Journal of Integrative Agriculture 2024, 23(7): 2476–2490

Available online at www.sciencedirect.com

ScienceDirect

RESEARCH ARTICLE

Effects of 1-methylcyclopropene on skin greasiness and quality of 'Yuluxiang' pear during storage at 20°C

Wanting Yu, Xinnan Zhang, Weiwei Yan, Xiaonan Sun, Yang Wang, Xiaohui Jia#

Research Institute of Pomology, Chinese Academy of Agricultural Sciences, Xingcheng 125100, China

Abstract

During storage at 20°C, specific pear cultivars may exhibit a greasy texture and decline in quality due to fruit senescence. Among these varieties, 'Yuluxiang' is particularly susceptible to peel greasiness, resulting in significant economic losses. Therefore, there is an urgent need for a preservative that can effectively inhibit the development of greasiness. Previous studies have demonstrated the efficacy of 1-methylcyclopropene (1-MCP) in extending the storage period of fruits. We hypothesize that it may also influence the occurrence of postharvest peel greasiness in the 'Yuluxiang' pears. In this study, we treated 'Yuluxiang' pears with 1-MCP. We stored them at 20°C while analyzing the composition and morphology of the surface waxes, recording enzyme activities related to wax synthesis, and measuring indicators associated with fruit storage quality and physiological characteristics. The results demonstrate that prolonged storage at 20°C leads to a rapid increase in skin greasiness, consistent with the observed elevations in L*, greasiness score, and the content of total wax and greasy wax components. Moreover, there were indications that cuticular waxes underwent melting, resulting in the formation of an amorphous structure. In comparison to controls, the application of 1-MCP significantly inhibited increments in L* values as well as grease scores while also reducing accumulation rates for oily waxes throughout most stages over its shelf period, additionally delaying transitions from flaky-wax structures towards their amorphous counterparts. During the initial 7 d of storage, several enzymes involved in the biosynthesis and metabolism of greasy wax components, including lipoxygenase (LOX), phospholipase D (PLD), and *β*-ketoacyl-CoA synthase (KCS), exhibited an increase followed by a subsequent decline. The activity of LOX during early shelf life (0–7 d) and the KCS activity during middle to late shelf life (14–21 d) were significantly suppressed by 1-MCP. Additionally, 1-MCP effectively maintained firmness, total soluble solid (TSS) and titratable acid (TA) contents, peroxidase (POD), and phenylalanine ammonia-lyase (PAL) activities while inhibiting vitamin C degradation and weight loss. Furthermore, it restrained polyphenol oxidase (PPO) activity, ethylene production, and respiration rate increase. These findings demonstrate that 1-MCP not only delays the onset of peel greasiness but also preserves the overall storage quality of 'Yuluxiang' pear at a temperature of 20°C. This study presents a novel approach for

Received 9 August, 2023 Accepted 25 January, 2024
Wanting Yu, E-mail: abcdefg1468929@qq.com; #Correspondence Xiaohui Jia, E-mail: jiaxiaohui@caas.cn

doi: 10.1016/j.jia.2024.03.017

developing new preservatives to inhibit pear fruit peel greasiness and provides a theoretical foundation for further research on pear fruit preservation.

Keywords: 'Yuluxiang' pear, skin greasiness, 1-methylcyclopropene, storage quality

1. Introduction

The 'Yuluxiang' (*Pyrus sinkiangensis*) is a popular pear cultivar in China, renowned for its exceptional flavor and prolonged storage capacity (Jia *et al.* 2016). It has been extensively cultivated in regions such as Shanxi, Liaoning, Ningxia, Shandong, and Hebei provinces/autonomous region of China, generating annual profits for local farmers (Jia *et al.* 2022). However, recent storage experiments conducted in our laboratory have revealed that as the room temperature storage period extends, particularly after 7 d of storage, the surface of the 'Yuluxiang' pear may exhibit a greasy texture resembling skin greasiness observed in specific apple cultivars. This condition impacts the fruit's appearance and diminishes its commercial value, resulting in significant economic losses for the fruit industry.

The greasy phenomenon observed in harvested fruit is attributed to a physiological disorder. Previous research suggests that the accumulation of fatty acids is closely associated with skin greasiness (Dadzie *et al.* 1995; Christeller and Roughan 2016). The continuous build-up of fatty acids in apple fruit exacerbates the greasiness issue. Additionally, an increase in free fatty acids acts as a synthetic precursor for ester accumulation. Notably, numerous unsaturated oleic acid linoleic acid esters have been identified within the wax of greasy 'Gala' apple skins (Christeller and Roughan 2016). Subsequent studies have revealed that specific fluid wax components such as linoleate and oleate esters of (E,E)-farnesol, along with short-chain alcohols (C_3–C_5), contribute to the development of greasiness on 'Jonagold' and 'Gripps Pink' apples (Yan *et al.* 2018, 2022). Furthermore, researchers speculate that changes in the ultrastructure of peel wax may be associated with this greasy phenomenon. Variations in epicuticular wax structures are observed, where skin greasiness arises from transitions of wax crystals into droplets (Curry 2008; Dong *et al.* 2012). Ethylene is also involved in the biosynthesis of wax and the occurrence of greasiness. Ju and Bramlage (2001) discovered that ethylene promotes the ripening of 'Delicious' apples and contributes to fruit greasiness development. Weight loss serves as a significant quality indicator during fruit storage, as a reduction in very long-chain wax biosynthesis can lead to rapid water loss and size reduction of the fruit (Leide *et al.* 2007; Wang *et al.* 2021). Previous studies have found positive correlations between weight loss and wax components, such as fatty acids and alcohols, during storage (Wang *et al.* 2014a, b). Recent research has identified L* as an additional physiological index that effectively reflects the extent of greasiness, with higher L* values corresponding to more severe levels of greasiness in 'Yuluxiang' pears (Jia *et al.* 2016).

