



Hydrogen sulfide treatment increases the antioxidant capacity of fresh Lingwu Long Jujube (*Ziziphus jujuba* cv. Mill) fruit during storage

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ABSTRACT

Hydrogen sulfide (H₂S) has been identified as an important gaseous signal molecule in plants. Here, we investigated the effects of H₂S on postharvest senescence and antioxidant metabolism of Lingwu Long Jujube (*Ziziphus jujuba* cv. Mill) fruits (LLJF). Fumigation of Jujube fruits with H₂S released from 0.4 mm NaHS could significantly prolong the postharvest shelf life of jujube fruits, reduce the decay rate of fruit, the weight loss of fruit, and inhibit the fruit loss, hardness, color, soluble solids, and titratable acidity. Compared with the control group, exogenous H₂S fumigation significantly decreased the loss of chlorophyll, carotenoids, soluble protein, ascorbic acid, phenols, and flavonoids in jujube fruits during post-harvest storage. At the same time, H₂S could significantly delay the accumulation of malondialdehyde (MDA), hydrogen peroxide (H₂O₂) and superoxide anion (O₂^{•-}) and promote catalase (CAT), superoxide dismutase (SOD), ascorbate peroxidase (APX), peroxidase (POD) activity, and inhibit polyphenol oxidase (PPO) activity. To summarize, H₂S can effectively alleviate postharvest senescence and decay of jujube fruits by regulating the ROS accumulation and antioxidant enzymes, and prolong the storage period of postharvest.

1. Introduction

Lingwu Long Jujube (*Ziziphus jujuba* cv. Mill) is a specialty of Lingwu city in Ningxia and an important economic fruit. It has been cultivated in Lingwu city for more than 1300 years, and is recognized as the best fresh jujube variety. The fruit is rich in nutrients, especially the highest content of vitamin C. (Dai et al., 2017; Han et al., 2019). It has high medicinal value, and has been used as a traditional folk medicine for more than 4000 years, e.g., it plays an important role in anti-oxidation, anti-allergic, anti-inflammatory, anti-cancer, anti-obesity, and gastrointestinal protection, etc (Xu et al., 2020; Rashwan et al., 2020; Feng et al., 2019). However, Lingwu Long Jujube fruits (LLJF) are easy to lose water after harvesting, which always result in fruit shrinkage, softening, decay, mildew, etc. The gradual decline in nutritional value and economic value has greatly affected the post-harvest storage and sales of jujube fruits (Liu et al., 2018), and severely restricted the development

of the fresh food industry of jujube fruits in China (Liu et al., 2018).

Hydrogen sulfide (H₂S) is colorless, flammable, and has a strong smell of rotten eggs. H₂S is the 3rd endogenous gaseous signal besides carbon monoxide (CO) and nitric oxide (NO), and is known to play multi-faceted roles in the regulation of plants and animals processes (Wang, 2012; Ali et al., 2019). In recent years, many reports have shown that H₂S plays a key role in adventitious root formation (Lin et al., 2012), stomatal movement and photosynthesis (Duan et al., 2015), and seed germination (Zhang et al., 2008) during plant growth and development. H₂S, as a gaseous regulator or signaling molecules, can also affect the harvested vegetables, such as bananas (Ge et al., 2018), persimmons (Niazi et al., 2021), kiwi fruit (Zhang et al., 2013a,b), cabbage (Al Ubeed et al., 2018), broccoli (Li et al., 2014a,b), etc., by regulating the active oxygen system, slowing down respiration and energy metabolism to delay the aging of fruits and vegetables (Huo et al., 2018).

Although, the recent research focuses on the fresh-keeping

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technology of jujube mainly on the aspects of modified atmosphere preservation (Xu et al., 2020), low-temperature preservation (Yu et al., 2021), chemical preservation (Li et al., 2014a,b), and film preservation (Zhang et al., 2014). Therefore, research on the new LLJF postharvest storage and preservation technology is of great significance to promote the jujube fresh food industry. To date, there is no study on the application of H₂S in the postharvest storage of LLJF.

We speculated that H₂S might be also involved in the regulation of physiological and biochemical characters of LLJF during postharvest storage. In present research, the effects of H₂S signal on the postharvest storage of LLJF were investigated, including of physicochemical properties (decay rate, hardness, color, and titratable acidity, etc.), the natural antioxidants, and the bioactivities of antioxidant related enzymes. The obtained results can provide a theoretical basis to extend the storage period of post-harvested LLJF.

2. Materials and methods

2.1. Treatments of fruits

LLJFs were collected from the farm in Lingwu county, Ningxia province (China) during Mid-September, 2021. The physically damaged LLJF were removed, and the fruits of regular shape, uniform size, and color, and disease-free were kept for further treating, they were soaked in 75% alcohol for 2 min for disinfection and then natural air-drying. Solution of NaHS·3H₂O (Sigma, Shanghai, China) was used as H₂S donor according to our previous study (Ni et al., 2016). NaHS solutions with concentrations of 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, and 1.1 mM were prepared in sealed containers for further testing on daily basis. Each group of LLJFs were treated with different concentration of H₂S (0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, and 1.1 mM) in the sealed containers at 25 °C in three replicates. During treatment, their photographs were taken and the phenotypic changes were documented such as the appearance of mildew and softening of the fresh LLJFs. Simultaneously, the rates of the rotten fruit and the quality of the fruit were also observed.

2.2. Appearance evaluation

Fruit decay rate was investigated every other day using the following formula, fruit decay rate (%) = rotten fruit number/total fruit number × 100% (Hu et al., 2019).

The rate of weight loss was determined using the weighing method: the weight of LLJFs was measured every 48 h, and the rate of weight reduction was calculated using the following formula (Zhang et al., 2020):

$$\text{Weight loss rate (\%)} = [(a-b)/a] \times 100\%$$

The hardness was measured with a texture analyzer (TMS-PRO physical property analyzer, FTC, USA) (Zhang et al., 2020). A cylindrical probe with a diameter (2 mm) was used for hardness measurement. The settings were as follows: The test speed was 30 mm/min; the downward pressure deformation was 40%; the trigger force was 0.15 N; with the average of 10 capsules in each test.

