Agricultural Sciences, 2023, 14, 1501-1515
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

Postharvest Application of 1-Methylcyclopropene Maintains Quality and Extends the Shelf-Life of *Zizania latifolia* during Storage at 25˚C

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How to cite this paper: Tong, X.Z., Chen, Y.N., Shi, N., Gouda, M.H.B., Kong, X.X., Jiang, K. and Luo, H.B. (2023) Postharvest Application of 1-Methylcyclopropene Maintains Quality and Extends the Shelf-Life of *Zizania latifolia* during Storage at 25˚C. *Agricultural Sciences*, **14**, 1501-1515.
https://doi.org/10.4236/as.2023.1411097

Received: September 11, 2023
Accepted: November 5, 2023
Published: November 8, 2023

Abstract

The effects of 1-methylcyclopropene (1-MCP) on postharvest quality of *Zizania latifolia* during storage at 25˚C were investigated. The results pointed out that a postharvest application of 1-MCP maintained the good visual appearance of fresh Z. *latifolia*, inhibited browning, mildew and weight loss at the bottom of *Z. latifolia*, and there is no significant changes on L, a*, b* and ΔE during the whole storage period. In addition, 1-MCP treatment inhibited the respiratory intensity of Z. *latifolia* during the first three days of storage, but it was significantly higher than that of the control on the sixth day of storage. Compared with the control, 1-MCP treatment maintained relatively high SOD, CAT, APX activities and low PAL, POD, PLD, lipase and LOX activities, delayed the decline of AsA content, reduced the accumulation of O_2^-, H_2O_2 and MDA, and ultimately maintained the integrity of cell structure and delayed the senescence of Z. *latifolia*. In addition, positive effects of 1-MCP on maintaining the cell structure integrity were observed in this investigation throughout the storage period at 25˚C.

Keywords

Zizania latifolia, 1-Methylcyclopropene, Browning, Enzyme, Membrane Damage

1. Introduction

Zizania latifolia, belongs to Oryzae family, has been harvested for more than

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thousands of years and used as an aquatic crop [1]. After, infection by the fungus *Ustilago esculenta*, the young shoots appear edible, soft and swollen. It also has a large nutritional and economical importance [2] [3]. Two varieties of Z. *latifolia* are cultivated in China namely: the one harvested once a year (single season culture) and the two seasons culture harvested twice a year in summer and autumn [1] [4].

The natural environment of Z. *latifolia* has shifted with the growth of human population and the drying of rice lakes, which have both limited the space covered by these species [5]. The largest area under harvesting in China is mostly situated in the area surrounding Taihu Lakes, in Jiangsu and Zhejiang provinces [1]. In addition, Yan *et al.* [5] stated that Z. *latifolia*, is prevalent throughout China except in Xinjiang and Tibet, and grows in lakes marshes, ponds, rivers and the wetlands, particularly abundant in Huai river basin and the middle and lower Yangtze river basins.

Z. latifolia is an important vegetable with high nutritional and economical values and also used to prevent and treat metabolic disease [5]. However, abiotic and biotic stresses can reduce its shelf-life during postharvest storage. In addition, tissue lignification, cut surface browning, and yellowing are considered as main causes of its quality loss [6] [7] [8] [9]. Therefore, effective postharvest treatments that can delay senescence and control the quality deterioration are needed. Previous study was based on the use of edible coating [10], high pressure CO_2 [11] for the storage of fresh-cut *Z. latifolia* and cold storage at 1˚C of whole *Z. latifolia* as well as the ultraviolet-C [12], nitric oxide [13] [14], melatonin [15] and ethanol vapor [16] treatments. However, little information regarding the use of 1-MCP on the physiological and cell ultrastructure changes of postharvest storage of *Z. latifolia* was available.

1-Methylcyclopropene (1-MCP), as an inhibitor of ethylene action, has been shown to passivate receptors by competing with ethylene to inhibit ethylene production and release, thereby preventing physiological and biochemical activities related to maturation [17]. 1-MCP provides commercial potential for controlling ripening, aging, yellowing, and softening caused by ethylene, and extends the shelf life of some vegetables, including pak choi, green pepper, bitter gourd, sweet basil leaves, and okra [18] [19] [20] [21]. Song *et al.* [18] applied 1-MCP treatment after harvesting *Brassica rapa* subsp. chinensis and found that the treatment could delay the yellowing of the leaves of *Brassica rapa* subsp. chinensis by maintaining the integrity of the chloroplast structure during storage at 20˚C. Hassan *et al.* [20] fumigated young immature bitter melons with different concentrations of 1-MCP for 12 hours and proved that 5 $\mu l \cdot L^{-1}$ 1-MCP treatment significantly improved the fruit quality of bitter melons and maintained the activity of antioxidant enzymes in bitter melons during early storage. Besides, the beneficial effects of 1-MCP on plant aging also include inhibition of antioxidant enzyme activity [17] and control of ROS production [22].

The purpose of this study was to investigate the effect of 1-MCP treatment on

the reactive oxygen metabolism and ultrastructure of *Z. latifolia* during postharvest storage at room temperature (25˚C). The study specifically based on the effect of 1-MCP on changes in overall appearance quality, physiological and biochemical parameters such as antioxidant system and lipid metabolism. The results can help to better understand the mechanism of 1-MCP treatment on the regulation of *Z. latifolia* postharvest senescence and provide a technical support for maintaining the quality and extending the shelf-life of *Z. latifolia*.

2. Materials and Methods

2.1. Plant Material

Fresh *Z. latifolia* stems were hand-harvested from a commercial farmland in Yixing, Jiangsu, China. They were selected on the basis of similarity in size, color and absence of visible defects and then arbitrarily divided into two groups of 15 kg vegetables each. The first group of vegetable was treated with 10 μl·L^{-1} 1-MCP (Agrofresh, USA) in a sealed chamber at room temperature (25˚C) for 20 h; the second group (CK) was subject to the same condition without exposure to 1-MCP. Following treatment, the chambers were opened and two groups of vegetable were stored at room temperature for 6 days. Samples were taken out at 0 (before treatment, CK0), 1 (CK1, 1-MCP1), 3 (CK3, 1-MCP3), 6 (CK6, 1-MCP6) day, respectively, and manually peeled carefully to remove boots. Next, about 5 cm stem portion was removed from each end of an individual with a sharp stainless-steel knife and the remainder was used for indexes analysis, or directly frozen in liquid nitrogen and stored at −80˚C until further analysis.

