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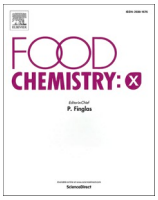

Melatonin treatment maintains the quality and delays senescence of postharvest cattails (*Typha latifolia L.*) during cold storage

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ABSTRACT

Melatonin treatment was investigated for the sensory quality and senescence in postharvest cattails (*Typha latifolia L.*) during cold storage. The 0.75 mM melatonin treatment reduced surface browning and delaying lignification of Cattails stored at 4 °C. The results showed that melatonin treatment slowed weight loss and firmness, maintained sensory quality and reducing sugar content. Melatonin treatment reduced browning by inhibiting the increase of MDA and H_2O_2 contents and POD activity. Melatonin treatment maintained high non-enzymatic antioxidant components (Vitamin C and total phenolic content) and antioxidant enzyme activities (SOD, CAT, and APX), thereby alleviating the browning and senescence of postharvest cattails. These findings indicate that melatonin treatment can maintain postharvest cattails quality.

1. Introduction

Cattails (*Typha latifolia* L.), perennial herbs, are widely found in wetlands, lakes, ponds, and slow-flowing areas of rivers (Zhang, Tapia, Webb, Huang, & Miao, 2008). In recent years, the primary research on cattails as a typical aquatic economic plant has concentrated on water purification, biofuel, and landscaping (Rebaque et al., 2017). However, research on cattails' quality and shelf life after harvest was limited. Cattails are the most local and precious artificially cultivated vegetable in Jianshui County, Yunnan Province, China. As high-end vegetables, they are an essential side dish for cross-bridge rice noodles. The young and new rhizomes are edible parts. The color of the cattails is creamy white, the texture is crisp and tender, and the taste is fresh and sweet. It contains rich phytonutrients, such as proteins, vitamins, polyphenols, and dietary fiber, as well as many inorganic elements, such as potassium, sodium, and calcium, which are popular with consumers. However, cattails' edible parts are mostly sponge structures with high moisture content, vigorous respiration, and fast metabolism. During storage and transport, cattails are susceptible to water loss and wilting, lignification, browning, and nutrient reduction, reducing their edible quality and making them lose their original flavor (Liu, Zeng, Fan, Meng, & Liu, 2022). This study aims to find a preservation technology to solve the quality fission of cattails.

Melatonin (MT) is an endogenous indole compound with multiple biological functions in plants (Reiter et al., 2015; Wei et al., 2020). As a green, safe and efficient indoleamine, it is involved in physiological activities, including plant growth and development, maturation and senescence, biotic or abiotic stress response (Jiao et al., 2022; Sun et al., 2015). Numerous studies have shown that melatonin can effectively regulate ripening and senescence, improve resistance to stress and disease, and keep quality in postharvest fruits and vegetables (Madebo, Hu, Zheng, & Jin, 2021). Melatonin treatment enhances disease resistance to *B. cinerea*-caused gray mold rot in cherry tomato fruit by promoting an increase in endogenous melatonin and regulating the benzene propane pathway (Li et al., 2019). Melatonin treatment maintains the quality of water bamboo shoots and controls lignin accumulation by regulating the enzyme activities involved in lignin biosynthesis and expression of corresponding genes (Yang et al., 2022). Melatonin maintains quality and reduces anthracnose incidence in guava fruit by improving antioxidant capacity and defense-related enzyme activities (Fan et al., 2022).

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Melatonin delays senescence and decay of strawberries by increasing melatonin biosynthetic-related gene expression and endogenous melatonin content (Liu et al., 2018). Melatonin protects peaches from chilling injury by reducing membrane lipid peroxidation and promoting phenolic accumulation (Gao et al., 2018). Melatonin delays senescence and browning in rambutan fruits by modulating reactive oxygen species and phenolics (Wei et al., 2022). Melatonin delays the senescence of peach fruit by increasing enzymatic and non-enzymatic antioxidant systems and decreasing membrane lipid peroxidation (Gao et al., 2016). Melatonin regulates the ripening period in pre-harvest cherries by participating in the regulation of hormonal balance (Tijero, Munoz, & Munne-Bosch, 2019). Melatonin prevents fresh-cut potatoes from browning by strengthening enzymatic and non-enzymatic systems to scavenge reactive oxygen species and maintain membrane integrity (Li et al., 2022).

To this day, melatonin has shown broad prospects in enhancing antioxidant activity, inhibiting browning, prolonging shelf life, and improving the quality of postharvest fruits and vegetables. Unfortunately, there is nothing available on the application of melatonin to preserve cattails. The authors believe that cattails treated with melatonin can also reduce water loss, delay lignification, and inhibit browning. Melatonin treatment was studied to evaluate its effects on several indicators of sensory attributes, quality indicators, and related enzymatic systems of cattails. Expecting to maximize the quality and nutritional value of cattails and meet the diverse needs of the market and consumers, simultaneously promoting the industrialization development of cattails in Yunnan province.

2. Materials and methods

2.1. Raw materials

Fresh cattails were harvested from the planting base in Jianshui, China. The cattails were transported to the laboratory within 2 h and precooled (24 h, 4 °C). Subsequent cattails with no apparent diseases or damages, uniformity of maturity and size, approximately 15 cm in length, and no signs of browning on the surface were selected for the preservation experiment.

2.2. Melatonin treatment

The screened cattails were washed with distilled water, soaked in 0.02 % (w/v) sodium hypochlorite solution for 15 s, and randomly divided into two groups. The cattail roots were immediately dipped in distilled water (control), 0.75 mM melatonin(Guangzhou Jianda Biotechnology Co., Ltd, Guangzhou, China) solutions for 5 min, air-dried by cold air at room temperature, placed in commercial polyethylene (PE) boxes (18×12×5.5 cm) and covered with 0.03 mm plastic wrap. All samples were stored at 4 °C, and the indexes were measured every 3 d. The 0.75 mM melatonin was selected from preliminary experiments with 0, 0.25, 0.50, 0.75, and 1.00 mM melatonin by sensory quality (Fig. S1).

2.3. Sensory quality

The shelf life of cattails was supposed to end when they became brown, wilted, and lignified. An assessment of the sensory attributes (color, texture, odor, decay, and acceptance) was conducted with a scale of 5 (best) to 1 (worst), where 3 is considered to be unmarketable. (Di et al., 2022). For the color evaluation, 5 stands for bright white without defects, 3 stands for yellowish with browning spots, 1 stands for severe browning. In respect with odor evaluation, 5 stands for no off-odors, 3 stands for slight but obvious off-odor, 1 stands for strong off-odor. Regarding texture evaluation, 5 stands for very tight and firm, 3 stands for slightly soften but acceptable, 1 stands for very soften. the acceptance evaluation according to following standard: 5 stands for excellent and having a freshly harvested appearance, 3 stands for average, and 1 stands for unmarketable.