The a*, b*, L*, C*, and H* values of peel and pulp color were measured on symmetrical two sides of the equatorial region of each fruit using a calibrated colorimeter (HP-200 colorimeter) in reference to the following method (Prabhakar et al., 2022). Briefly, L* indicates brightness, ranging from 0 (black) to 100 (white); a* value indicate a red (+) to green (−) bias in substances colored; b* value indicates yellow (+) to blue (−) bias; saturation C* = (a*² + b*²)^{1/2}; tonal angle H* = arctan (b*/a*); total changes in color are indicated with ΔE, the color difference value ΔE represents the difference in color (L, a, b) at Nth day of storage of fruit compared to that at 0th day of storage (L*, a*, b*) (Zhang et al., 2021; Chen et al., 2014). ΔE was calculated as follows:

$$\Delta E = \sqrt{(L - L^*)^2 + (a - a^*)^2 + (b - b^*)^2}$$

Total 10 LLJFs were investigated each time using the average values.

Total soluble solids (TSS) were measured using a digital refractometer (Tongfang Inc., Shanghai, China) with values being expressed as % (Jiang et al., 2004).

The titratable acidity (TA) of the LLJFs (three replicates of each treatment) was assayed using titration with NaOH (0.1 mM) at pH 8.3 (Francisca et al., 2016).

2.3. Assay of chlorophyll and carotenoid content

Chlorophyll and carotenoid contents of LLJFs were determined as follows (Nath et al., 2011; Eitzbach et al., 2020). An accurate amount of LLJFs was homogenized and incubated on ice in a flask containing 10 mL of an absolute ethanol: acetone solution: water volume ratio of 4.5 : 4.5 : 1 (measure 45 mL of acetone, 45 mL of absolute ethanol and distilled water to make the volume to 100 mL, and mix well) as an extraction solvent. And then, the extractions were kept in darkness for 48 h at 4 °C. After centrifugation, the values of OD_{663 nm}, OD_{645 nm}, and OD_{440 nm} of supernatant were assayed, respectively (Lichtenthaler and Wellburn, 1983). The contents of chlorophyll and carotenoid (mg·g⁻¹) were calculated as follows:

$$\text{Carotenoid} = A_{440} \text{ V/W}; \text{Chla} = (12.72 \cdot A_{663} - 2.59 \cdot A_{645}) \text{ V/W};$$

$$\text{Chlb} = (22.88 \cdot A_{645} - 4.67 \cdot A_{663}) \text{ V/W};$$

$$\text{Chl} = \text{Chla} + \text{Chlb}$$

2.4. Assay of ascorbic acid (Vc), total phenols, flavonoids, and soluble protein

Ascorbic acid (Vc) in samples were determined according to the method by Moo-Huchin et al. (2014). LLJF samples (2.0 ± 0.05 g) were ground using 20 g/L oxalic acid, diluted to the volume of 100 mL, extracted for 10 min, and filtered for filtrate collection. Further, the 10 mL of the filtrate was poured in a 100 mL Erlenmeyer flask and titrated with 2,6-dichlorophenol-indophenol until a pink color appeared and remained unchanged for 15 s.

The total phenolics and flavonoid in LLJFs were determined followed the descriptions by previous reports (Pirie and Mullins 1976; Zhishen et al., 1999). 0.2 g of LLJFs sample was mixed with 2 ml pre-cooled HCl-methanol solution (1%), and grind on ice; and then, the mixture was diluted the volume to 10 ml with HCl-methanol solution (1%), and incubated 4 °C for 20 min under dark. After filtration, the values of OD_{280nm} and OD_{325nm} of filtrates were measured, respectively. Based on the standard curve with gallic acid and rutin, the content of total phenols and flavonoids of samples were calculated and expressed as mg·g⁻¹ FW (Pirie and Mullins 1976; Zhishen et al., 1999).

For determination of soluble protein contents LLJFs samples (1.0 ± 0.05 g) were obtained as a homogenate and centrifuged (12,000 rpm for 20 min) at 4 °C followed by mixing of supernatant (1 mL) with Coomassie Brilliant Blue (5 mL) (Bradford, 1976). The values of OD_{595 nm} of different samples were recorded, and the soluble protein contents were calculated and expressed as mg·g⁻¹ FW.

2.5. Assay of MDA, H₂O₂ and O₂^{•-} content in samples

The MDA, H₂O₂, and O₂^{•-} contents were determined according to the manufacturer's instructions using kits (Suzhou Comin Biotechnology Co., Ltd. Suzhou, China). For MDA assay, 1.0 g samples were grinded with 5.0 ml TCA solution (100 g/L); After centrifugal at 10,000 g for 20 min at 4 °C, the supernatants were obtained and used for measurement

using kit A003-1 (Suzhou Comin Biotechnology Co., Ltd. Suzhou, China). H_2O_2 and $O_2^{\cdot -}$ content of samples were measured using H_2O_2 -1-Y kit and SA-1-G kit (Suzhou Comin Biotechnology Co., Ltd. Suzhou, China), respectively. All treatments were repeated three times.

2.6. Determination of CAT, SOD, APX, POD, and PPO activities

The activities of CAT, SOD, APX, POD and PPO were determined using respective assay kit (Suzhou Comin Biotechnology Co., Ltd. Suzhou, China) following the manufacturer's instructions. All treatments were repeated three times. CAT activity of samples was assayed based on method of ammonium vanadate-molybdate using CAT-1-W kit (Suzhou Comin Biotechnology Co., Ltd. Suzhou, China). SOD, APX, POD and PPO activity of samples were assayed using SOD-1-W kit (WST-1 method), APX-1-W kit, BC0090 kit, PPO-1-Y kit (Suzhou Comin Biotechnology Co., Ltd. Suzhou, China), respectively.