1-MCP is an ethylene inhibitor that competes with ethylene receptors for binding sites, thereby inhibiting ethylene production (Hu *et al.* 2019). It is extensively employed in postharvest fruit preservation to prolong shelf life (Dias *et al.* 2021). Presently, research on the utilization of 1-MCP in postharvest storage and preservation of fruits primarily focuses on regulating ethylene through 1-MCP treatment, evaluating the effects of 1-MCP treatment on maintaining freshness across various fruits and investigating the impact of combined treatments with 1-MCP treatment on fruit storage quality (Mubarok *et al.* 2022; Thewes *et al.* 2023; Wan *et al.* 2023). Shi *et al.* (2023) demonstrated that injecting calcium during flowering and applying post-harvest treated with 1-MCP could effectively suppress the increase in ethylene release rate and delay the deterioration of grape berry quality during storage. Additionally, Krupa *et al.* (2023) revealed that the application of 1-MCP reduced firmness loss in mini kiwifruit during storage; however, it also impeded the ripening process, leading to decreased sweetness and increased acidity levels. Kiwi fruits treated with 1-MCP exhibited enhanced antioxidant activity and elevated bioactive compound content. The inhibitory effect of 1-MCP on the greasy sensation of apple peel during shelf life, aiming to improve the fruit's commercial value, was not discovered until 2008 (Curry 2008). In 2013, Nock and Watkins (2013) demonstrated that single or repeated treatments with 1-MCP could effectively reduce the greasiness of the 'Empire' apples. In the following year, Wang *et al.* (2014a, b) found that treatment with 1-MCP could effectively inhibit peel wax content, delay dynamic changes in peel wax ultrastructure, and prevent the occurrence of a greasy

texture on 'Pink Lady' apple peels. In a later study, Yang *et al.* (2017) pointed out that easters in peel wax may be related to the greasiness of some apple peels and found no significant increase in transcription levels of genes related to long-chain wax biosynthesis after treatment with 1-MCP. In 2023, Yang *et al.* (2023) discovered that treatment with 1-MCP could reduce greasiness in 'Korla' pear fruit during storage.

This study aims to investigate the influence of 1-MCP treatment on the greasiness of 'Yuluxiang' pears while ensuring good storage quality. Firstly, we compared the appearance-based greasiness levels of 'Yuluxiang' pears treated with 1-MCP and untreated ones. Then, we determined the influence of 1-MCP treatment on pear peel greasiness by observing changes in peel microstructure and analyzing the composition and content of peel wax. Finally, we further demonstrated the effects of 1-MCP treatment on fruit peel greasiness by measuring lipid anabolic enzyme activity and product content. Simultaneously, we assessed fundamental storage quality and physiological indicators during shelf life to demonstrate that 1-MCP effectively reduces fruit skin greasiness without compromising fruit quality. These findings will provide a theoretical foundation for future investigations into pear peel greasiness and enhance the comprehension and application of 1-MCP in pear preservation.

2. Materials and methods

2.1. Experimental materials

'Yuluxiang' pears were harvested from a well-managed orchard in Huludao City, Liaoning Province of China, at the stage of marketable maturity. Twenty representative trees were selected, and fruits were picked from different directions, including the outer periphery and inner bore. Each pear fruit was packed with hollow foam pockets and transported to the laboratory within 2 h. Only fruits of uniform size and color, without cracks, diseases, or pests, were carefully selected for further experiment. The postharvest fruits were randomly divided into two groups consisting of 300 fruits each. One group was fumigated with 1.0 μL L^{-1} 1-MCP for 24 h in a sealed plastic tent (4 m^3), while the other group remained untreated as the control. After treatment, all the fruits mentioned above were packed in polyethylene plastic bags with a thickness of 0.02 mm and stored at an ambient temperature of 20°C. Two slices of peel were selected from the symmetrical part along the vertical axis of each fruit at intervals of 7 d and immediately frozen in liquid nitrogen, then stored at –80°C for enzyme analysis.

