gradually decreased. As shown in Fig. 5B, the CAT activity in all groups rose slightly during the first 20 days of storage. Peak reached in 20 days, with CAT activity of 380.16 ± 12.86 U/g in the CK group, 416.68 ± 5.43 U/g in the UV-C-treated group, 436.41 ± 8.35 U/g in the L-cys-treated group, and 447.66 ± 2.58 U/g in the UV-C/L-cys-treated group. Then the CAT activity deceased rapidly from 20 days to the end of the storage period (50 days). UV-C, L-cys, and UV-C/L-cys treatments significantly enhanced SOD and CAT activities during storage ($P < 0.05$). Higher activities of SOD and CAT have been linked to the delayed senescence of post-harvest fruits. Jiang et al. (2018) reported that chitosan treatment induced the disease resistance of litchi fruit due to increased SOD and CAT activities. These results indicate that UV-C/L-cys treatment increased SOD and CAT activities to resist ROS-induced damage, leading to a delay in the senescence and deterioration of lily bulbs during storage.

3.5.4. *ABTS-scavenging activity*

Measurement of the ABTS-scavenging activity is one of the most widely used techniques for assessing the overall antioxidant capacity of fruits and vegetables. As shown in Fig. 5C, all groups showed an initial increase followed by a decrease in ABTS-scavenging activity during storage, with the UV-C, L-cys, and UV-C/L-cys treatments significantly enhancing the ABTS-scavenging capacity during storage ($P < 0.05$). These findings indicated that the post-harvest treatments activated the antioxidant defense system of the lily bulbs, which may partially reflect the improvement in SOD and CAT activities, and thus directly enhanced the antioxidant capacity. Furthermore, previous studies demonstrated strong correlations between antioxidant capacity and total phenols (Lin et al., 2020), suggesting that the increased antioxidant capacity of the UV-C/L-cys treatment may have also contributed to the preservation of a higher total phenolic content after 50 days of storage. Soleimani Aghdam, Sayyari and Luo (2021) showed that 150 nM phytosulfokine-α enhanced the ABTS-scavenging capacity in strawberry fruit, which was attributed to the high accumulation of phenolics, flavonoids, and anthocyanins.

3.5.5. *Ultrastructure of lily bulbs*

In addition to the peroxidation and degradation of the cell membrane, mitochondria are particularly vulnerable to attack by ROS. In general, excessive ROS production leads to mitochondrial dysfunction (Chotikakham et al., 2022). To confirm the protective effect of UV-C/L-cys against ROS-induced damage, the ultrastructure of the mitochondria was evaluated by TEM at the end of the storage period of lily bulbs. Compared with those of the treatment groups, the CK group had fewer mitochondria and a lower matrix density, and the membrane structure was discontinuous and even damaged in some cases, with breakage of the intracellular compartmentalization. The majority of the mitochondria appeared swollen and partially disintegrated, resulting in matrix leakage (Fig. 6A). Moreover, many black particles were formed because the phenolics were oxidized into quinones, resulting in the aggregation of black particles. The UV-C-treated bulbs had less swollen and injurious mitochondria with a reduced number of black particles (Fig. 6B). The L-cys-treated and UV-C/L-cys-treated bulbs contained many mitochondria, the majority of the cristae were closely arranged, and the double-membrane structure was visible without obvious swelling (Fig. 6C, D), which was consistent with the effects of these treatments in reducing the H_2O_2 content and $O_2^{\cdot-}$ generation rate. Notably, the UV-C/L-cys-treated bulbs contained spherical starch granules, which is in line with the relatively slow degradation of starch in this treatment group. These results indicated that the rupture of mitochondria that causes a metabolism disorder due to the ROS attack in lily bulbs at the end of storage could be delayed or prevented with UV-C/L-cys treatment. A similar study demonstrated that exogenous polyamine treatment preserved the pericarp mitochondrial structure and decreased the rate of increase and the amplitude of mitochondrial membrane permeability to ultimately maintain mitochondrial energy levels in “Nanguo” pears (Li, Luo, Zhou, et al., 2021).

3.6. *Correlation analysis between storage quality, volatile compounds and ROS metabolism*

In order to explore the correlation between storage quality, volatile compounds and ROS metabolism, the Mantel test was established (Fig. 7). The upper right diagram shows the Pearson correlation of storage quality and ROS metabolism. The decay rate was poitively correlated with H_2O_2 content, $O_2^{\cdot-}$ generation rate, LOX enzyme activity, and MDA content; and it was negatively correlated with ROS-scavenging enzyme (CAT and SOD) activities and the levels of ROS-scavenging substances (total phenol and ascorbic acid). These findings indicate that the senescence of Lanzhou lily bulbs was accompanied by the increase of ROS accumulation, leading to a decrease of overall quality, which confirmed the close relationship between ROS metabolism and senescence in Lanzhou lily bulbs. In addition, these correlations demonstrated that increasing the activity of ROS-scavenging enzymes (CAT and SOD) and the content of ROS-scavenging substances (total phenols and ascorbic acid) can alleviate active oxygen attacks and delay aging during post-harvest storage. The bottom left graph shows the Mantel test between volatile compounds, storage quality and ROS metabolism. Results of the Mantel test indicated that aromatic volatile compounds had significant correlations ($P < 0.05$) with decay rate,