2.2. Color Determination

The Minolta CR-200 portable colorimeter was used to measure Z. *latifolia*'s CIE L, a*, b* values. Brightness was represented by L value (L = 0, black; L = 100, white), positive a value represented the degree of redness, negative a* value represented the degree of greenness, b*+ represented the degree of yellowness and b represented the degree of blueness.

The total color difference (ΔE) was calculated as follows:

$\Delta E = \left[\left(L - L_0 \right)^2 + \left(a^* - a_0^* \right)^2 + \left(b^* - b_0^* \right)^2 \right]^{1/2}$ according to the method of Gouda *et al.* [23] (where, L_0, a_0^* and b_0^* are the readings at the beginning of storage, and L, a^* and b^* are the individual readings at each storage time point thereafter).

2.3. Weight Loss and Respiration Rate

The weight loss assessment was made using the following formula: Weight loss rate% = (weight before storage − weight after storage) × 100/weight before storage.

The CheckMate 3 portable headspace analyser (PBI Dansensor, Denmark) was used to determine the percentage of O_2 consumed and the volume of CO_2 generated per unit time in a fixed-volume airtight container. The result was ex-

pressed as mg $CO_2 \cdot Kg^{-1} \cdot h^{-1}$.

2.4. Visualization of Ultrastructure

The visualization Z. *latifolia* cell ultrastructure was conducted using the method of Li *et al.* [24] with some modification. Z. *latifolia* pieces were collected from the cut surface of three Z. *latifolia* per treatment. The pieces were resuspended in phosphate buffered saline (PBS) containing 5 mM cerium chloride ($CeCl_3$), incubated at 28˚C for 1.5 h after pretreatment. Cells were collected by centrifugation and the supernatant containing residual $CeCl_3$ was discarded. The cells were resuspended in 3% glutaraldehyde for more than 4 hours, and the cells were pelleted by centrifugation. After fixing with OsO_4 and embedding with epoxy resin, the slices were sliced, and the slices were observed under 80 kV with a transmission electron microscope.

2.5. Ascorbic Acid (AsA) Content Determination

The AsA content was measured using the 2,6-dichlorophenol indophenol method as stated by Li *et al.* [25]. The result was expressed as gram of AsA per kilogram on a fresh weight basis.

2.6. Determination of Superoxide Anion ($O_2^{\cdot-}$), Hydrogen Peroxide (H_2O_2) and Malondialdehyde (MDA)

The $O_2^{\cdot-}$ production rate, H_2O_2 and MDA contents were determined using the method of Gouda *et al.* [23]. The results were expressed as $\mu M \cdot kg^{-1} \cdot min^{-1}$, $mM \cdot kg^{-1}$ and $\mu M \cdot kg^{-1}$, respectively.

2.7. Determination of Superoxide Dismutase (SOD), Catalase (CAT) and Ascorbate Peroxidase (APX)

The SOD, CAT and APX activities were evaluated following the method reported by Luo *et al.* [6]. One unit of SOD activity was defined as the quantity of enzyme that inhibited 50% of the photo-reduction of NBT at 560 nm. The CAT and APX activity were expressed as the change in A_{240} and A_{290} per minute per gram of fresh weight, respectively.

2.8. Determination of Phenylalanine Ammonia Lyase (PAL) and Peroxidase (POD)

The standard procedure reported by Gao *et al.* [26] was used for the determination of PAL and POD activities. One unit of PAL and POD activities were defined as the amount of enzyme that caused an increase in absorbance of 0.01 at 290 nm in 1 h, and at 460 nm in 1 min, respectively.

2.9. Determination of Phospholipase D (PLD), Lipoxygenase (LOX) and Lipase

The method used to determine the enzymatic activity of PLD was the usual

protocol documented by Song *et al.* [18]. A 0.01 change in the absorbance (A_{520}, A_{243}, $A_{520,}$) value per minute were defined as a unit of PLD, LOX and lipase enzyme activity, respectively.

2.10. Statistical Analysis

Physiological data were performed as mean ± standard deviation of three replicate samples. SPSS 22.0 software and the Duncan's multiple range test were used to perform one-way analysis of variance and to determine differences in each treatment at p = 0.05. The process was repeated three times for each treatment, and the results were expressed as the mean ± standard deviation.

3. Results

3.1. Effect of 1-MCP on Visual Appearance Quality of *Z. latifolia* during Storage

As indicated in Figure 1, the control sample of Z. *latifolia* presented a better appearance with a bright green shell, white skin and internal color at day 0, but after 6 days of storage at room temperature, the shell turned yellow and its epidermis was browned and blackened. In addition, some hollow bran appeared and there were signs of deterioration. However, after 6 days of storage, sample treated with 1-MCP retained an excellent color and visual appearance.

3.2. Effect of 1-MCP on Color Change during Storage at 25˚C

As seen in Table 1, there is no significant difference of L value between the treated and control sample, however, the treated sample kept lower the a^*, b^* and ΔE values throughout the storage time comparing with those of the control sample.

3.3. Effect of 1-MCP on the *Z. latifolia* Cell Ultrastructure

As observed in Figure 2, the cell structure of Z. *latifolia* is intact at day 0 with

Figure 1. Effect of 1-MCP on visual appearance quality of *Z. latifolia* during storage at 25˚C ((A) CK 0 d; (B) CK 1 d; (C) CK 3 d; (D) CK 6 d; (E) 1-MCP 1 d; (F) 1-MCP 3 d; (G) 1-MCP 6 d).

Table 1. Effect of 1-MCP on *L*, *a**, *b** and *ΔE* values changes during *Z. latifolia* storage at 25˚C.