2.2. Determination of greasiness score, L*, and weight loss

The greasiness level of stored fruits was quantitatively assessed using a 'greasiness score' as described in a report (Yang *et al.* 2017) with slight modifications. The greasiness score was determined by subjectively rubbing the fruit against the hand. Grease levels were categorized as follows: none (0≤grease score<25), slight (25≤grease score<50), moderate (50≤grease score<75), or severe (grease score≥75). L* value was measured using a portable colorimeter (CR-400, Minolta, Japan) with a CIE C illuminant. Weight loss was measured through gravimetric analysis and expressed as a percentage (%). Each pear's initial weight (M_0) was recorded, and the weight of each pear was labeled as M_1 every 7 d during storage. Weight loss was calculated using the following equation: Weight loss (%)=(M_0–M_1)/M_0×100. All the above indices were replicated three times except for L* measurements conducted on ten fruits.

2.3. Scanning electron microscopy (SEM) analysis

Pericarp pieces measuring 2–5 mm in diameter and 1 mm in thickness were obtained from the equatorial zone of three fruits using a cork borer and a razor blade. The samples were fixed with 100 μL of 2.5% glutaraldehyde for 12 h, followed by rinsing in 1 mL of 0.1 mol L^{-1} phosphate buffer saline (PBS, pH 7.2) for 3 min. Subsequently, the samples underwent dehydration using a gradient series of ethanol concentrations (30, 50, 70, 80, 90, and 95%, and twice with absolute ethanol), each step lasting 10 min, before being subjected to vacuum drying. Next, the samples were affixed onto metallic stubs using carbon stickers and sputter-coated with gold for 30 s utilizing a Ion sputtering apparatus (MC1000, Hitachi, Japan). Finally, images were captured using a scanning electron microscope (SU8100, Hitachi, Japan).

2.4. Estimation of fruit surface area and wax extraction

The surface area of the fruit pericarp was calculated using the method proposed by Huang *et al.* (2022), while epidermis wax extraction was carried out following the method proposed by Zhao *et al.* (2015) with slight modifications. In a fume hood, each group of three pears was immersed in a mixture of chloroform and dichloromethane solvent (2:1, v/v) for 90 s, stirring continuously with a glass rod. It is important to note that this process does not cause any damage to the pear

skin. The washings were then filtered, and three replicate samples were obtained. The extracts were concentrated to approximately 10 mL using a rotary evaporator, and an ultrasonic oscillator was employed along with 20 mL of chloroform solvent to dissolve the wax on the wall of the distillation flask. The solutions were then combined and transferred to pre-weighed vessels, dried with nitrogen at 40°C, and weighed again to determine their final weight. Finally, the total wax content was calculated by dividing the total wax weight by the surface area of fruits expressed as μg cm^2.

2.5. Gas chromatography-mass spectrometry (GC-MC) analysis

After drying, the wax samples were incubated in 200 μL of bis-N, N-(trimethylsilyl) trifluoroacetamide (BSTFA, contains 1% TMCS, SILYL-991, MACHEREY-NAGEL, Germany) at a temperature of 70°C for 1 h before GC-MS analysis. The excess BSTFA was eliminated under a nitrogen flow, and the resulting derivatives were dissolved in 30 mL of chloroform. The mixture was subjected to vortexing for 1 min, followed by sonication for 2 min, and centrifugation at room temperature for 10 min (12,000×g, 20°C). Supernatants (600 μL) were dissolved in a mixture of chloroform and dichloromethane solvent (1:1, v/v), with an *n*-heptadecane serving as an internal standard at a concentration of 100 μg mL^{-1}.

The wax sample was analyzed using a GC-MS (QP2020, SHIMADZU, Kyoto, Japan) equipped with an HP-5MS capillary column (30 m×0.25 mm×0.25 μm). The inlet temperature was set at 260°C, and the helium carrier gas was programmed for a constant flow of 1 mL min^{-1}. The GC temperature was initially set at 80°C for 2 min, followed by an increase of 3°C min^{-1} until reaching 260°C. Then, it increased by 2°C min^{-1} until it reached 300°C and held steady for another 30 min. The MS operated in the positive electron ionization mode with an energy of 70 eV and scanned mass-to-charge ratio (*m*/*z*) from 50 to 600. The transfer line and iron source temperatures were maintained at 280 and 200°C, respectively. Wax compounds were identified by comparing their mass spectra with those in the NIST17 MS library, while retention indices were calculated for the detected wax compounds.

2.6. Determination of lipoxygenase (LOX), long-chain-acyl-coenzyme A synthetase (LACS), phospholipase D (PLD), and *β*-ketoacyl-acyl-coenzyme A synthase (KCS) activity

All the enzymes' activities were quantified using a Plant Enzyme-Linked Immunosorbent Assay (ELISA) Kit (MEIMIAN, Jiangsu, China), following the manufacturer's protocol. All values were determined based on a standard curve and expressed as U L^{-1} (LOX, LACS, PLD, and KCS). Pericarp powder (1 g) was extracted with 9 mL of 0.1 mol L^{-1} phosphate buffer saline (PBS, pH 7.2), and the resulting extracts were utilized for subsequent measurements. Each treatment was repeated three times.