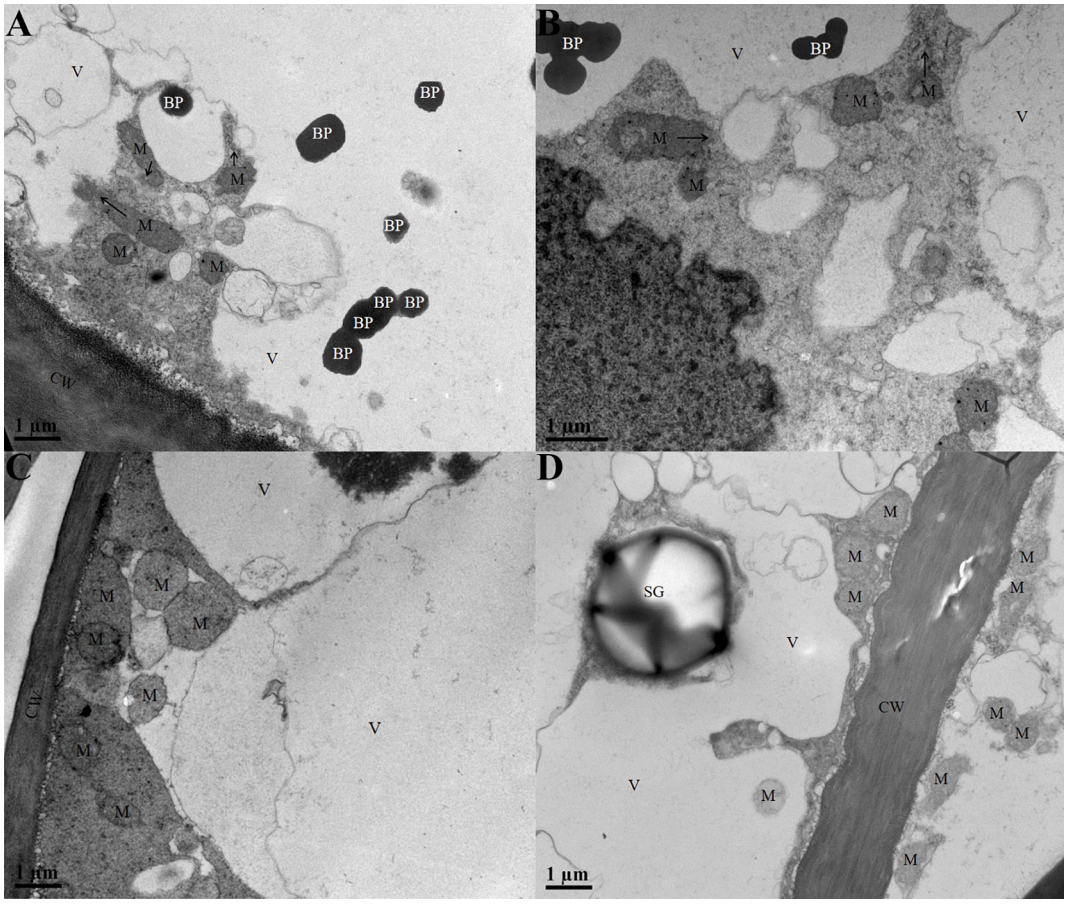

Fig. 6. Ultrastructure of Lanzhou lily bulbs in the CK group (A), UV-C-treated group (B), L-cys-treated group (C), and UV-C/L-cys-treated group (D) at 50 days of storage. CW, cell wall; M, mitochondria; V, vacuole; BP, black particles; SG, starch granule.