Indices	Treatment	Storage time (days)			
		0	1	3	6
L	Control	58.25 ± 2.16[a]	60.19 ± 2.84[a]	61.38 ± 2.10[a]	62.18 ± 2.08[a]
	1-MCP	58.25 ± 2.61[a]	59.43 ± 2.90[b]	60.37 ± 2.65[a]	60.58 ± 2.86[a]
*a**	Control	−7.83 ± 0.24[a]	−7.17 ± 0.12[a]	−6.92 ± 0.25[a]	−6.32 ± 0.16[a]
	1-MCP	−7.83 ± 0.24[a]	−7.56 ± 0.16[b]	−7.40 ± 0.24[b]	−7.11 ± 0.34[b]
*b**	Control	20.96 ± 0.45[a]	21.19 ± 0.31[a]	22.19 ± 0.25[a]	22.50 ± 0.16[a]
	1-MCP	20.96 ± 0.45[a]	20.80 ± 0.34[b]	21.50 ± 0.21[b]	21.87 ± 0.26[b]
ΔE	Control	0 ± 0.00[a]	4.26 ± 0.66[a]	12.13 ± 1.25[a]	14.86 ± 1.16[a]
	1-MCP	0 ± 0.00[a]	1.50 ± 0.57[b]	4.96 ± 0.68[b]	6.75 ± 1.37[b]

Data are expressed as means ± SD of triplicate assays. Within the same index, mean values with different lowercase letters in same column are significantly different ($p < 0.05$).

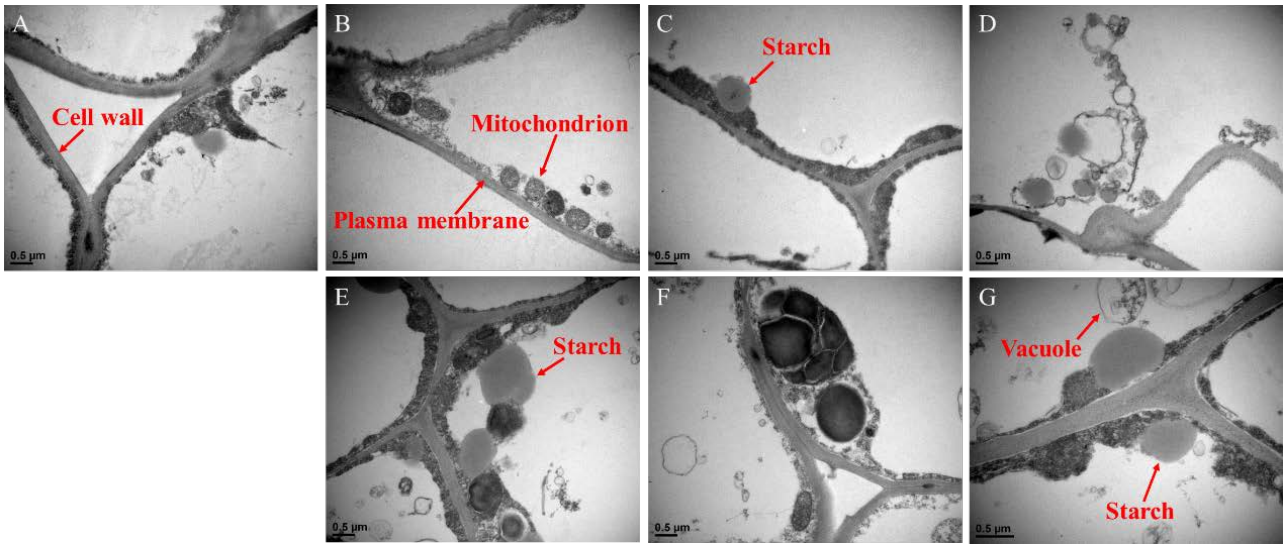

Figure 2. Effect of 1-MCP treatment on cell ultrastructure of *Z. latifolia* during storage at 25˚C ((A) CK 0 d; (B) CK 1 d; (C) CK 3 d; (D) CK 6 d; (E) 1-MCP 1 d; (F) 1-MCP 3 d; (G) 1-MCP 6 d).

visible cell wall, nucleus and mitochondria. However, after 6 days of storage, the cell wall and plasma membrane of the control sample was significantly degraded with unclear mitochondria. Meanwhile, the treated samples kept their cell wall and plasma membrane intact with a visible and abundant mitochondria. These observations indicated that 1-MCP treatment has positive effect in the maintenance of Z. *latifolia* cell ultrastructure.

3.4. Effect of 1-MCP on the Weight Loss and Respiratory Intensity of *Z. latifolia* during Storage

Weight loss in vegetable and fruit is related to the loss of water caused by tran-

spiration and loss of carbon due to the respiration processes. Therefore, in our study, the weight loss and respiration rate were monitored (Table 2).

As seen in Table 2, throughout the storage time, the weight loss in sample treated with 1-MCP was lower than that in control sample. This indicated that 1-MCP treatment had a better performance on inhibition of water loss. However different pattern was observed concerning the respiratory rate. 1-MCP treatment maintained lower the respiratory rate of Z. *latifolia* during the first three days. This decrease trend was followed by an increase of respiratory rate which led to high respiratory rate of 1-MCP treated sample than that of the control group (Table 2).

3.5. Effect of 1-MCP on $O_2^{\cdot-}$, H_2O_2 and MDA Contents

According to Table 2, there is an increase and decrease trend of $O_2^{\cdot-}$ production rate and H_2O_2 accumulation in both control and treated samples. Interestingly, sample treated with 1-MCP shown the lower content of H_2O_2 and $O_2^{\cdot-}$ through the storage period comparing to the control. In addition, the Table 2 showing the content of MDA during storage indicated the lower MDA content in samples treated with comparing with the control group along with the storage time prolongs. These data suggest that 1-MCP treated had a positive impact on inhibiting $O_2^{\cdot-}$ production, H_2O_2 and MDA accumulation in Z. *latifolia* during storage at 25˚C.

3.6. Effect of 1-MCP on SOD, CAT and APX Activities and AsA Content

Table 3 shown that APX activity of Z. *latifolia* decreased in the early period of

Table 2. Effect of 1-MCP on the weight loss, respiratory intensity, $O_2^{\cdot-}$ production rate, H_2O_2 and MDA contents of *Z. latifolia* during storage at 25˚C.