2.7. Determination of fruit firmness, total soluble solids (TSS), titratable acid (TA), and vitamin C

The symmetrical firmness of the equatorial part of the fruit peel was determined using a texture analyzer (GS-2, FTA2, South Africa) equipped with an 11.3 mm probe diameter and expressed as kg cm^{-2}. The TSS of the fruit was measured using a refractometer (PR-101, ATAGO) and defined as %. The TA and vitamin C content were analyzed using an automated smart titrator (808Titrado, Sweden) with a 0.1 mol L^{-1} NaOH standard solution and 2, 6-dichloroindophenol indophenol sodium salt, respectively, expressed as g kg^{-1} and mg 100 g^{-1}. A subset of 10 fruits from each treatment group was periodically sampled to estimate the parameters mentioned above, and the results were presented as the means±standard deviation based on measurements from these 10 fruits.

2.8. Determination of malondialdehyde (MDA) content, peroxidase (POD), polyphenol oxidase (PPO), and phenylalanine ammonia-lyase (PAL) activity

The MDA content was determined using a method described by Dhindsa *et al.* (1981) with little modifications. Pear peel tissue (0.1 g) was homogenized with 1 mL of 10% trichloroacetic acid containing 0.5% (w/v) thiobarbituric acid. Subsequently, the mixture was treated at 100°C for 10 min, followed by rapid cooling and centrifugation at 5,000×g for 15 min. The absorbance of the resulting supernatant was measured at a wavelength of 532 nm. The MDA content was quantified as nmol g^{-1} based on fresh weight.

Pear peel tissue (0.1 g) was homogenized in precooled buffers (4°C) to prepare extracts for assay of the following enzymes: 1 mL of 0.05 mol L^{-1} sodium phosphate buffer (pH 6.8) containing polyvinylpyrrolidone for POD, PPO, PAL (Hyodo 1971; Kochba *et al*. 1997; Luo *et al*. 1999). Subsequently, the tissue homogenates were centrifuged at 12,000×g at 4°C for 15 min, and the resulting supernatants were utilized for the enzyme assays. The absorbance of the resulting supernatant was measured at a wavelength of 470, 410, 290 nm, in turn. The POD,

PPO, PAL activities were quantified as U g^{-1} based on fresh weight.

2.9. Determination of respiration rate and ethylene production

The fruit respiration rate and ethylene production were determined using a gas chromatograph (SP9890, Lunan Ruihong Instrument Company, Shandong, China). The results were expressed in mg kg^{-1} h^{-1} (CO_2) and μL kg^{-1} h^{-1} (C_2H_2). Nitrogen was used as the carrier gas at a flow rate of 55 mL min^{-1}, while hydrogen served as the fuel gas at a flow rate of 25 mL min^{-1}. The chromatographic parameters were as follows: inlet temperature, 80°C; column temperature, 100°C; detection temperature, 160°C; converter furnace temperature, 360°C. Each treatment consisted of three replicates with three fruits per replicate. The fruits were placed in a sealable box with a capacity of 2.25 L and sealed at 20°C for 1 h. One milliliter of headspace gas was extracted using a syringe and subsequently injected into the gas chromatograph for analysis. Both measurements were repeated thrice.

2.10. Statistical analysis

Significant differences were analyzed using ANOVA (P<0.05) and Duncan's new multiple-range test with the SPSS software V20.0 (IBM Corp, Armonk, USA). The correlation and clustering analyses were performed based on Pearson's correlation map and clustering heat map using TBtools V1.120 software.

3. Result

3.1. Effects of 1-MCP treatment on pear skin greasiness during shelf life

The appearance of the 'Yuluxiang' pear gradually became brighter over time, accompanied by an increase in perceived oiliness (Fig. 1-A). Based on the findings, the L* value consistently increased throughout the entire shelf period (Fig. 1-B). Pears in the control group displayed a more pronounced oily appearance and a higher L* value than those treated with 1-MCP. Moreover, there was a significant increase in greasiness score compared to d 0 of storage (Fig. 1-C). By d 21 of shelving, fruits in the control group had developed yellow peel coloration and showed severe greasiness, resulting in diminished commercial value. In contrast, fruits treated with 1-MCP exhibited moderate greasiness but maintained their green surface well-preserved. Therefore, applying 1-MCP delays the fruit-greasing process and preserves its commercial viability.

3.2. Effects of 1-MCP treatment on fruit surface wax microstructure during shelf life

The cuticular wax morphology was examined using SEM to gain a deeper understanding of the epidermal characteristics contributing to the formation of greasiness. Upon harvest, the fruits' wax film appeared relatively smooth and well-organized, with fewer visible cracks (Fig. 2-A). However, noticeable differences