2.4. Weight loss

The weight loss of cattails was assessed gravimetrically. The weight loss was calculated by weighing the initial weight and the weight of each sampling point, and the results were expressed as %.

2.5. Color

The surface color of cattails was determined using a colorimeter (WSC-S, Shanghai precision instrument Co., Ltd., Shanghai, China). The color was measured at 3–5 cm from cattail roots and recorded numerical values of L*, a*, and b*.

2.6. Firmness

The firmness of cattails was determined using a texture analyzer (TA. new plus, ISENSO, United States) with a 2 mm diameter puncture probe. The test speed was 2 mm s^{-1}. The cattails were penetrated 5 mm in depth. Measurements were carried out at 1–2 cm from cattail roots. Results were expressed as newtons (N).

2.7. Lignin content

With minor modifications, the lignin content in cattails was measured by gravimetric methods (Zheng, Li, Xu, & Zheng, 2019). 1 g cattails were homogenized with 20 mL 70 % H_2SO_4 at 25 °C for 1 h. then added 200 mL distilled water and heated at 100 °C for 4 h. The solution was cooled and filtered through a constant-weight G4 sand core funnel. The residue was washed to neutral with distilled water and baked to a stable weight at 90 ℃. The constant weight of the residue is the lignin content and results were expressed as %.

2.8. Reducing sugar content and lignin content

Reducing sugar content was determined by the 3, 5-dinitrosalicylic acid. 0.5 g cattails were homogenized for 2 min with 10 mL distilled water and heated at 80 °C for 30 min. The solution was cooled and centrifuged (10,000 × g, 15 min), and then a mixed solution containing 0.5 mL supernatant solution, 1.5 mL distilled water, and 1.5 mL 3, 5-dinitrosalicylic acid was boiled at 100 °C for 5 min. The absorbance value of the above reaction solution was measured at 540 nm, the reducing sugar content was calculated from the glucose standard curve, and the results were expressed as g kg^{-1}.

2.9. Malondialdehyde (MDA) content and hydrogen peroxide (H_2O_2) content

With minor modifications, MDA content was measured using the thiobarbituric acid (TBA) method (Fan, Zhang, & Jiang, 2019). 1 g cattails were homogenized in an ice bath with 5 mL 100 g L^{-1} cold TCA for 10 min. The supernatant solution was obtained from the crude extract by centrifugation (10,000 × g, 15 min, 4 °C). Then a mixture containing 2 mL supernatant solution and 2 mL 6.7 g L^{-1} thiobarbituric acid was boiled at 100 °C for 20 min. The cooled supernatant was taken at 450, 532, and 600 nm to measure the absorbance and calculate MDA content, and the results were expressed as nmol kg^{-1}·H_2O_2 content in cattails was measured using a commercial detection Kit (Solarbio Science & Technology Co., Ltd., Beijing, China).

2.10. Vitamin C content

The vitamin C content in cattails was measured by the spectrophotometric method (Chi et al., 2019) with minor modifications. 1 g cattails

were homogenized in an ice bath with 5 mL 1% cold HCl and centrifuged in a brown centrifuge tube (10,000 × g, 20 min, 4 °C). A mixture contained 1 mL supernatant solution, 0.2 mL 10 % HCl, and was volumized to 10 mL with distilled water. We measured the absorbance at 243 nm, calculated the vitamin C content using the standard curve for ascorbic acid, and expressed the results as g kg^{-1}.

2.11. Total phenolic content

With a few minor modifications, we measured the total phenolic content of cattails by Folin-Ciocalteu method (Rastegar, Hassanzadeh Khankahdani, & Rahimzadeh, 2020). 1 g cattails were homogenized with a little cold 1% HCl-methanol solution, fixed to 10 mL with 1% HCl-methanol solution, then extracted in an ultrasonic instrument for 30 min at 40 °C. The supernatant was obtained from the crude extract by centrifugation (5000× g, 30 min, 4 °C). 0.5 mL supernatant and 1 mL 0.25 mM Folin-Ciocalteu reagent are reacted in the dark for 5 min, then 3 mL 7 % Na_2CO_3 solution is added, and then the volume is fixed with distilled water to 10 mL. The solution was thoroughly mixed and reacted at room temperature for 2 h in the dark. We measured the absorbance at 765 nm, calculated the total phenolic content using a gallic acid standard curve, and expressed the results as g kg^{-1}.

2.12. Antioxidant capacity

The antioxidant capacity was analyzed by 2, 2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity and reducing power. DPPH scavenging activity and reducing power were determined by the method (Fan et al., 2018) with minor modifications. For the DPPH scavenging activity assay, 1 g cattails were homogenized with 5 mL methanol and centrifuged (10,000 × g, 15 min, 4 °C). After mixing 0.1 mL sample extract with 2.9 mL 0.1 mM DPPH methanol and incubating for 30 min at 25 °C in the dark. The absorbance was measured at 517 nm and recorded as A_1. Methanol replaced methanol extract and recorded as A_0. Methanol replaced DPPH solution and recorded as A_2. The DPPH scavenging activity was calculated according to the formula: DPPH scavenging activity $(\%) =) = \left(1\text{-}\frac{A_1\text{-}A_2}{A_0}\right) * 100$.

For reducing power assay, A mixture contained 0.5 mL the above sample extract, 2.5 mL 200 mM sodium phosphate buffer (pH 6.6), and 2.5 mL 1 % potassium ferricyanide. The mixture was placed in a water bath at 50 °C for 20 min, and terminated the reaction by adding 2.5 mL 10 % trichloroacetic acid (W/V), obtained supernatant by centrifugation (4000× g, 15 min). A mixture solution of 2.5 mL supernatant and 2.5 mL distilled water was mixed with 0.5 mL 0.1% ferric chloride and allowed to react for 10 min at room temperature. Higher absorbance indicates higher reducing power, which was measured at 700 nm.