2.7. Statistical analysis

The One-way or Two-way analysis of variance (ANOVA) to data were used for significant differences analysis using SPSS Statistics software at $p < 0.05$ (SPSS version 20.0, Armonk, NY, USA).

3. Results

3.1. Effects of H_2S on the appearance and decay rate of jujube fruit during storage

LLJFs were fumigated with H_2S (0.1 mM–1.1 mM) and water treatment as control (Fig. 1.) Treatment under 0.4 mM hydrogen sulfide (H_2S) delays the senescence and rotting of jujube fruits in a dose-dependent manner. As the storage time prolonged, the decay rate of higher concentration of NaHS treatment was increased. Particularly, 0.4 mM NaHS showed the remarkable inhibitory effects on the decay, moldy growth, softening, and shrinkage of Jujube fruits. Therefore, this concentration was used for the subsequent experiments throughout the study (Fig. 2).

3.2. Effects of H_2S on weight loss, hardness, color difference, and titratable acidity in fruit

After harvest, the weight loss rate of jujube fruit increased linearly with the storage time owing to water transpiration (Fig. 3 A). Furthermore, the weight loss in control was higher significant than those of the H_2S treated groups during storage ($p < 0.05$).

Hardness is an important parameter reflecting the degree of fruit

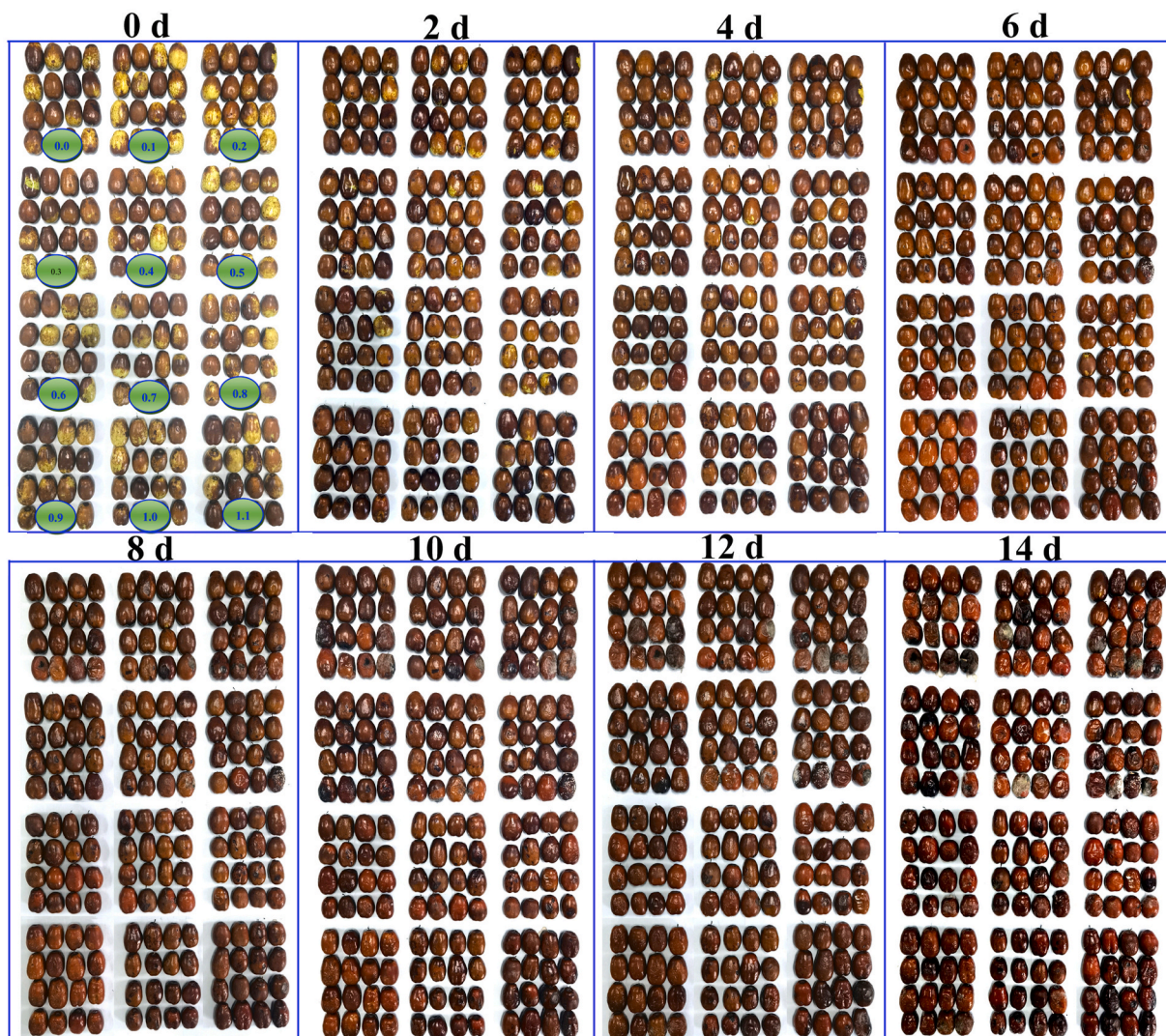


Fig. 1. The photographs of LLJFs after H_2S treatment. Jujube fruit was fumigated daily with various concentrations of aqueous NaHS (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, and 1.1 mM). The preservation temperature was 25 °C.