Indices	Treatment	Storage time (days)			
		0	1	3	6
Weight loss (%)	Control	0 ± 0.00^a	4.91 ± 0.25^a	6.52 ± 0.33^a	12.93 ± 0.65^a
	1-MCP	0 ± 0.00^a	3.85 ± 0.19^b	5.45 ± 0.27^b	9.72 ± 0.49^b
Respiration rate (mg $CO_2 \cdot kg^{-1} \cdot h^{-1}$)	Control	206.06 ± 8.28^a	186.32 ± 9.32^a	101.34 ± 5.07^a	121.47 ± 6.07^b
	1-MCP	206.06 ± 8.28^a	151.36 ± 7.56^b	96.20 ± 4.81^b	161.21 ± 8.05^a
$O_2^{\cdot-}$ production rate ($\mu M \cdot kg^{-1} \cdot min^{-1}$)	Control	10.47 ± 0.28^a	21.64 ± 1.08^a	8.99 ± 0.31^a	5.54 ± 0.19^a
	1-MCP	10.47 ± 0.28^a	10.58 ± 1.30^b	4.27 ± 0.30^b	4.20 ± 0.35^b
H_2O_2 contents ($mM \cdot kg^{-1}$)	Control	30.82 ± 1.58^a	44.12 ± 3.08^a	47.52 ± 2.51^a	40.78 ± 2.75^a
	1-MCP	30.82 ± 1.58^a	42.50 ± 2.92^b	35.7 ± 3.49^b	36.83 ± 3.98^b
MDA contents ($\mu M \cdot kg^{-1}$)	Control	0.73 ± 0.07^a	0.70 ± 0.04^a	0.50 ± 0.09^a	0.33 ± 0.07^a
	1-MCP	0.73 ± 0.07^a	0.48 ± 0.08^b	0.36 ± 0.02^b	0.16 ± 0.05^b

Data are expressed as means ± SD of triplicate assays. Within the same index, mean values with different lowercase letters in same column are significantly different ($p < 0.05$).

storage and then increased in both control and treated samples. However, the APX activity of samples treated with 1-MCP (48.00 ± 1.05 $U \cdot g^{-1}$) was higher than the control samples (43.60 ± 1.67 $U \cdot g^{-1}$). In addition, samples treated with 1-MCP shown the highest SOD and CAT activities (Table 3) throughout the storage compared with the control samples. As indicated in Table 3, there is a decrease of AsA content in the control and treated sample during the storage time. However, the AsA content in the treated samples was still higher than that of the control group at the end of storage period. These results suggested that 1-MCP treatment was efficient to maintain higher the activity of antioxidant enzymes.

3.7. Effect of 1-MCP on POD, PAL Activities

As seen in Table 4, POD activity significantly increased in the control samples throughout storage while the POD activity in the treated samples decreased at day 1 and 3 and increased up to 573.1 ± 66.04 $U \cdot g^{-1}$ at day 6, which is lower than that on the control samples (581.5 ± 20.85 $U \cdot g^{-1}$). The same pattern was observed in Table 4 where sample treated with 1-MCP presented a lower PAL enzyme activity during the whole storage period.

3.8. Effect of 1-MCP on LOX, PLD and Lipase Activities

In order to gain a better understanding regards the effect of 1-MCP during the postharvest storage of Z. *latifolia*, three membranes lipids degrading enzymes including PLD, lipase and LOX activities were investigated and represented. Lipase has an effect on the membrane lipids of fruits and vegetables. PLD affects the structure, function and stability of the membrane by hydrolyzing phospholipids in the cell membrane. LOX is closely involved in the lipid action of fruit and

Table 3. Effect of 1-MCP on APX, SOD, CAT activities and AsA content of *Z. latifolia* during storage at 25˚C.

Indices	Treatment	Storage time (days)			
		0	1	3	6
SOD activity ($U \cdot g^{-1}$)	Control	24.62 ± 0.14^a	21.85 ± 0.39^b	24.79 ± 0.24^b	24.00 ± 0.19^b
	1-MCP	24.62 ± 0.14^a	26.07 ± 0.07^a	25.37 ± 0.19^a	24.66 ± 0.21^a
CAT activity ($U \cdot g^{-1}$)	Control	196.00 ± 2.70^a	101.83 ± 2.75^a	58.67 ± 4.07^b	55.83 ± 3.75^b
	1-MCP	196.00 ± 2.70^a	43.83 ± 2.83^b	68.00 ± 2.18^a	64.83 ± 3.06^a
APX activity ($U \cdot g^{-1}$)	Control	52.55 ± 0.83^a	42.05 ± 0.38^b	41.90 ± 0.88^b	43.60 ± 0.84^b
	1-MCP	52.55 ± 0.83^a	44.80 ± 0.43^a	44.00 ± 0.31^a	48.00 ± 1.05^a
AsA content ($g \cdot kg^{-1}$)	Control	3.14 ± 0.05^a	2.61 ± 0.05^b	1.05 ± 0.02^b	1.58 ± 0.03^b
	1-MCP	3.14 ± 0.05^a	3.17 ± 0.03^a	1.56 ± 0.03^a	2.11 ± 0.04^a

Data are expressed as means ± SD of triplicate assays. Within the same index, mean values with different lowercase letters in same column are significantly different ($p < 0.05$).

Table 4. Effect of 1-MCP on POD and PAL activities of *Z. latifolia* during storage at 25˚C.

Indices	Treatment	Storage time (days)			
		0	1	3	6
POD activity ($U \cdot g^{-1}$)	Control	428.40 ± 29.89[a]	531.30 ± 11.34[a]	533.20 ± 14.09[a]	581.50 ± 20.85[a]
	1-MCP	428.40 ± 29.89[a]	427.40 ± 33.90[b]	399.80 ± 38.12[b]	573.10 ± 66.05[a]
PAL activity ($U \cdot g^{-1}$)	Control	289.25 ± 5.63[a]	182.50 ± 8.23[a]	130.50 ± 1.30[a]	205.25 ± 6.81[a]
	1-MCP	289.25 ± 5.63[a]	157.75 ± 1.73[b]	128.75 ± 4.88[a]	200.25 ± 5.25[a]

Data are expressed as means ± SD of triplicate assays. Within the same index, mean values with different lowercase letters in same column are significantly different ($p < 0.05$).