2.13. Enzyme activity assays

With minor modifications, the peroxidase (POD) was measured using the method (Wu et al., 2021). 5 g cattails were homogenized in an ice bath with 5 mL 0.1 mM cold acetic acid sodium acetate buffer (pH 5.5) containing 4 % (w/v) insoluble PVP and extracted at 4 °C for 1 h. The extracts were centrifuged (10,000 × g, 30 min, 4 °C) and the supernatant was collected as an enzyme extract. A mixture contained 0.5 mL enzymatic extract, 3 mL 2 % guaiacol, and 0.5 mL 500 mM H_2O_2. POD activity was measured by recording the change in absorbance at 470 nm for 3 min, and the results were expressed as U kg^{-1} min^{-1} Phenylalanine ammonia lyase (PAL), catalase (CAT), superoxide dismutase (SOD), and ascorbate peroxidase (APX) activity were measured using a commercial detection Kit (Nanjing Jiancheng Bioengineering Institute, Nanjing, China).

2.14. Statistical analysis

All data were expressed as mean ± standard deviation. Significance analysis was performed using Duncan's multiple comparison test and T-test with SPSS 22.

3. Results and discussion

3.1. Sensory quality

As presented in Fig. 1a – d, the sensory quality scores of cattails in both groups decreased gradually with storage time. From Fig. 1 a, the color score of the melatonin treatment was not significantly different at 3 d, while control showed a significant decrease. The color score of the melatonin treatment was within the acceptable range during the storage period compared to control, which was unsellable (score <3) at 12 d of storage. The texture indicated the degree of lignification of cattails. From Fig. 1b, the texture of melatonin treatment and control treatment changed little at 3 d of storage. After refrigeration up to 6 d, melatonin treatment in cattails scored higher in texture than control ($P < 0.05$). The texture score of control was close to 3 at 12 d of storage, while the melatonin treatment was at 15 d of storage. From Fig. 1c, both cattails began to lose their freshness and decreased rapidly with increasing storage time from 6 d. Melatonin treatment scored higher than 3 throughout whole storage, while control was unacceptable after 12 d. It shows that melatonin treatment maintained the fragrant flavor of cattails. All cattails were not rotted during the entire storage period (data not shown). From Fig. 1d, A significant difference between melatonin treatment and control for acceptance of cattails was observed between 6 and 15 d but not from 0 to 3 d. The control group was unacceptable at 12 d with significant surface browning and high lignification, while the melatonin treatment was acceptable at 15 d with slight surface browning and root lignification. The acceptance of the melatonin treatment was sellable at the end of storage, although the texture score was lower than 3. The cattail roots are usually excised 2–3 cm for home cooking and eating.

3.2. Weight loss

Water loss or transpiration has an essential impact on the quality of vegetables. Most vegetables will show marked wilting and skin shrinkage as soon as the water loss reaches 4–6 % of the total weight. As shown in Fig. 2, the weight loss of the two groups of cattails increased gradually with increasing storage time. Melatonin treatment weight loss was lower than that of control at 6–15 d of storage ($P < 0.05$). The weight loss of control treatment was greater than 5 % at 12 d of storage, while the weight loss of the melatonin treatment was only 4 % at 15 d. Combined with the above sensory quality data, weight loss of cattails <5 % is considered acceptable. The results demonstrated that melatonin markedly decreased weight loss of cattails during postharvest storage.

3.3. Color and appearance

Color is a crucial factor affecting consumer acceptability of cattails during storage. Color measurements (L*, a *, and b *) can monitor the quality of cattails during storage. Table 1 shows during the whole storage time, L* value of cattails in the two groups gradually decreased, and L * value in melatonin treatment was higher than that in control treatment ($P < 0.05$). The L * value was 78 (value < 80) in control at 12 d, while the L* value was 87 in melatonin treatment at 15 d, which indicates the inhibition effect of cattails darkening was obvious. The a * value gradually increased from negative to positive with increasing storage time, and a * values of control increased more than those of melatonin ($P < 0.05$). It indicates that melatonin slows down the reddening of cattails. Similarly, b * value of all samples increased continuingly. Melatonin reduced the increase in b* values compared