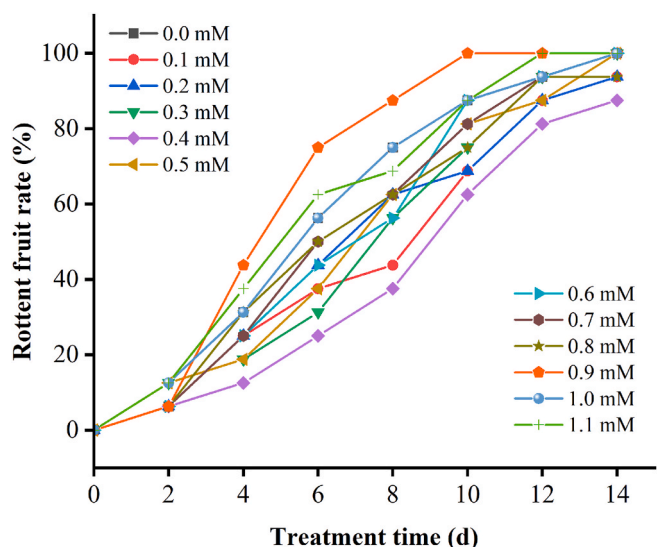


Fig. 2. The rotten rate of LLJF after H₂S treatment during preservation. Every day, jujube fruits were fumigated with various concentrations of aqueous NaHS (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 and 1.1 mM). The preservation temperature was 25 °C.

ripeness and softening. The hardness (Fig. 3B) of jujube fruit declines with storage time; however, the loss in hardness is delayed in H₂S treated jujube fruit compared to the control group. From the 2nd day of the treatment, the hardness of H₂S treated groups were higher than that of the control, and from the 4th day of H₂S treatment, a significant difference ($p < 0.05$) was observed. It shows that treatment under 0.4

mM H₂S obviously delay the senescence and softening process of jujube fruit during post-harvest storage.

The color change of the skin and pulp of jujube fruit during storage was depicted in Fig. 3. The color difference (ΔE) result indicates that the color difference between H₂S treated and control group grew with the storage time and that the color difference between the skin (Fig. 3C) and pulp (Fig. 3D) of jujube fruit treated with H₂S slowly changed. H₂S can retard fruit ripening and senescence by altering the pigment color difference.

The soluble solids (TSS) content in fruit increased at first and then decreased with storage time (Fig. 3E). Throughout the storage period, the soluble solids content in treated group was continuously greater than that of the control with significant difference ($p < 0.05$) from 4th day to 14th day. Titratable acidity (Fig. 3F) in the control and H₂S treated jujube fruit gradually dropped with the prolonged storage period. On the contrary, titratable acidity in NaHS treatment was in decreasing trend yet significantly higher than that of untreated group ($p < 0.05$) during storage period (Fig. 3E).

3.3. Effects of H₂S on the chlorophyll and carotenoid contents in jujube fruit

The total chlorophyll, chlorophyll a, chlorophyll b, and carotenoids (Fig. 4A–D) of LLJFs showed a rising trend at first and then decrease with the extension of the storage period. The content of total chlorophyll and chlorophyll a in the treatment group reached the maximum on the 8th day, while the control group raised to the highest content on the 4th day, the chlorophyll b content of the treatment group and the control group reached the highest on the 4th day, and the carotenoid content reached the highest on the 6th day, and then revealed a downward trend during post-harvest storage in both un-treated and H₂S treated groups,