Table 5. Effect of 1-MCP on lipase, PLD and LOX activities of *Z. latifolia* during storage at 25˚C.

Indices	Treatment	Storage time (days)			
		0	1	3	6
Lipase activity ($U \cdot g^{-1}$)	Control	785.00 ± 22.72[a]	928.00 ± 1.00[a]	923.83 ± 3.40[a]	819.50 ± 1.32[a]
	1-MCP	785.00 ± 22.72[a]	824.83 ± 1.61[b]	797.33 ± 28.40[b]	763.00 ± 17.33[b]
PLD activity ($U \cdot g^{-1}$)	Control	70.14 ± 1.70[a]	90.71 ± 2.08[a]	137.57 ± 1.65[a]	111.57 ± 4.89[a]
	1-MCP	70.14 ± 1.70[a]	73.86 ± 1.19[b]	103.86 ± 1.29[b]	93.71 ± 2.65[b]
LOX activity ($U \cdot g^{-1}$)	Control	40.36 ± 0.52[a]	52.06 ± 1.45[a]	57.40 ± 1.19[a]	52.04 ± 1.46[a]
	1-MCP	40.36 ± 0.52[a]	52.04 ± 1.22[a]	52.20 ± 2.48[b]	40.52 ± 2.29[b]

Data are expressed as means ± SD of triplicate assays. Within the same index, mean values with different lowercase letters in same column are significantly different ($p < 0.05$).

vegetable cells. And Lipase, PLD and LOX is considered an important enzyme that causes post ripening and aging of fruits and vegetables [22]. As seen in Table 5, PLD activity significantly increased from 70.14 ± 0.017 $U \cdot g^{-1}$ at day 0 to 137.57 ± 0.016 $U \cdot g^{-1}$ and 103.86 ± 0.013 $U \cdot g^{-1}$ at day 3 in the control samples and treated samples respectively. In addition, the PLD enzyme activity of both groups significantly decreased with the lower value in the treated group (93.71 ± 0.027 $U \cdot g^{-1}$) at the end of storage. Meanwhile, during the storage period, decrease of lipase activity was observed in the control and treated sample (Table 5). However, the sample treated with 1-MCP showed the lower lipase activity. Moreover, LOX activity increased during the early storage time in both samples to reach the values of 52.04 ± 1.46 $U \cdot g^{-1}$ in the control samples and 40.52 ± 2.29 $U \cdot g^{-1}$ in 1-MCP treated samples at the end of storage (Table 5).

Taken together, PLD, lipase and LOX activities in 1-MCP treated group were finally lower than that of the control groups after the storage. These data indicate that 1-MCP treatment significantly inhibited the PLD, lipase, and LOX activities.

4. Discussion

Senescence is known as a series of active degenerative processes of a cell and or-

ganism that are under genetic control. The loss of visual appearance of vegetables could be the result of senescence and considered as a negative attribute in commercial condition [27]. 1-MCP treatment has been reported to delay the weight loss and maintain a good visual quality appearance of horticultural products such as yardlong bean [28], cherry tomato [29], mango fruit [30]. In addition, 1-MCP treatment had a positive effect on delaying the weight loss during the postharvest storage of sweet basil leaf [20]. In our study, 1-MCP treatment significantly retarded the weight loss and maintained the visual appearance as well as preserved the color of *Z. latifolia* by keeping lower a, b and ΔE values as well as delaying the formation of hollow bran. These results are consistent with the findings of Luo *et al.* [31].

In addition, previous study reported the effect of 1-MCP on the inhibition of respiration rate [22] [32]. It was reported that 1-MCP treatment could reduce the respiration rate of horticultural products during storage. However, our current finding showed that sample treated with 1-MCP have a lower respiration rate during the 3 first day which become higher than the control samples rate after 6 days of storage. Similarly, Mccollum *et al.* [33] found that grape fruit treated with 75 $nL \cdot L^{-1}$ 1-MCP had higher respiration rate than those treated with 15 or 30 $nL \cdot L^{-1}$ 1-MCP. Therefore, they conclude that 1-MCP can retard or increase the respiration rate in grape fruit according on the concentration and time after treatment. In addition, 1-MCP treatment had no significant effect on respiration rate during the storage of "shatangu" mandarin at the end of storage (20 days) at 20˚C [34].

In our study 1-MCP treatment kept higher the total amount of AsA which is known as a crucial nutritional component in horticultural products with positive biological activity in human body [35]. A high amount of AsA in horticultural products was found to be important on the prevention of brown pigments synthesis. This result was in agreement with the positive effect of 1-MCP retarding the decrease of AsA in yardlong bean [28].

The senescence of horticultural products during postharvest storage is related to the accumulation of ROS [36]. In addition, previous study reported that an abundance of ROS may induce oxidative reactions with lipids, thereby, inducing the production of harmful substances including MDA. MDA content is commonly considered as indirect indicator of membrane integrity, and a high content may imply loss of membrane integrity [23]. Loss of membrane integrity in fruits and vegetables is an indicator of increased activity of membrane-related lipolytic enzymes, including PLD, lipase and LOX. PLD hydrolyzes phospholipids to phosphatidic acid and diacylglycerol, which are subsequently degraded to free fatty acids by lipase whereas LOX catalyzes the peroxidation of polyunsaturated fatty acids [35] [37]. A positive correlation between LOX activity, MDA content and ROS level was observed by Chomkitichai *et al.* [38] during the storage of "Daw" longan fruit. In our current study, it was seen that the contents of ROS (O_2^- , H_2O_2) were significantly inhibit by 1-MCP which therefore led to the

lower levels of MDA content, PLD, lipase and LOX activities. Similar effect of 1-MCP on the inhibition of ROS was also observed in baby squash treated with 1-MCP [39]. Additionally, Huang *et al.* [21] found that 1-MCP treatment significantly delayed the loss of membrane integrity in Okra (*Hibiscus esculentus*) during storage at 7˚C for 18 days. Our findings are also consistent with those of Wang *et al.* [37].