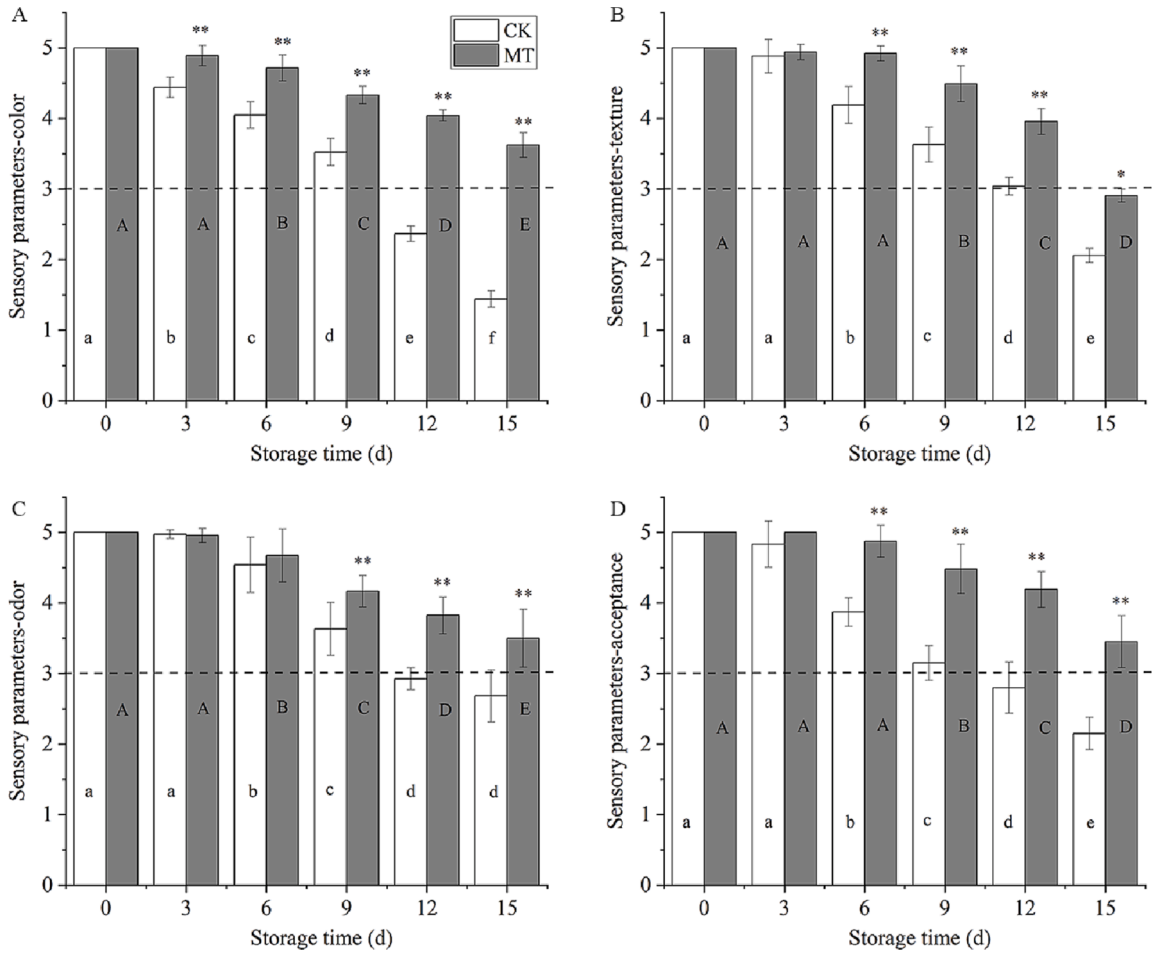

Fig. 1. Effect of melatonin (MT) treatment on sensory quality (color A, texture B, oder C, and acceptance D) of cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$). Different lowercase letters and capital letters indicate significant differences between control (CK) and melatonin (MT) treatment among various storage days, respectively ($P < 0.05$).

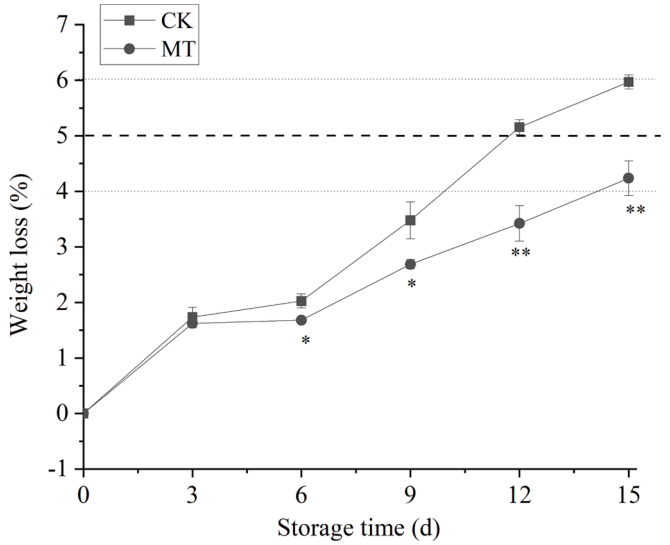

Fig. 2. Effect of melatonin (MT) treatment on weight loss of cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

with control, indicating that melatonin treatment inhibited the yellowing of cattails.

In Fig. 3, the whiteness of cattails was also acceptable by melatonin treatment for 15 d, while control was unacceptable for 12 d. As described above, the results were consistent with sensory quality and color data. Cattails in control showed significant wilting and water loss at 12 d of storage, while the melatonin treatment had wilting of about 2 cm in the tail after 15 d of storage. As mentioned above, removing 2–3 cm of the tail for home cooking and eating is necessary, so melatonin treatment for 15 d is acceptable. Therefore, the melatonin treatment was accepted for 15 d of storage, which corresponds to the fact that the cattails had a 5 % weight loss and were still edible.

3.3.4. *Firmness*

It is widely acknowledged that texture is essential in determining postharvest vegetable quality and shelf life. To some extent, the firmness of cattails can reflect the lignification and water loss. As shown in Fig. 4, the firmness of all samples gradually increased during the whole storage period, with smaller increases and no significant differences between control and melatonin treatment from 0 to 3 d ($P > 0.05$). The firmness of cattails in control increased rapidly after 3 d, but the firmness in melatonin treatment increased rapidly after 6 d, and was higher in control than in melatonin treatment from 6 to 15 d ($P < 0.05$). There was a similar trend in firmness to that observed in the sensory parameters-texture data above, suggesting that melatonin may help maintain the crispness of cattails and reduce the increase in firmness.

Table 1
Effect of melatonin (MT) treatment on color of cattails during storage at 4 ℃.

Color parameter	Storage time (d)	Treatment	
		CK	MT
L*	0	96.18±0.57^{a}	96.18±0.57^{a}
	3	85.02±0.44^{b}	92.58±0.41^{b,**}
	6	83.23±0.70^{bc}	89.43±0.55^{c,**}
	9	80.39±0.54 ^{cd}	89.37±0.55^{c,**}
	12	78.07±0.67^{d}	88.77±0.49^{c,**}
	15	73.26±4.01^{e}	86.49±0.30 ^{d,**}
a*	0	−2.21 ± 0.13^{a}	−2.21 ± 0.13^{a}
	3	1.39±0.34^{b}	−1.34 ± 0.11^{b,**}
	6	4.43±0.50^{c}	1.79±0.26^{c,**}
	9	4.61±0.44 ^{cd}	2.53±0.27^{d,**}
	12	5.36±0.23^{d}	3.58±0.55^{e,**}
	15	9.76±0.68^{e}	4.74±0.32^{f,**}
b*	0	0.05±0.04^{a}	0.05±0.04^{a}
	3	8.47±0.44^{b}	4.39±0.27^{b,**}
	6	10.57±0.63^{c}	5.15±0.51^{c,**}
	9	14.08±1.06^{d}	5.55±0.17^{c,**}
	12	17.29±0.47^{e}	6.62±0.50^{d,**}
	15	21.27±0.97^{f}	7.92±0.47^{e,**}

Different superscript lowercase letters in the same column indicate significant differences between control (CK) or melatonin (MT) treatments among various storage days ($P < 0.05$). Superscript asterisks indicate significant differences between control (CK) and melatonin (MT) treatments with the same storage time (**$P < 0.01$, *$P < 0.05$).

3.3.5. Lignin content

The increase in lignin content affected the cattails' crisp taste and edible quality and reduced the sensory characteristics and commercial value. As shown in Fig. 5, all samples in lignin content exhibited increases during storage. In cattails stored for 3 d, there was no significant difference in lignin content between melatonin and control treatments ($P > 0.05$). In comparison, the lignin in content control was higher than that of the melatonin treatment from 6 to 15 d ($P < 0.05$). Cattails in control had 2 times more lignin than those in melatonin treatment after 15 d. The changing trend of lignin content was similar to the firmness, which indicated that the synthesis and deposition of lignin would make the food texture rough and the quality worse.