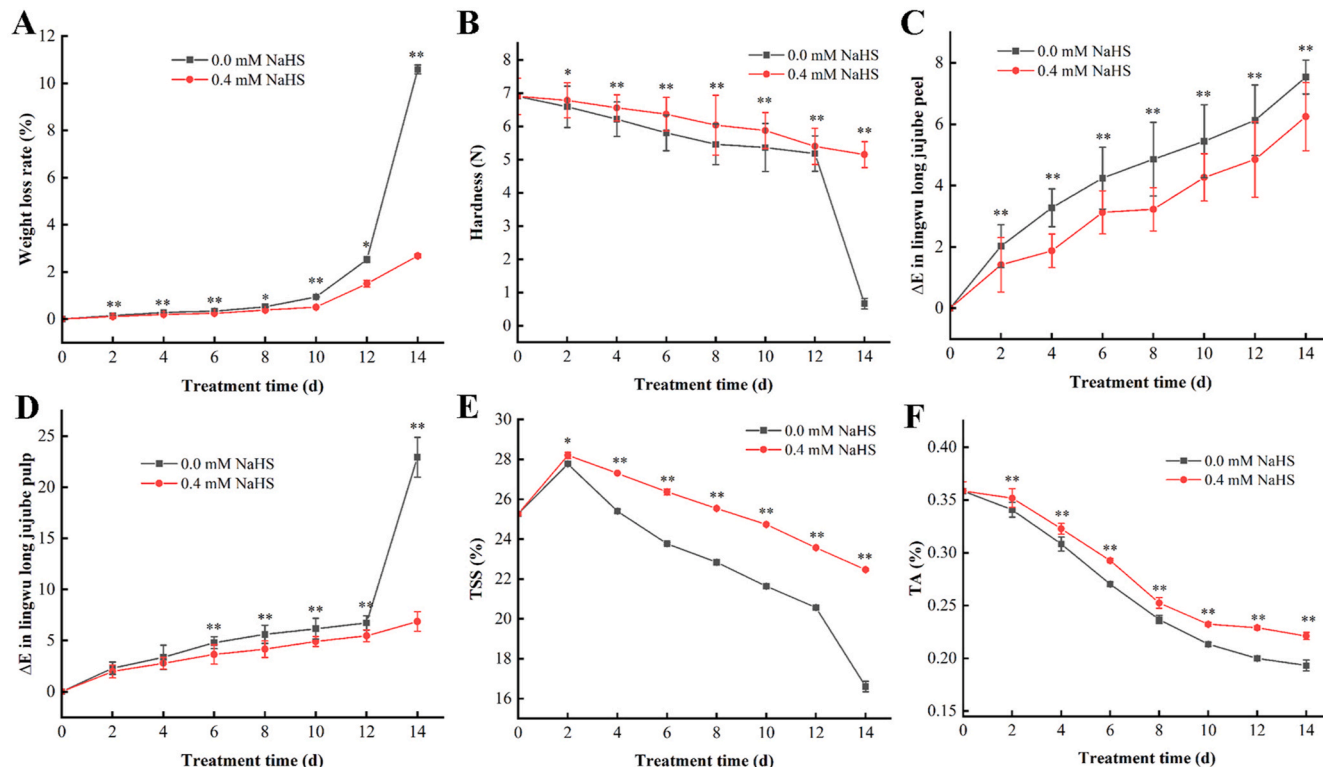


Fig. 3. Effects of H₂S on weight loss rate (A), hardness (B), peel color difference (C), pulp color difference (D), total soluble solids (TSS) (E) and titratable acidity (F) of Lingwu Long Jujube fruits. Jujube fruits were fumigated with 0.4 mM H₂S donor NaHS aqueous solution with water as the control groups for 0–14 d. Data are presented as means \pm SD (n = 3 replicates for A, E, F), n = 10 replicates for (B, C, D). The symbols * and ** in figure and the following ones stand for a significant difference between control and 0.4 mM NaHS treatment at $p < 0.05$ and $p < 0.01$, respectively. FW = fresh weight. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

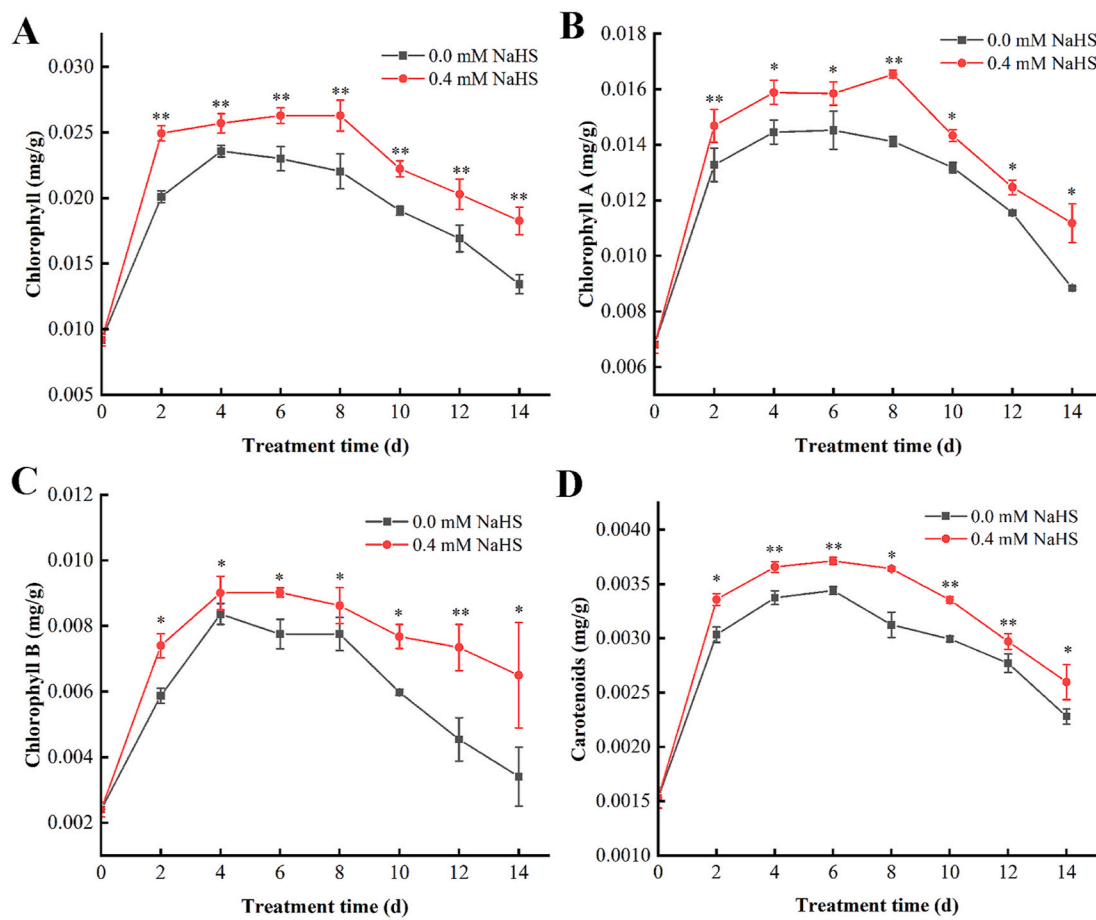


Fig. 4. Effects of hydrogen sulfide on the contents of total chlorophyll (A), chlorophyll a (B), chlorophyll b (C) and carotenoids (D) in Lingwu Long Jujube fruits. Jujube fruits were fumigated with 0.4 mM H₂S donor NaHS aqueous solution with water as the control groups for 0–14 d. Data are presented as means \pm SD (n = 3). FW = fresh weight.

whereas H₂S could restore relatively higher level during storage period. The above results indicate that the H₂S treatment can delay the degradation of chlorophyll and carotenoids in jujube fruits, maintain the fresh color of the fruit, and delay the senescence of the fruit after harvest.

3.4. Effects of hydrogen sulfide on the contents of Vc, total phenols, flavonoids, and soluble protein in jujube fruit

The ascorbic acid in two groups increased firstly and then decreased with the storage, and reached the highest on the day 11 with 336.49 mg/100 g and 330.26 mg/100 g, respectively (Fig. 5A). The reason is that ascorbic acid is gradually consumed during fruit ripening after harvest, the ascorbic acid content of the H₂S treated groups were dramatically higher than that of the un-treated group ($p < 0.05$) during storage.

The total phenol content of the H₂S treated groups were always higher than that of the control group throughout the storage period (Fig. 5B). And during the storage process, the total phenol content was first decreased, then increased, and then decreased. From day 6 to day 10 of storage, the total phenol content slowly recovered, while the rising trend of the control group was comparatively lower. The similar trend was noticed for the alterations in flavonoid content (Fig. 5C). H₂S treatment could considerably alleviate the decline and maintain the elevated levels of phenolics and flavonoid throughout the storage period.