At the same time 1-MCP treatment enhanced the activity of antioxidant enzymes such as CAT, SOD and APX which are important to scavenge the over accumulation of ROS. SOD enzyme is known to convert superoxide ion into H_2O_2 which is eliminate by CAT [19]. Our results corroborate recent findings in green bell pepper where Cao *et al.* [17] monitored the effect of 1-MCP treatment on green bell pepper senescence during storage at 20˚C found that 1-MCP treatment increase the activity of antioxidant enzyme (APX, CAT and SOD) indirectly lowers the ROS content. In addition, 1-MCP treatment increases and lowers the antioxidant enzymes activities and MDA content respectively during the storage of broccoli [35].

The result of our study also showed that, 1-MCP treatment significantly inhibits the activities of PAL and POD. PAL is known to be responsible for the synthesis of phenolic compounds, which then become substrates for oxidation enzymes such as PPO and POD. The higher amount of POD is reported to be involved in the chlorophyll degradation of horticultural products leading to their senescence [40] [41]. Therefore, we can suggest that the lower POD is probably related to the lack of substrate due to the inhibitory action of 1-MCP on PAL. Our results were in accordance of those of Salvador *et al.* [42] and Massolo *et al.* [43] where they respectively found that 1-MCP treatment reduced PAL activity in mandarin ("Nova" and "Ortanique") and POD activity in eggplant.

5. Conclusion

Positive effects of 1-MCP were observed in this investigation on physicochemical quality of Z. *latifolia* during storage at 25˚C for 6 days. A postharvest application of 1-MCP significantly maintained the visual appearance of fresh Z. *latifolia* and retarded the increase of weight loss. In addition, the effect of 1-MCP treatment on delaying the senescence could be attributed to its capacity to retard the decrease of AsA content, improve the activities of antioxidant enzymes (APX, CAT and SOD) and inhibit the accumulation of ROS, MDA, thereby PLD, LOX, lipase as well as POD and PAL were inhibited. The shelf-life of Z. *latifolia* could prolong to 6 d during storage at 25˚C.

Acknowledgments

This work was funded by the research start-up funding from Nanjing Normal University (184080H202B117) and the general scientific research project of Zhejiang Provincial Department of Education (Y202147859).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Guo, H., Li, S., Peng, J. and Ke, W. (2007) *Zizania latifolia* Turcz. Cultivated in China. *Genetic Resources and Crop Evoluton*, **54**, 1211-1217. https://doi.org/10.1007/s10722-006-9102-8

[2] Wang, Z., Yan, N., Luo, X., Guo, S., Xue, S., Liu, J., Zhang, J. and Guo, D. (2020) Gene Expression in the Smut Fungus *Ustilago esculenta* Governs Swollen Gall Metamorphosis in *Zizania latifolia*. *Microbial Pathogenesis*, **143**, Article ID: 104107. https://doi.org/10.1016/j.micpath.2020.104107

[3] Zhang, Z., Xu, S., Kong, M., Dai, H., Liu, Y. and Miao, M. (2021) Isolation, Identification and Artificial Inoculation of *Ustilago esculenta* on *Zizania latifolia*. *Horticultural Plant Journal*, **7**, 347-358. https://doi.org/10.1016/j.hpj.2020.08.004

[4] Xu, X.W., Ke, W.D., Yu, X.P., Wen, J. and Song, G. (2008) A Preliminary Study on Population Genetic Structure and Phylogeography of the Wild and Cultivated *Zizania latifolia* (Poaceae) Based on *Adh1a* Sequences. *Theorical and Applied Genetic*, **116**, 835-843. https://doi.org/10.1007/s00122-008-0717-3

[5] Yan, N., Du, Y., Liu, X., Chu, C. and Zhang, Z. (2018) Morphological Characteristics, Nutrients, and Bioactive Compounds of *Zizania latifolia*, and Health Benefits of Its Seeds. *Molecules*, **23**, Article 1561. https://doi.org/10.3390/molecules23071561

[6] Luo, H., Jiang, L., Zhang, L., Jiang, J. and Yu, Z. (2012) Quality Changes of Whole and Fresh-Cut *Zizania latifolia* during Refrigerated (1˚C) Storage. *Food and Bioprocess Technology*, **5**, 1411-1415. https://doi.org/10.1007/s11947-010-0459-5

[7] Luo, H., Bao, Y., Jiang, J., Zhang, L., Song, L., Jiang, L. and Yu, Z. (2012) Proteome Changes of Fresh-Cut *Zizania latifolia* during Refrigerated (1˚C) storage. *European Food Research and Technology*, **235**, 1011-1021. https://doi.org/10.1007/s00217-012-1828-2

[8] Yang, B., Fang, X., Han, Y., Liu, R., Chen, H. and Gao, H. (2022) Analysis of Lignin Metabolism in Water Bamboo Shoots during Storage. *Postharvest Biology and Technology*, **192**, Article ID: 111989. https://doi.org/10.1016/j.postharvbio.2022.111989

[9] Huang, J., Wu, W., Fang, X., Chen, H., Han, Y., Niu, B. and Gao, H. (2022) *Zizania latifolia* Cell Wall Polysaccharide Metabolism and Changes of Related Enzyme Activities during Postharvest Storage. *Foods*, **11**, Article 392. https://doi.org/10.3390/foods11030392

[10] Luo, H., Jiang, L., Bao, Y., Wang, L. and Yu, Z. (2013) Effect of Chitosan/Nano-Chitosan Composite Coating on Browning and Lignification of Fresh-Cut *Zizania latifolia*. *Journal of Food Quality*, **36**, 426-431. https://doi.org/10.1111/jfq.12056