3.3.6. Reducing sugar content

Reducing sugar content is closely related to fruit and vegetable quality, maturity, and storage. As shown in Fig. 6, reducing sugar content in control and melatonin treatment decreased with prolonged storage time. Compared with melatonin treatment, the reducing sugar content in control was lower ($P < 0.05$). The decreasing rate of reducing sugar content of all samples was fast from 0 to 3 d, while the decreasing rate of reducing sugar was relatively slow at the later period, which might be due to the vigorous physiological metabolism and respiratory consumption at the early storage of cattails harvesting. Compared to the initial storage period, the reducing sugar content of cattails in control decreased by 77 % at 15 d, while the reducing sugar content of cattails in melatonin treatment decreased by 56 %.

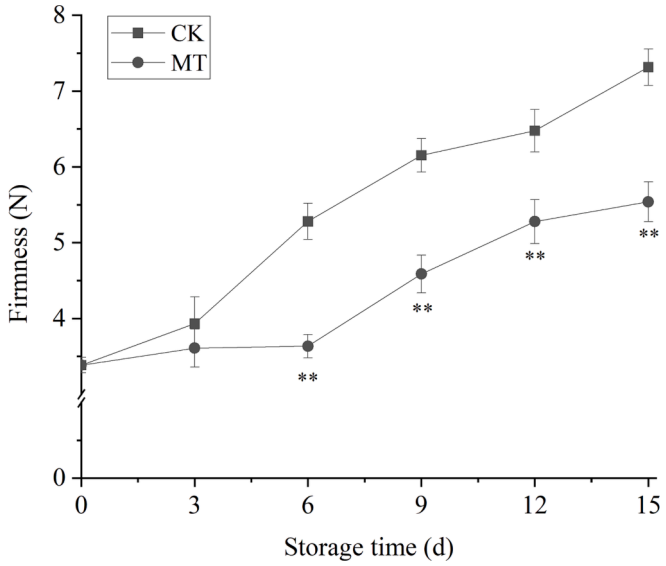

Fig. 4. Effect of melatonin (MT) treatment on firmness of cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

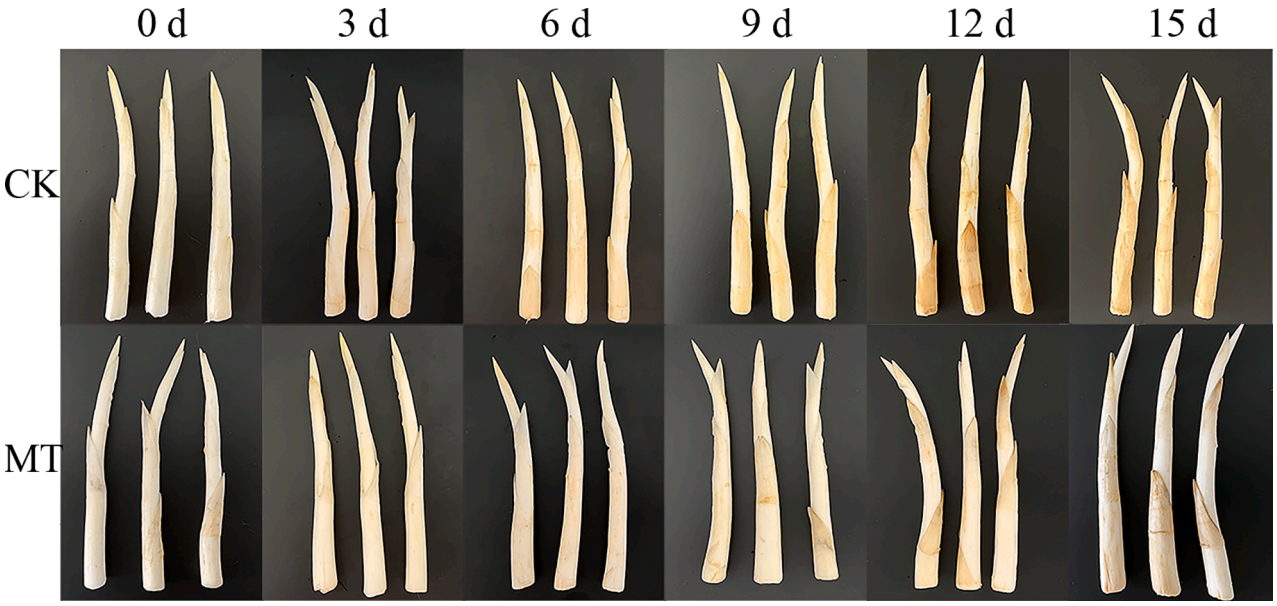

Fig. 3. Effect of melatonin (MT) treatment on appearance of cattails during storage at 4 ℃.

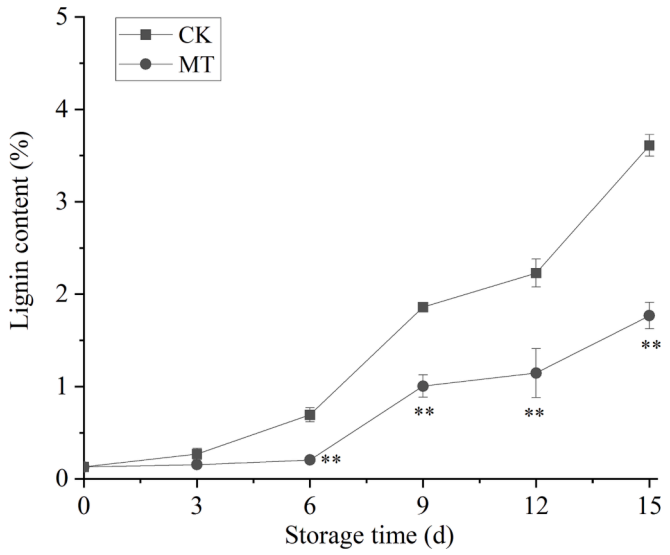

Fig. 5. Effect of melatonin (MT) treatment on lignin content of cattails during storage at 4℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