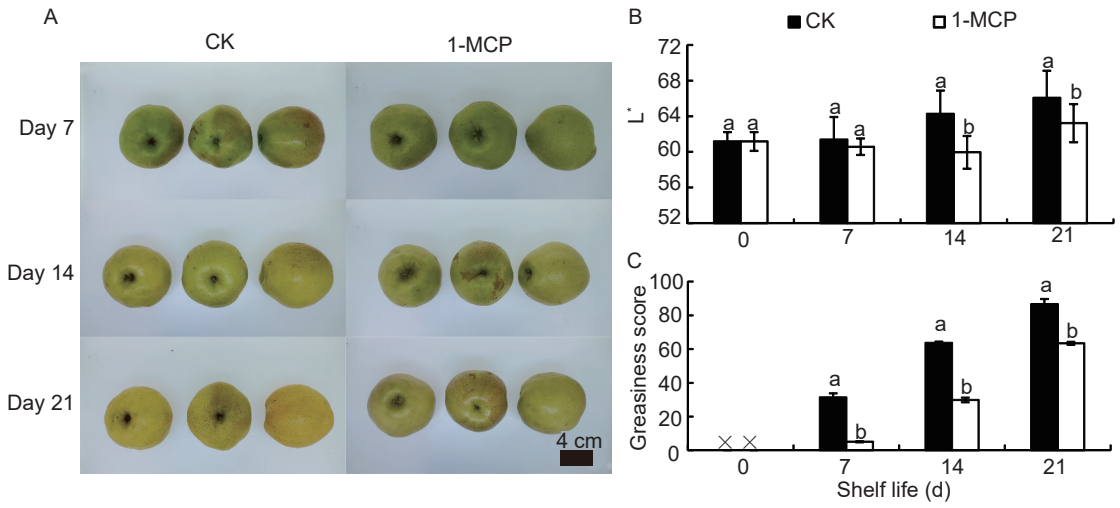

Fig. 1 Effects of 1-MCP treatment on fruit appearance (A), L* (B), and greasiness score (C) of 'Yuluxiang' pear during storage at 20°C. Error bars represent ±standard deviation (n=3). Letters in graphs indicate significant differences at the level of P<0.05.

in wax microstructures were observed between the two treatments by d 7. The untreated fruits exhibited a melting appearance of wax crystals, whereas the 1-MCP-treated fruits showed no discernible variations compared to freshly harvested ones. Over time, the untreated fruits displayed an increase in both the size and quantity of platelet-shaped wax crystals, which became more prominent by d 14 (Fig. 2-C). By d 21, numerous aggregations of lumpy-shaped wax covered the entire surface of untreated fruits (Fig. 2-D), while 1-MCP-treated fruits exhibited an abundance of platelet crystals until 14 d during storage (Fig. 2-F). The SEM analysis conducted in this study revealed changes in wax crystal structure that correlated with levels of fruit surface greasiness. Initially, the skin of freshly picked fruit did not possess any greasy texture and exhibited a relatively flat microstructure within its peel wax layer. As greasiness intensified, there was evidence suggesting that the microstructure underwent melting and rearrangement into a new configuration.

3.3. Effects of 1-MCP treatment on fruit surface wax composition during shelf life

The total wax content of pear fruits increased throughout storage, as depicted in Fig. 3-A. Consistent with the observation that the largest wax crystals were arranged in clusters, the control group displayed the highest total wax content on d 21. Untreated fruits consistently exhibited higher levels of total wax content than those treated with 1-MCP during shelf life. Alkanes (45.14% of total wax) constituted the predominant components in epidermal wax before storage; however, their levels significantly decreased within the first 7 d of storage in the control group. Conversely, 1-MCP-treated fruits demonstrated lower alkane content than untreated fruits during this initial period and did not exhibit significant changes thereafter. Fatty acids and aldehydes showed substantial variations throughout the entire storage duration for both groups, characterized by a continuous increase in aldehydes levels and an initial growth followed by a subsequent decline in fatty acid concentrations. Esters, another constituent of peel wax, accounted for a smaller proportion of total wax quantity compared to fatty acids and aldehydes; nevertheless, they experienced a considerable increase within the first week of storage for untreated fruits and a noticeable rise after 14 d for those treated with 1-MCP. Consequently, besides reducing overall wax content, the application of 1-MCP also delayed the accumulation of specific components over time.

To further elucidate the impact of specific wax components on peel greasiness and the effects of 1-MCP on these constituents, we conducted GC-MS analysis on a total of 28 selected compounds, encompassing alcohols, aldehydes, fatty acids, alkenes, and esters. Subsequently, a heatmap was generated, and cluster analysis was performed. Based on Fig. 3-C, two distinct copolymerization patterns were observed in relation to different treatments and shelf life. The untreated fruits' wax components from d 7, 14, and 21 formed one cluster, while another cluster comprised the fresh fruits' wax components from d 0, along with those treated with 1-MCP for d 7, 14, and 21. On d 0 of storage, most wax components exhibited their lowest content levels, particularly for stigmata-3,5-diene, palmitic acid, and stearic acid, as indicated by blue or light blue coloration in Fig. 3-C. By the 7th d of storage, the control group's fruits displayed a rapid increase in various wax component contents, with notable changes observed in the contents of 1-heptacosanol, (E)-9-octadecenoic acid, and hexadecenoic acid, octadecyl ester. However, compared to d 0 on the shelf, few wax components in fruits treated with 1-MCP at d 7 showed a low increase.