[11] Zhang, J., Murtaza, A., Zhu, L., Iqbal, A., Ali, S.W., Xu, X., Pan, S. and Hu, W. (2021) High Pressure CO_2 Treatment Alleviates Lignification and Browning of Fresh-Cut Water-Bamboo Shoots (*Zizania latifolia*). *Postharvest Biology and Technology*, **182**, Article ID: 111690. https://doi.org/10.1016/j.postharvbio.2021.111690

[12] Bo, W., Cheng, Z., Hu, Y., Boon-Ek, Y., Wongs-Aree, C. and Supapanich, S. (2019) Ultraviolet-C Treatment Maintains Physicochemical Quality of Water Bamboo (*Zizania latifolia*) Shoots during Postharvest Storage. *Postharvest Biology and Technology*, **152**, 65-72. https://doi.org/10.1016/j.postharvbio.2019.02.017

[13] Qian, C., Ji, Z., Lin, C., Zhang, M., Zhang, J., Kan, J., Liu, J., Jin, C., Xiao, L. and Qi, X. (2022) Nitric Oxide Extends the Postharvest Life of Water Bamboo Shoots Partly by Maintaining Mitochondrial Structure and Energy Metabolism. *International Journal of Molecular Sciences*, **23**, Article 1607. https://doi.org/10.3390/ijms23031607

[14] Qi, X., Ji, Z., Lin, C., Li, S., Liu, J., Kan, J., Zhang, M., Jin, C. and Qian, C. (2020) Nitric Oxide Alleviates Lignification and Softening of Water Bamboo (*Zizania latifolia*) Shoots during Postharvest Storage. *Food Chemistry*, **332**, Article ID: 127416. https://doi.org/10.1016/j.foodchem.2020.127416

[15] Yang, B., Han, Y., Wu, W., Fang, X., Chen, H. and Gao, H. (2022) Impact of Melatonin Application on Lignification in Water Bamboo Shoot during Storage. *Food Chemistry*: *X*, **13**, Article ID: 100254. https://doi.org/10.1016/j.fochx.2022.100254

[16] Dong, G., Wang, C., Liu, H., Liu, C. and Qiao, Y. (2022) Impact of Ethanol Vapor treatment on the Quality of Water Bamboo (*Zizania caduciflora* L.) Shoots during Cold Storage. *Journal of Food Processing and Preservation*, **46**, e16494. https://doi.org/10.1111/jfpp.16494

[17] Cao, S., Yang, Z. and Zheng, Y. (2012) Effect of 1-Methylcyclopene on Senescence and Quality Maintenance of Green Bell Pepper Fruit during Storage at 20˚C. *Postharvest Biology and Technology*, **70**, 1-6. https://doi.org/10.1016/j.postharvbio.2012.03.005

[18] Song, L., Yi, R., Luo, H., Jiang, L., Gu, S. and Yu, Z. (2020) Postharvest 1-Methylcyclopropene Application Delays Leaf Yellowing of Pak Choi (*Brassica rapa* subsp. chinensis) by Improving Chloroplast Antioxidant Capacity and Maintaining Chloroplast Structural Integrity during Storage at 20˚C. *Scientia Horticulturae*, **270**, Article ID: 109466. https://doi.org/10.1016/j.scienta.2020.109466

[19] Han, C., Zuo, J.H., Wang, J., Xu, L., Wang, Z., Dong, H. and Gao, L. (2015) Effects of 1-MCP on Postharvest Physiology and Quality of Bitter Melon (*Momordica charantia* L.) *Scientia Horticultutrae*, **182**, 86-91. https://doi.org/10.1016/j.scienta.2014.07.024

[20] Hassan, F.A.S. and Mahfouz, S.A. (2010) Effect of 1-Methylcyclopropene (1-MCP) Treatment on Sweet Basil Leaf Senescence and Ethylene Production during Shelf-Life. *Postharvest Biology and Technology*, **55**, 61-65. https://doi.org/10.1016/j.postharvbio.2009.07.008

[21] Huang, S., Li, T., Jiang, G., Xie, W., Chang, S. and Jiang, Y. (2012) 1-Methylcyclopropene Reduces Chilling Injury of Harvested Okra (*Hibiscus esculentus* L.) Pods. *Scientia Horticulturae*, **141**, 42-46. https://doi.org/10.1016/j.scienta.2012.04.016

[22] Song, L., Luo, H., Jiang, L., Hou, J., Zhang, T., Dai, L. and Yu Z. (2020b) Integrative Analysis of Transcriptome and Metabolome Reveals the Possible Mechanism of Leaf Yellowing in Pak Choi (*Brassica rapa* subsp. *chinensis*) with 1-Methylcyclopropene Treatment during Storage at 20˚C. *Postharvest Biology and Technology*, **169**, Article ID: 111300. https://doi.org/10.1016/j.postharvbio.2020.111300

[23] Gouda, M.H.B., Zhang, C., Peng, S., Kong, X., Chen, Y., Li, H., Li, X., Luo, H. and Yu, L. (2021) Combination of Sodium Alginate-Based Coating with L-Cysteine and Citric acid Extends the Shelf-Life of Fresh-Cut Lotus Root Slices by Inhibiting Browning and Microbial Growth. *Postharvest Biology and Technology*, **175**, Article ID: 111502. https://doi.org/10.1016/j.postharvbio.2021.111502

[24] Li, X., Zhao, C., Li, H., Zhu, W., Ma, H. and Feng, H. (2009) Bacterial Impact on H_2O_2 Accumulation during the Interaction between *Xanthomonas* and Rice. *Journal of Plant Production Science*, **12**, 133-138. https://doi.org/10.1626/pps.12.133

[25] Li, X., Peng, S., Yu, R., Li, P., Zhou, C., Qu, Y., Li, H., Luo, H. and Yu, L. (2022) Co-application of 1-MCP and Laser Microporous Plastic Bag Packaging Maintains Postharvest Quality and Extends the Shelf-Life of Honey Peach Fruit. *Foods*, **11**, Article 1733. https://doi.org/10.3390/foods11121733

[26] Gao, H., Chai, H.K., Cheng, N. and Cao, W. (2017) Effects of 24-Epibrassinolide on Enzymatic Browning and Antioxidant Activity of Fresh-Cut Lotus Root Slices. *Food Chemistry*, **217**, 45-51. https://doi.org/10.1016/j.foodchem.2016.08.063