As shown in Fig. 5D, the soluble protein content decreased during the post-harvest storage; H₂S treatment could alleviate the decreasing of soluble protein content significantly ($p < 0.05$). The above results demonstrated that H₂S treatment could prevent the protein degradation

in jujube fruit during storage.

3.5. Effects of H₂S treatment on the MDA, H₂O₂ and O₂^{•-} in jujube fruits

The MDA content of jujube fruits increased throughout the storage in both of groups (Fig. 6A). MDA content in fruits of the un-treated group increased rapidly, while the increasing trend was relatively slow in the treatment group. The MDA content in treatment groups were consistently higher than that of the un-treated group (from day 4 to day 14) ($p < 0.05$). As an index of lipid peroxidation (Li et al., 2019), H₂S treatment significantly reduced MDA accumulation suggesting the role of H₂S in alleviating the lipid peroxidation.

Fig. 6B illustrated the influence of H₂S on H₂O₂ of LLJFs after post-harvest. Throughout the storage period, the H₂O₂ content of the H₂S treated groups were always lower than that of the un-treated group ($p < 0.05$). H₂S treatment could slow down the accumulation of H₂O₂ content. Fig. 6C illustrated the influence of H₂S on the O₂^{•-} content of post-harvest LLJFs. During the storage period, the content of O₂^{•-} increased at first, then decreased followed by further alterations; however, the treatment group always showed the lower content than the control group. The H₂S treatment group can delay the appearance of the accumulation peak of O₂^{•-} content. The above results indicated that H₂S treatment significantly prevented the synthesis of H₂O₂ and O₂^{•-} during storage, and hence delayed the post-harvest senescence process.

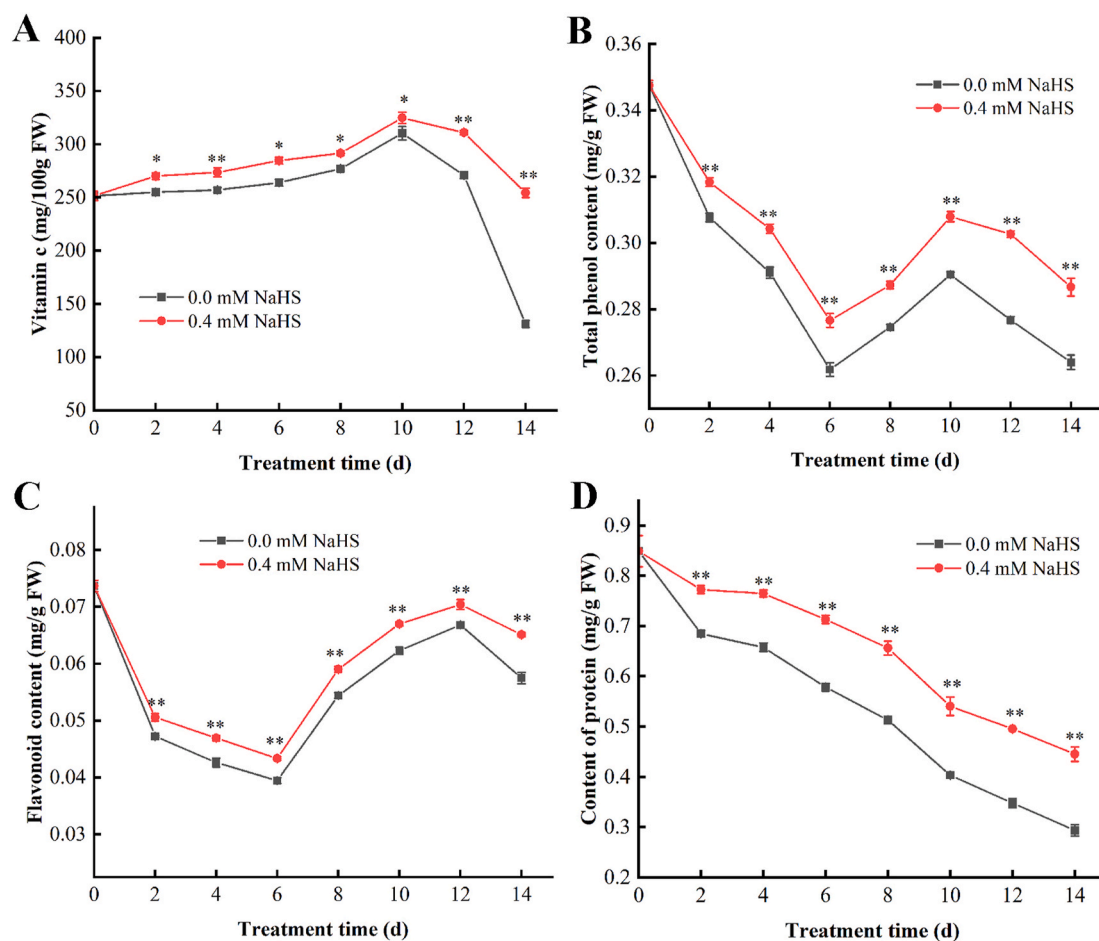


Fig. 5. Effect of hydrogen sulfide on the content of ascorbic acid (A), total phenols (B), flavonoids (C) and soluble protein (D) in Lingwu Long Jujube fruits. Jujube fruits were fumigated with 0.4 mM H₂S donor NaHS aqueous solution for 0–14 days, and distilled water was used as the control group. Data are expressed as mean ± SD (n = 3). FW = fresh weight.