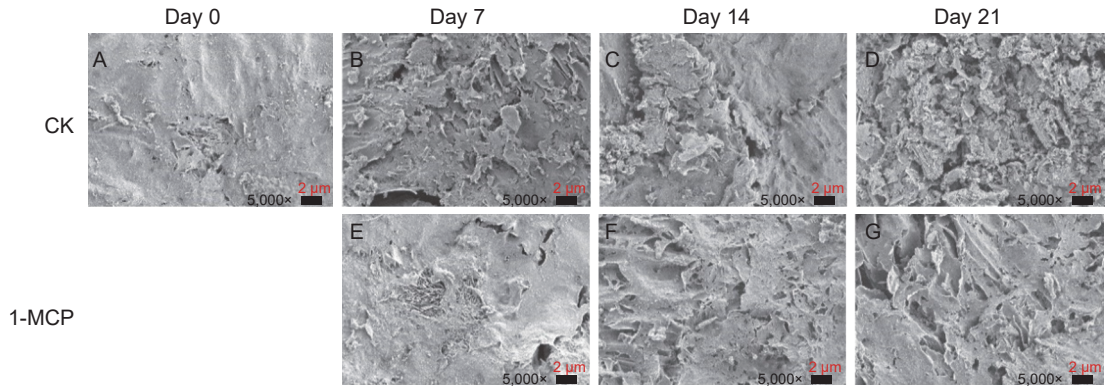

Fig. 2 Effects of 1-MCP treatment on fruit wax morphology of 'Yuluxiang' pear during storage at 20°C. Samples stored for 0 d were labeled as (A). Untreated samples for 7, 14, and 21 d were labeled as (B)–(D), while samples treated with 1-MCP for identical durations were labeled as (E)–(G). Scale bars represent 2 μm (total magnification: 5,000×).

These includes stigmata-3,5-diene, eicosanal and arachidic acid. Most of the wax component contents in 1-MCP-treated fruits were almost negligible. Limited *α*-farnesene content was observed until 14 d of storage in 1-MCP-treated fruits. On the 14th d of storage, a slight elevation in tetracosanol, docosanol, and 9-tricosanol acetate content was noted in untreated fruit. However, the content levels remained higher than those found in 1-MCP-treated fruit during this same period. Therefore, it is postulated that treatment with 1-MCP can delay the onset of peel greasiness by inhibiting levels of specific alkenes, alcohols, aldehydes, fatty acids, and esters in the peel wax.