[27] Pogson, B.J. and Morris, S.C. (2004) Postharvest Senescence of Vegetables and Its Regulation. *Plant Cell Death Process*, 319-329. https://doi.org/10.1016/B978-012520915-1/50025-4

[28] Jiang, Z., Zeng, J., Zheng, Y., Tang, H. and Li, W. (2018) Effects of 1-Methylcyclopropene Treatment on Physicochemical Attributes of "Hai Jiang" Yardlong Bean during Cold Storage. *Journal of Food Quality*, **2018**, Article ID: 7267164. https://doi.org/10.1155/2018/7267164

[29] Taye, A.M., Tilahun, S., Hong, S., Su, P. and Jeong, C.S. (2019) Effects of 1-MCP on Quality and Storability of Cherry Tomato (*Solanum lycopersicum* L.) *Horticulturae*, **5**, Article 29. https://doi.org/10.3390/horticulturae5020029

[30] Sakhale, B.K., Gaikwad, S.S. and Chavan, R.F. (2018) Application of 1-Methylcyclopropene on Mango Fruit (Cv. Kesar): Potential for Shelf Life Enhancement and Retention of Quality. *Journal of Food Science and Technology*, **55**, 776-781. https://doi.org/10.1007/s13197-017-2990-0

[31] Luo, H., Zhou, T., Kong, X., Tao, M. and Yu, Z. (2019) iTRAQ-Based Mitochondrial Proteome Analysis of the Molecular Mechanisms Underlying Postharvest Senescence of *Zizania latifolia*. *Journal of Food Biochemestry*, **43**, e13053. https://doi.org/10.1111/jfbc.13053

[32] Xie, G., Feng, Y., Chen, Y. and Zhang, M. (2020) Effects of 1-Methylcyclopropene (1-MCP) and Ethylene on Postharvest Lignification of Common Beans (*Phaseolus vulgaris* L) *ACS Omega*, **5**, 8659-8666. https://doi.org/10.1021/acsomega.0c00151

[33] Mccollum, G. and Maul, P. (2007) 1-Methylcyclopropene Inhibits Degreening But Stimulates Respiration and Ethylene Biosynthesis in Grape Fruit. *Horticultural Science*, **42**, 120-124. https://doi.org/10.21273/HORTSCI.42.1.120

[34] Li, Q., Wu, F.W., Li, T.T., Su, X., Jiang, G., Qu, H., Jiang, Y. and Duan, X. (2012) 1-Methylcyclopropene Extends the Shelf-Life of "Shatangju" Mandarin (*Citrus reticulate Blanco*) Fruit with Attached Leaves. *Postharvest Biology and Technology*, **67**, 92-95. https://doi.org/10.1016/j.postharvbio.2012.01.001

[35] Yuan, G., Sun, B., Yuan, J. and Wang, Q. (2010) Effect of 1-Methylcyclopropene on Shelf Life, Visual Quality, Antioxidant Enzymes and Health-Promoting Compounds in Broccoli Florets. *Food Chemestry*, **118**, 774-781. https://doi.org/10.1016/j.foodchem.2009.05.062

[36] Huo, J.Q., Huang, D.J. Zhang, J., Fang, H., Wang, B., Wang, C. and Liao, W. (2018) Hydrogen Sulfide: A Gaseous Molecule in Postharvest Freshness. *Frontiers in Plant Science*, **9**, 1-8. https://doi.org/10.3389/fpls.2018.01172

[37] Wang, H., Chen, G., Shi, L., Lin, H. and Fan, Z. (2020) Influences of 1-Methylcyclopropene-Containing Papers on the Metabolisms of Membrane Lipids in Anxi Persimmons during Storage. *Food Quality and Safety*, **4**, 143-150. https://doi.org/10.1093/fqsafe/fyaa021

[38] Chomkitichai, W., Chumyam, A., Rachtanapun, P., Uthaibutra, J. and Saengnil, K. (2014) Reduction of Reactive Oxygen Species Production and Membrane Damage

during Storage of "Daw" Longan Fruit by Chlorine Dioxide. *Scientia Horticulturae*, **170**, 143-149. https://doi.org/10.1016/j.scienta.2014.02.036

[39] Kurubaş, M.S., Sabotic, J. and Erkan, M. (2021) The Effects of 1-Methylcyclopropene (1-MCP) Treatment on Antioxidant Enzymes and Fruit Quality Parameters of Cold-Stored Baby Squashes. *Turkish Journal of Agriculture and Forestry*, **45**, 33-45. https://doi.org/10.3906/tar-2004-112

[40] Yamauchi, N., Funamoto, Y. and Shigyo, M. (2004) Peroxidase-Mediated Chlorophyll Degradation in Horticultural Crops. *Phytochemestry Review*, **3**, 221-228. https://doi.org/10.1023/B:PHYT.0000047796.98784.06

[41] Zhang, Y., Huber, D.J., Hu, M., Jiang, G., Gao, Z., Xu, X., Jiang, Y. and Zhang, Z. (2018) Delay of Postharvest Browning in Litchi Fruit by Melatonin via the Enhancing of Antioxidative Processes and Oxidation Repair. *Journal of Agricultural and Food Chemistry*, **66**, 7475-7484. https://doi.org/10.1021/acs.jafc.8b01922

[42] Salvador, A., Carvalho, C.P. and Monterde, A. (2006)1-MCP Effect on Chilling Injury Development in "Nova" and "Ortanique" Mandarins. *Food Science and Technology International*, **12**, 165-170. https://doi.org/10.1177/1082013206063736

[43] Massolo, J.F., Concellón, A., Chaves, A.R. and Vicente, A.R. (2011) 1-Methylcyclopropene (1-MCP) Delays Senescence, Maintains Quality and Reduces Browning of Non-Climacteric Eggplant (*Solanum melongena* L.) Fruit. *Postharvest Biology and Technology*, **59**, 10-15. https://doi.org/10.1016/j.postharvbio.2010.08.007