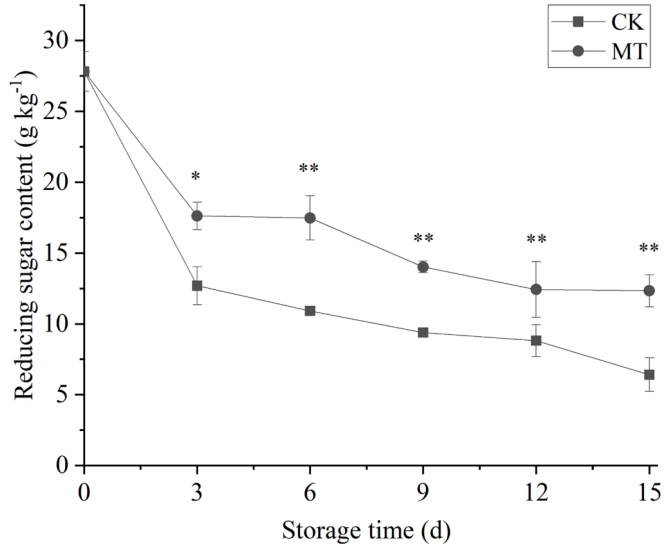

Fig. 6. Effect of melatonin (MT) treatment on reducing sugar content of cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

3.3.7. *MDA content and H_2O_2 content*

MDA and H_2O_2 are considered the main product of lipid peroxidation in the cell membrane of plants (Liu et al., 2020; Zhang, Zhang, Devahastin, & Guo, 2019). Increased MDA and H_2O_2 could damage the cell membrane, causing brown polymers to accumulate (Lin et al., 2016; Zheng et al., 2019). As shown in Fig. 7a, MDA content increased continuously with increasing storage time, both in control and melatonin treatment of cattails. There was no difference between control and melatonin treatment at 3 d ($P > 0.05$), and control was higher than the melatonin treatment from 6 to 15 d ($P < 0.05$). Compared to cattails in control, melatonin treatment reduced the MDA content at late storage by 57 %.

As shown in Fig. 7b, the changing trend of H_2O_2 content is basically the same as that of MDA, and H_2O_2 content showed an overall increasing trend during storage. A decrease in H_2O_2 accumulation was observed with melatonin treatment compared to control. The H_2O_2 content in the melatonin treatment was only 80% of that in control at the end of storage. MDA and H_2O_2 contents were inhibited by melatonin treatment, cell membrane structure was maintained, and brown polymer formation was reduced.

3.3.8. *Vitamin C content and total phenolic content*

A non-enzymatic antioxidant, vitamin C is an essential indicator of fruits and vegetables' nutrition and storage quality (Ze, Gao, Li, Yang, & Jiang, 2021). According to Fig. 8a, The vitamin C content of cattails decreased as storage time increased, and the melatonin treatment delayed vitamin C decline compared to control ($P < 0.05$). At the beginning of storage, vitamin C content in cattails was 0.46 g kg^{-1}. After 15 d of storage, vitamin C content in control and melatonin treatment were 0.23 g kg^{-1} and 0.29 g kg^{-1}, respectively.

Non-enzymatic antioxidants, such as phenols, can enhance disease resistance and improve fruit and vegetable quality (Ze et al., 2021). Moreover, phenolic compounds are also substrates for enzymatic browning, which affects fruit and vegetable browning. The variations in the total phenolic content of cattails treated with melatonin and control are shown in Fig. 8b. Total phenolic content of all samples first increased and then decreased during storage time, peaking at 6 d. Melatonin increased the rise and inhibited the fall of total phenolic content compared to control ($P < 0.05$). The melatonin treatment improved cattails' antioxidant capabilities and stress resistance by reducing oxidative damage to Vitamin C and phenolics.

3.3.9. *DPPH scavenging capacity and reducing power*

The antioxidant capacity of cattails was evaluated using DPPH scavenging capacity and reducing power. Fig. 9a shows that all samples' DPPH scavenging capacity decreased continuously during storage. After 6 d, cattails in melatonin treatment performed better at DPPH scavenging capacity than control ($P < 0.05$). At 15 d, the DPPH scavenging ability of cattails treated with control and melatonin decreased by 41 % and 27 %, respectively.

As shown in Fig. 9b, the trend of reducing power gradually decreased, similar to DPPH scavenging capacity through storage. Cattails in melatonin treatment had higher reducing power than control between 9 and 15 d ($P < 0.05$), while the difference was not significant between 0 and 6 d ($P > 0.05$). These results concluded that melatonin could maintain DPPH scavenging capacity and reducing power in cattails. The higher antioxidant capacity may be attributed to the cattails' vitamin C and total phenols in melatonin treatment. Cattails in melatonin treatment demonstrated higher DPPH scavenging capacity and reducing power throughout storage, thereby delaying browning, which is consistent with the previous conclusions on sensory quality, color, and appearance.

3.3.10. *PAL activity*

Increasing the activity of PAL, a crucial enzyme in the phenylpropane pathway, can improve plants' capacity to adapt to biotic and abiotic stressors (Wang, Kou, Wu, Fan, & Li, 2020). As shown in Fig. 10, the PAL activity of both control and melatonin treatment increased initially, decreased, and reached a peak at 6 d. PAL activity in melatonin treatment was higher than in control during the whole period ($P < 0.05$). We found that melatonin treatment boosted PAL activity and promoted phenolic accumulation in cattails, increasing their quality and disease resistance. A similar effect was obtained in pomegranate, which confirmed that melatonin could increase PAL activity, promote the accumulation of phenolic substances and reduce the oxidative damage of fruit (Aghdam et al., 2020).

3.3.11. *SOD activity, CAT activity, APX activity, and POD activity*

Fruit and vegetables were ripened and senescenced along with ROS gets accumulated during postharvest, SOD, CAT, APX and POD are important ROS scavenger of antioxidant defense system (Yang et al.,

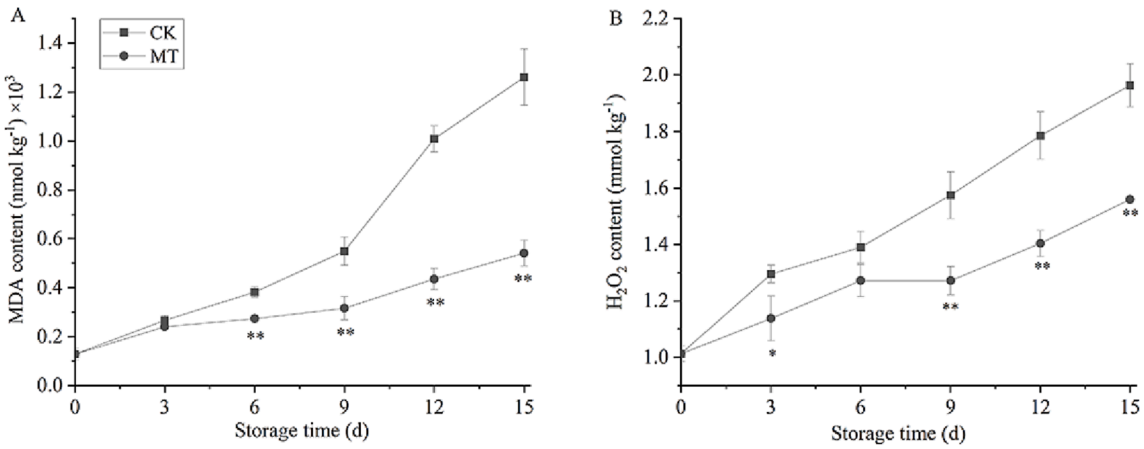

Fig. 7. Effect of melatonin (MT) treatment on MDA content A and H_2O_2 content B in cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