3.4. Effects of 1-MCP treatment on fruit lipid metabolism parameters during shelf life

To further elucidate the impact of 1-MCP on peel

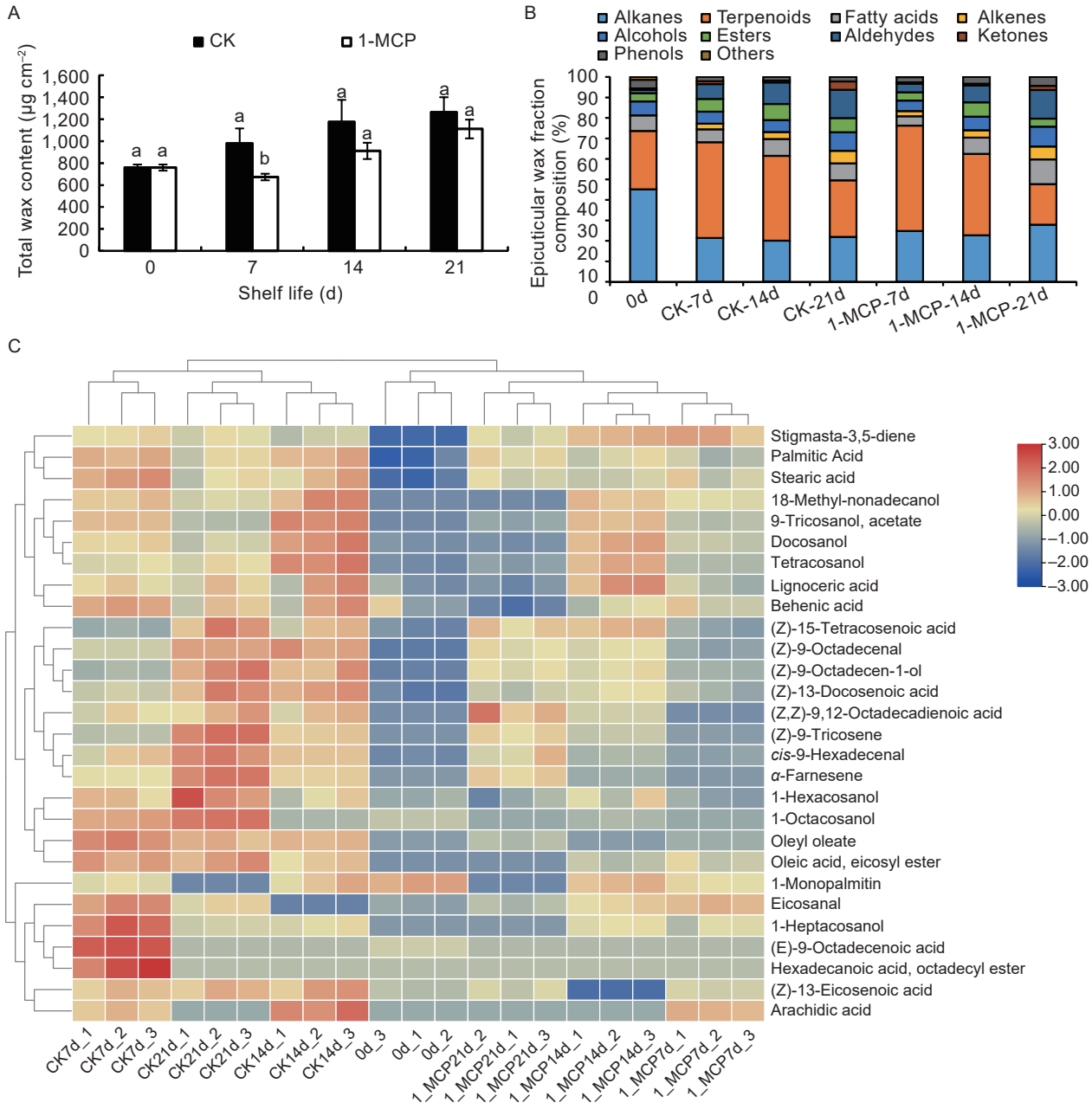

Fig. 3 Effects of 1-MCP treatment on the total wax content (A), epicuticular wax fraction composition (B), and 28 types of peel wax composition content (C) of 'Yuluxiang' pear during storage at 20°C. Error bars represent ±standard deviation (n=3). Different letters indicate significance at P<0.05.

greasiness, we investigated the levels of MDA content, PLD, LOX, KCS, and LACS enzyme activities in differently-treated fruits. In our study, the levels of MDA content, PLD, LOX, and KCS activities exhibited an initial increase followed by a subsequent decrease throughout the entire shelf period (Fig. 4-A–D); however, LACS activity gradually increased over time (Fig. 4-E). The levels of MDA content, KCS, and PLD activity were significantly higher in fruits treated with 1-MCP than those in the control group during the first 14 d of storage. Still, they showed no significant difference between both groups on d 21. On d 7 of storage, LOX activity was significantly lower in 1-MCP-treated fruits than in control. Throughout the shelf period, LACS activity remained consistently lower in 1-MCP-treated fruits relative to control fruits.

3.5. Effects of 1-MCP treatment on fruit quality during storage

To evaluate the storage quality during shelf life, we assessed firmness, TSS, TA, and vitamin C content (Table 1). The firmness of pears did not exhibit significant changes in two groups over time during storage; it has an initial value of 4.87 kg cm^{-2} on d 0 and a final value of 4.71 kg cm^{-2} on d 21. Moreover, there was no notable difference in firmness between untreated and 1-MCP-treated fruits throughout the entire storage period. On the 7th d of shelf life, TSS in the control group was significantly higher than in the fruits treated with 1-MCP. However, after the 14th d of shelf life, no significant difference was observed in TSS between both groups for the remaining shelf life duration. Initially, TA content decreased and then increased throughout the entire shelf period. On the 14th d of the shelf, fruit from the control group exhibited a higher TA content. On the 21st d of the shelf, the fruit treated with 1-MCP showed a higher TA content. Vitamin C content rapidly declined during the first 14 d for fruits from the control group but tended to stabilize thereafter; however, fruits treated with 1-MCP gradually declined throughout their entire shelf life instead. Furthermore, vitamin C content in 1-MCP-treated fruits was significantly higher than that found in untreated ones. In conclusion, our study demonstrated that applying 1-MCP can effectively preserve the firmness, TSS, and TA content of 'Yuluxiang' pear fruits during their 20°C shelf life while significantly inhibiting the decline in vitamin C content.