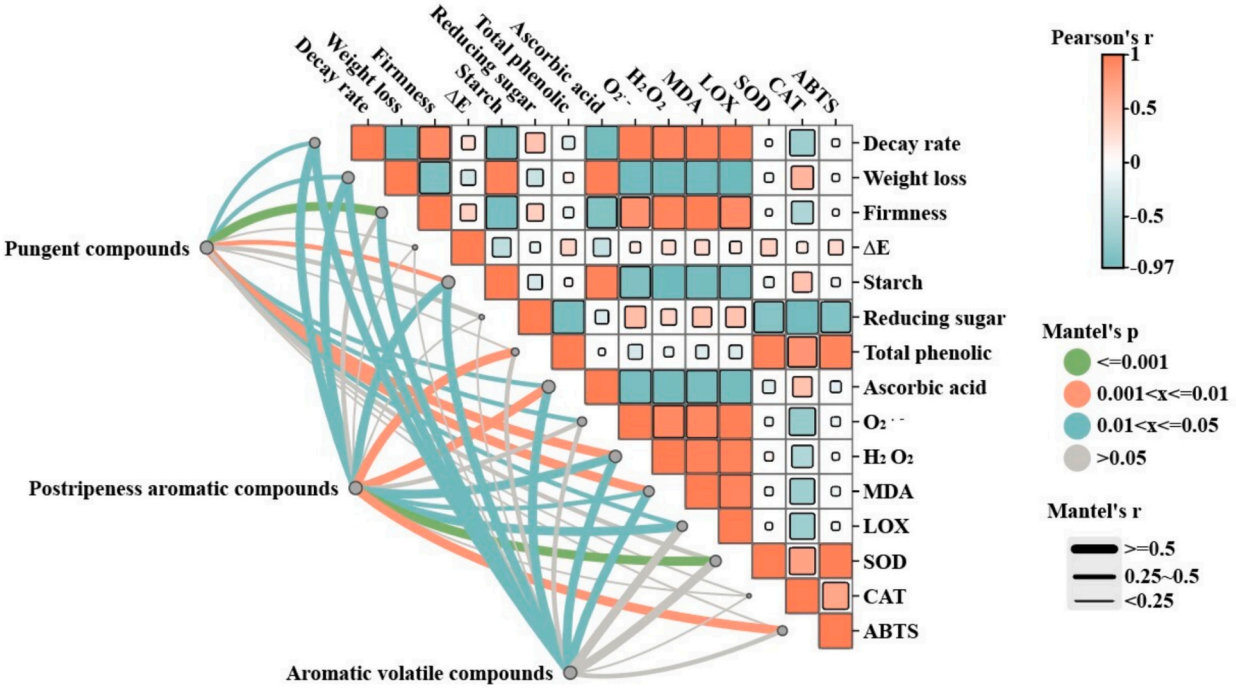

Fig. 7. Mantel test between storage quality, volatile compounds and ROS metabolism.

weight loss, firmness, starch, ascorbic acid, H_2O_2, and MDA. Pungent compounds had significant correlations ($P < 0.05$) with decay rate, weight loss, ascorbic acid, $O_2^{\cdot-}$, and LOX and a highly significant correlation ($P < 0.01$) with firmness, starch, ascorbic acid, H_2O_2, and MDA. Postripeness aromatic compounds had significant correlations ($P < 0.05$) with decay rate, weight loss, starch, H_2O_2, MDA, LOX and a highly significant correlation ($P < 0.01$) with total phenolic, ascorbic acid, SOD, and ABTS. The results indicated that the volatile compounds in Lanzhou lilies were closely related to the metabolism of ROS. UV-C/L-cys treatment can control the reduction of $O_2^{\cdot-}$, H_2O_2, and MDA content and improved SOD enzyme activity, thereby regulating the respiration rate, maintaining the quality of Lanzhou lily bulb and delaying the loss of aromatic compounds.

4. Conclusions

In summary, this study showed that UV-C radiation and L-cys treatment can effectively regulate ROS metabolic pathways to improve the post-harvest quality of Lanzhou lily bulbs and the potential regulatory mechanisms have been described. In particular, the combined UV-C/L-cys treatment delayed the decay rate, weight loss, discoloration, and reducing sugar content, while maintaining a high firmness and starch content in the lily bulbs during storage. The flavor profile fingerprint and PCA results showed that UV-C/L-cys treatment promoted the release/inhibited the loss of typical fruity aromatic volatile compounds and delayed the generation of pungent substances. UV-C/L-cys treatment effectively reduced ROS production and decreased the peroxidation of membrane lipids, resulting in overall improvement of mitochondrial function by maintaining higher activities of ROS-scavenging enzymes and higher contents of ROS-scavenging substances. Mantel test indicated that storage quality and volatile compounds was closely related to ROS metabolism. Overall, these results demonstrate that UV-C radiation and L-cys treatment can be used as a simple, eco-friendly, and safe post-harvest processing method for maintaining the quality of lily bulbs during storage, which is of great significance to expand and develop the Lanzhou lily industry.

CRediT authorship contribution statement

Le Cheng: Writing – original draft, Investigation, Conceptualization. **Mingfang Zhang:** Investigation, Conceptualization. **Haoyue Bai:** Visualization, Formal analysis. **Fengping Yang:** Visualization, Formal analysis. **Xiuhai Zhang:** Visualization, Data curation. **Difeng Ren:** Writing – review & editing, Supervision. **Yunpeng Du:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101813.

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