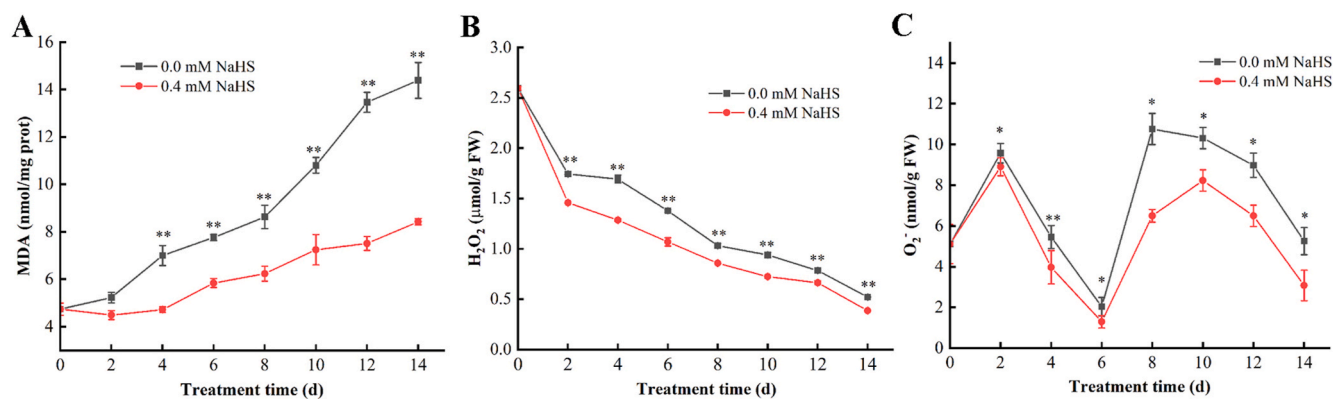


Fig. 6. Effects of H₂S on the content of malondialdehyde (MDA) (A), hydrogen peroxide (H₂O₂) (B) and superoxide anion (O₂⁻) (C) in Lingwu Long Jujube fruits. Jujube fruits was fumigated with 0.4 mM H₂S donor NaHS aqueous solution for 0–14 days, and distilled water was used as the control group. Data are expressed as mean ± SD (n = 3). FW = fresh weight.

3.6. Effects of H₂S on the activities of CAT, SOD, APX, POD and PPO in jujube fruit

Fig. 7A illustrated the influence of H₂S on the CAT activity of jujube fruits following harvest. H₂S treatment could rapidly increase the CAT activity on day 2 followed by a gradual decrease. Throughout the storage period, the CAT activity of the H₂S groups were constantly higher than that of the un-treated group (*p* < 0.05). H₂S considerably improved

the CAT activity in jujube fruits throughout the storage period (Fig. 7A).

SOD is an important antioxidant enzyme in the antioxidant system of fruits. Its main function is to protect the cell membrane system from the damage of ROS, thereby delay the fruit ripening. The SOD activity of jujube fruits in the treatment group was consistently more significant than that in the control group (*p* < 0.05) (Fig. 7B), which indicated that H₂S treatment could delay the decline of SOD activity.

Fig. 7C illustrated the influence of H₂S on the APX activity of jujube

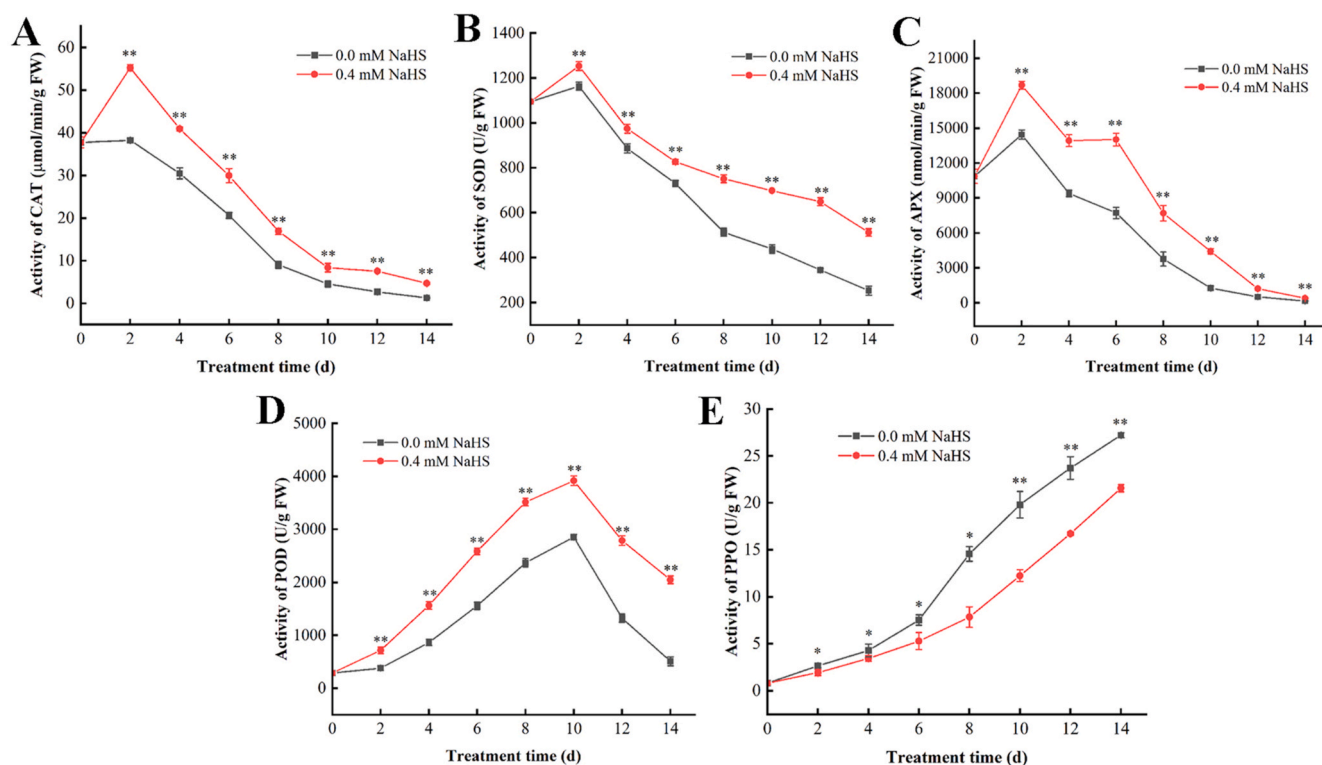


Fig. 7. Effects of H_2S on the activities of catalase (CAT), superoxide dismutase (SOD), ascorbate peroxidase (APX), peroxidase (POD), polyphenol oxidase (PPO) activity in Lingwu Long Jujube fruits. Jujube fruits was fumigated with 0.4 mM H_2S donor NaHS aqueous solution for 0–14 days, and distilled water was used as the control group. Data are expressed as mean \pm SD ($n = 3$). FW = fresh weight.

fruits following harvest. H_2S treatment could rapidly increase the APX activity of Jujube fruits on day 2 followed by a gradually decreasing. Throughout the storage period, the APX activity of jujube fruits in the treatment group was consistently more significant ($p < 0.05$).