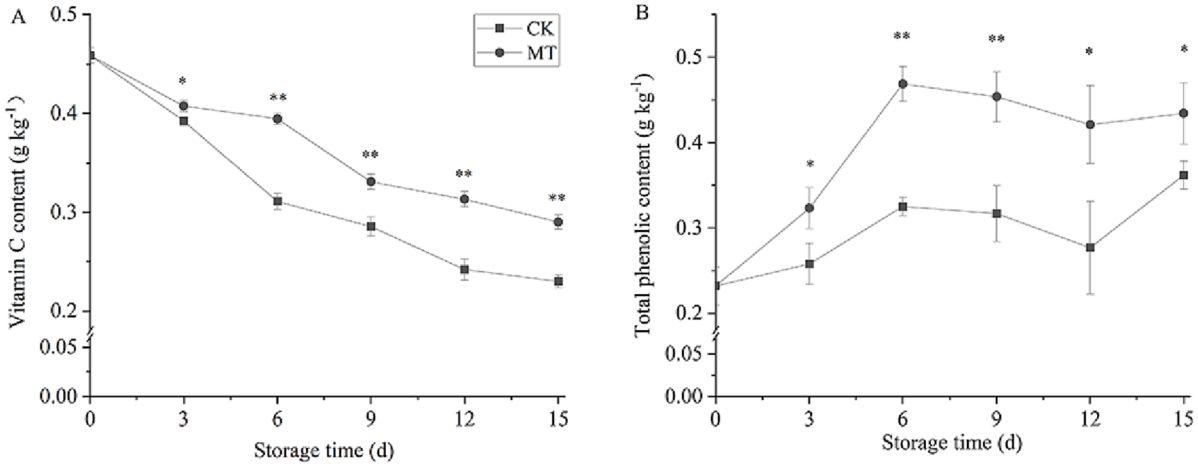

Fig. 8. Effect of melatonin (MT) treatment on vitamin C content A and total phenolic content B in cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

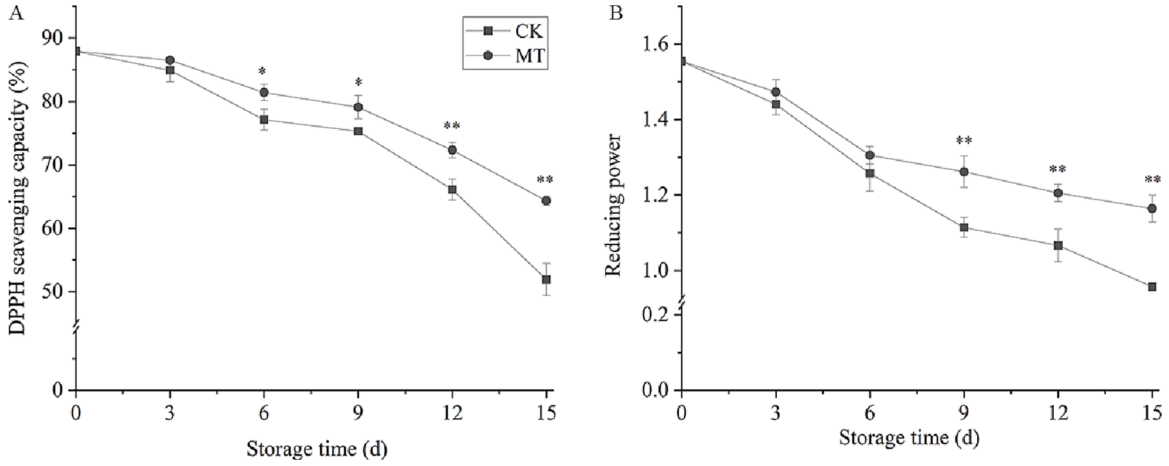

Fig. 9. Effect of melatonin (MT) treatment on DPPH scavenging capacity A and reducing power B in cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

2021). SOD is an important antioxidant enzyme that catalyzes O_2^- in plants to generate H_2O_2 and O_2 (Fan et al., 2022). As shown in Fig. 11a, all cattails' SOD activity first increased, then decreased, and melatonin maintained high SOD activity. In cattails, melatonin treatment promoted an increase and inhibited a decrease in SOD activity, and reached a peak at 3 d. The findings demonstrated that melatonin also preserved greater SOD activity compared to control.

CAT is an active oxygen scavenging enzyme that catalyzes the

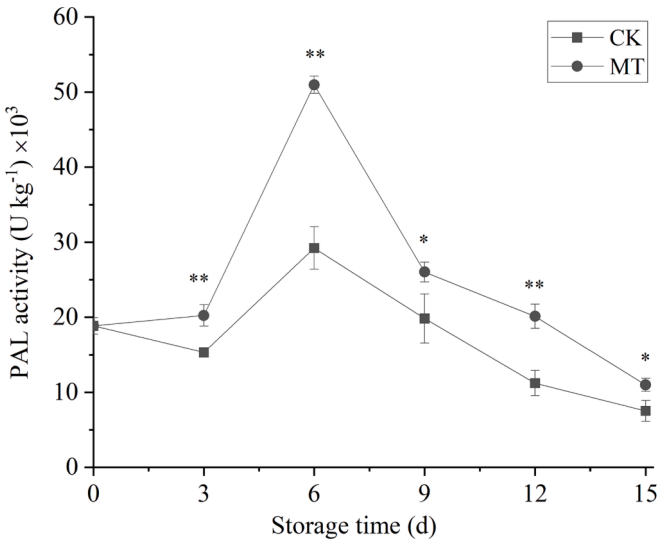

Fig. 10. Effect of melatonin (MT) treatment on PAL activity in cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

decomposition of H_2O_2 into H_2O and O_2, reducing the oxidative damage caused by H_2O_2. In Fig. 11b, there is a similar change in CAT activity to the change in SOD activity. The CAT activity of cattails peaked at 3 d and gradually decreased during the storage period. At 3 d, the CAT activity of cattails in melatonin treatment reached 24.53×10^6 U kg^{-1} prot. However, the CAT activity in control was only 13.74×10^6 U kg^{-1} prot. Melatonin treatment in cattails displayed CAT activity that was 2 times higher than control at the end of storage, indicating that melatonin could maintain high CAT activity.

As the primary enzyme responsible for VC metabolism, APX catalyzes the redox reaction between VC and H_2O_2, thereby reducing the toxic effect of H_2O_2 and improving plant resistance to external stresses. According to Fig. 11c, APX activity in cattails fluctuated during storage. Melatonin treatment was consistent with control, but melatonin treatment had a higher APX activity than control, indicating that melatonin also maintained higher APX activity in cattails.

POD can scavenge free radicals and delay the senescence of harvested vegetables. In addition, POD can catalyze the oxidation and polymerization of phenols and flavonoids in the presence of H_2O_2, resulting in browning. As shown in Fig. 11d, The POD in control showed an upward trend with storage time, which may be due to the accumulation of H_2O_2 in cattails resulting in the oxidation of the cell membrane, thus stimulating enhanced POD activity. Melatonin reduced POD activity in cattails compared to control ($P < 0.05$). The results suggested that melatonin inhibits POD activity, thus delaying the browning and senescence of the postharvest cattails.

4. Conclusion

In this study, melatonin treatment effectively maintained the quality and delayed senescence of postharvest cattails during cold storage. Melatonin positively affects the change of sensory quality and color, the reduction of lignin and firmness, the decrease of reducing sugar content, and the maintenance of antioxidant capacity. These findings suggested that the application of exogenous melatonin may improve cattails

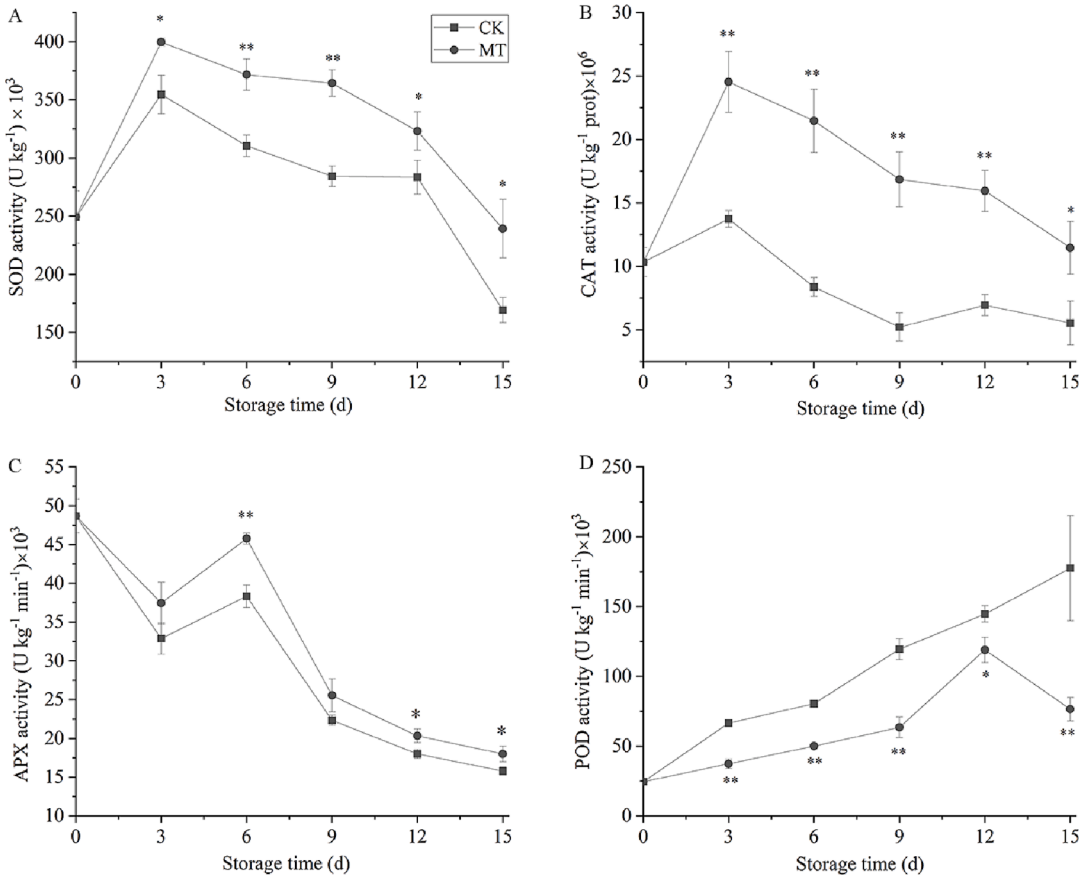

Fig. 11. Effect of melatonin (MT) treatment on SOD activity A, CAT activity B, APX activity C, and POD activity D in cattails during storage at 4 ℃. Asterisks indicate significant differences between control (CK) and melatonin (MT) treatment with the same storage time (**$P < 0.01$, *$P < 0.05$).

preservation by inhibiting respiratory, which delayed reducing sugar and Vitamin C degradation rate, ultimately senescence was effectively delayed and quality was maintained. Melatonin inhibited the increase of MDA, H_2O_2 content, and POD activity in cattails, thereby delaying browning. Melatonin treatment significantly delayed senescence in postharvest cattails by increasing antioxidant enzyme activity (SOD, CAT, and APX). Overall, the postharvest life and postharvest quality in cattails were improved by melatonin treatment. Further research will be required to reveal mechanism that melatonin treatment delaying cattails browning from omics perspectives (Genome, Transcriptome, Proteome, Metabolome) and expected to achieve the commercial application of melatonin in cattails preservation, providing technical support for promoting the development of this characteristic agricultural products in Yunnan province.

CRediT authorship contribution statement

Aiping Fan: Supervision, Funding acquisition. **Chunpeng Wan:** Writing – review & editing. **Huilian Liu:** Investigation, Methodology. **Xueqi Xiong:** Investigation, Methodology. **Yuping Nong:** Investigation. **İbrahim Kahramanoğlu:** Writing – review & editing. **Ruopeng Yang:** Data curation, Formal analysis, Writing – original draft. **Liping Zeng:** Data curation, Formal analysis, Writing – original draft.

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.2023.100796.

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