Throughout the storage period, both the control and treatment groups demonstrated an initial increase followed by a further decrease. POD activity reached the maximum value on the day 10 of storage, and then showed a downward trend (Fig. 7D). The POD activity of the H_2S group showed comparatively higher level from the day 2 of storage ($p < 0.05$).

The PPO activity in jujube fruits showed an upward trend throughout the storage (Fig. 7E). The PPO activity of the H_2S treatment groups were comparatively lower than that of un-treated samples ($p < 0.05$).

Above results of indicated that H_2S could reduce the ROS accumulation, increase the activity of antioxidant enzymes, and inhibit the activity of polyphenol oxidase, thereby alleviated the postharvest senescence of fruits, and maintained the jujube fruit quality.

4. Discussion

LLJFs have bright color, thin skin, thick flesh, and rich nutrient content (Feng et al., 2019). However, it is very easy to lose water and shrink after harvest, leading to metabolic disorders, and it is prone to softening, mildew and other phenomena, the fruits became darker, and the color difference was gradually increased with the extension of storage time, which seriously affect its nutritional and economic values (Zhou et al., 2019; Chen et al., 2014). Our study revealed that H_2S treatment could effectively reduce the weight loss in jujube fruits and maintain the higher firmness. H_2S fumigation slowed the degradation of TSS and TA in jujube fruits indicating its role in delaying fruit maturation. Color is also a significant indicator of the fruit's quality and worth as a commodity, H_2S fumigation significantly reduced the color intensity change (ΔE) of the skin and pulp of jujube fruits during storage. Our

results were consistent with the reports by Hu et al. (2012) and Yao et al. (2020), who reported that strawberry fruits fumigated with different concentrations of H_2S had significantly lowered rot index and fruit hardness compared with the control group, and H_2S treatment can also slow the change of tomato and strawberry color and delay the ripening of the fruits during post-harvest storage.

Fruit ripening and senescence are always accompanied by chlorophyll degradation (Fu et al., 2017; Hörtensteiner, 2006). In our study, H_2S treatment could significantly prevent the chlorophyll and carotenoid degradation in jujube fruits, which was consistent with the previous findings suggesting that H_2S treatment could significantly prevent the chlorophyll and carotenoid degradation in Fresh-cut Kiwifruit (Zhang et al., 2013a,b).

Ascorbic acid, phenols, flavonoids, and soluble proteins are important nutrients in jujube fruits (Ni et al., 2016; Shukanta et al., 2020). In our study, H_2S treatment could significantly prevent the content of ascorbic acid, phenols, flavonoids, and soluble proteins degradation in jujube fruits, which was consistent with the previous findings suggesting that H_2S treatment could significantly prevent the phenols, flavonoids, and soluble proteins degradation in Fresh-cut Kiwifruit and eggplant fruit and hawthorn fruit (Zhang et al., 2013a,b; Barzegar et al., 2021; Aghdam et al., 2018).

Environmental stress and tissue aging can lead to the ROS accumulation in fruit and vegetable tissues, inducing a large number of free radicals, damaging biological cell membranes, and producing a large number of membrane peroxidation products such as malondialdehyde (Li et al., 2019). ROS are the primary mediators of oxidative damage in plants, and they mainly consist of H_2O_2 and $\text{O}_2^{\cdot-}$. Accumulation of a certain amount can cause oxidative damage to cell components and promote fruit senescence and spoilage (Zhang et al., 2013a,b). We found that H_2S could effectively lower the H_2O_2 accumulation and $\text{O}_2^{\cdot-}$ content via significantly enhancing the activities of CAT, SOD, POD, and APX in Lingwu Long Jujube (*Ziziphus jujuba* cv. Mill) fruit. In our study, H_2S

treatment could comparatively restore the higher levels of ascorbic acid, flavonoid, and phenolics in jujube fruits. The flavonoids content in Chinese jujube treated with composite coating was relatively higher indicating that the composite coating can delay the decomposition of flavonoids (Yu et al., 2021).

PPO is the main enzyme that causes enzymatic browning. The ripening and senescence of fruit tissue is often accompanied by the increase of PPO activity, which eventually leads to the browning of fruit tissue, which changes the color of the fruit and affects its storage quality (Li et al., 2014a,b). We found that H₂S donor treatment could inhibit the rapid rise of PPO activity in the fruit, thereby alleviating the degree of browning of the fruit during storage.

This was consistent with the H₂S treatment that could effectively inhibit the postharvest rot of fruits and vegetables (Fu et al., 2017), and the changes in physiological and biochemical indicators during maturation and senescence of plants such as fresh cut flowers (Zhang et al., 2011; Zhang et al., 2021), fresh cut pears (Hu et al., 2017), and mulberries (Hu et al., 2014).

5. Conclusions

To summarize, we demonstrated that exogenous H₂S can effectively delay the degradation of jujube fruits following harvest and preserves their hardness, color, nutrients, and natural antioxidants. H₂S could inhibit the buildup of ROS such as H₂O₂ and O₂⁻ and the lipid peroxidation products MDA and PPO activity. Moreover, it could also enhance the antioxidant enzymes CAT, SOD, APX and POD activities which ultimately prolonged the senescence of post-harvested jujube fruits.

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CRedit authorship contribution statement

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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.

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