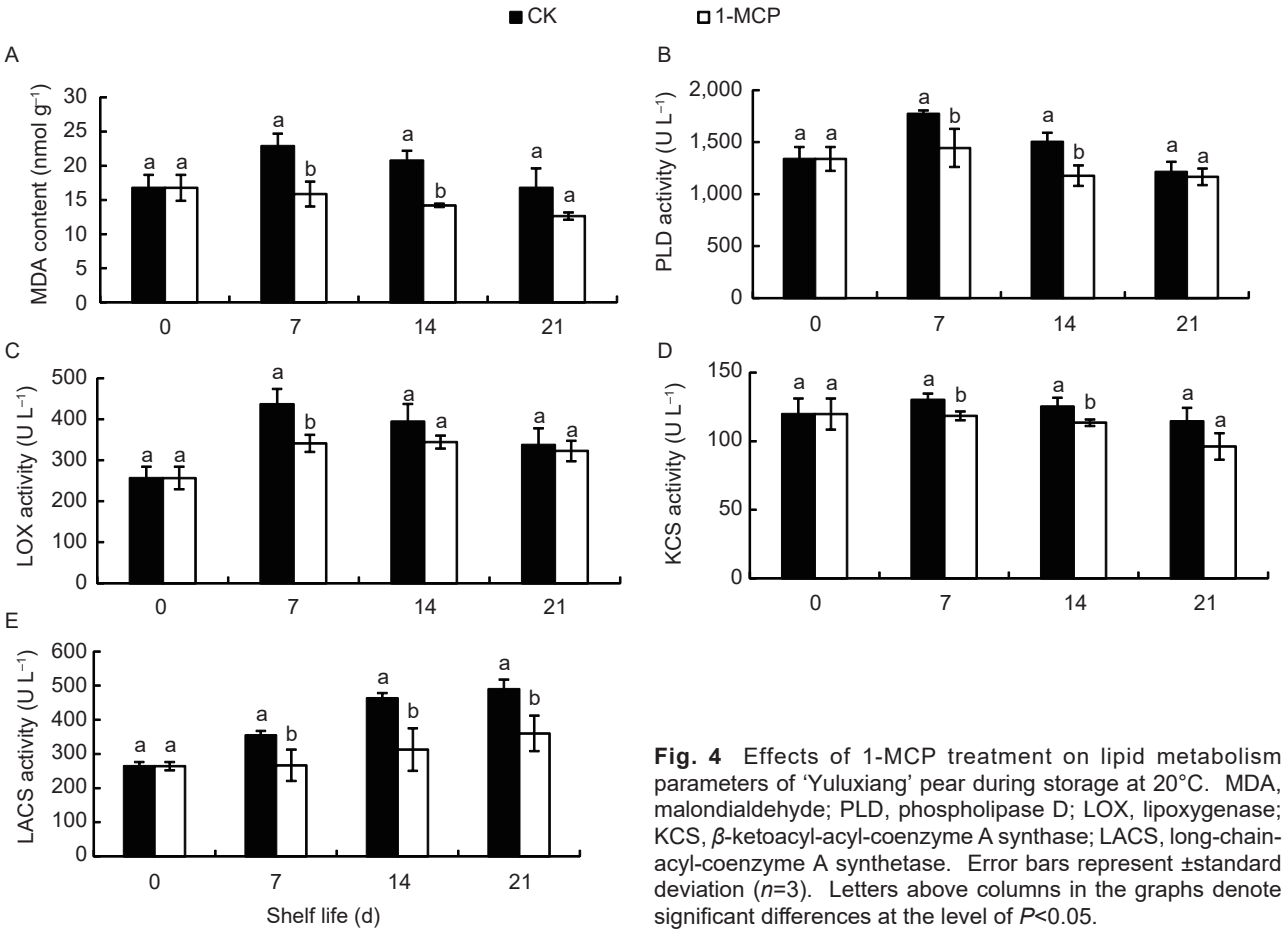

Fig. 4 Effects of 1-MCP treatment on lipid metabolism parameters of 'Yuluxiang' pear during storage at 20°C. MDA, malondialdehyde; PLD, phospholipase D; LOX, lipoxygenase; KCS, *β*-ketoacyl-acyl-coenzyme A synthase; LACS, long-chain-acyl-coenzyme A synthetase. Error bars represent ±standard deviation (n=3). Letters above columns in the graphs denote significant differences at the level of P<0.05.

3.6. Effects of 1-MCP treatment on fruit physiological changes during shelf life

We assessed the fruit weight loss and enzyme activities of PPO, POD, and PAL, which indicate fruit physiological changes and can serve as indicators for evaluating fruit storage quality. Overall, the weight loss rate and PAL activity increased with prolonged storage time, while PPO and POD activities initially increased but eventually decreased over time. Notably, fruits treated with 1-MCP exhibited a rapid decline in PPO activity on d 7 of shelf life, followed by a gradual increase and eventual stabilization (Fig. 5-B). Throughout the entire shelf period, the control group consistently demonstrated a significantly higher weight loss rate than fruits treated with 1-MCP (Fig. 5-A). Therefore, treatment with 1-MCP effectively inhibited water loss during room temperature storage. The PAL activity in fruits treated with 1-MCP remained consistently higher than that in the control group; however, no significant difference was observed between the two groups (Fig. 5-D). On d 7 and 14 of shelving, fruit from the 1-MCP group exhibited significantly higher

Table 1 Effects of 1-MCP treatment on fruit quality of 'Yuluxiang' pear during storage at 20°C

Shelf life (d)	Treatment	Fruit quality index			
		Firmness (kg cm^{-2})	Total soluble solid (%)	Titratable acid (g kg^{-1})	Vitamin C (mg 100 g^{-1})
0	–	4.87±0.47	10.93±0.61	0.53±0.003	5.52±0.05
7	CK	4.92±0.56 a	11.18±0.56 a	0.557±0.006 a	3.57±0.02 b
	1-MCP	4.76±0.54 a	10.88±0.34 b	0.560±0.001 a	4.76±0.00 a
14	CK	5.06±0.56 a	10.78±0.47 b	0.321±0.015 a	2.42±0.04 b
	1-MCP	5.00±0.53 a	11.26±0.33 a	0.280±0.000 b	3.32±0.22 a
21	CK	4.71±0.50 a	11.08±0.65 a	0.393±0.013 b	2.31±0.01 b
	1-MCP	4.89±0.48 a	11.03±0.60 a	0.467±0.000 a	2.45±0.05 a

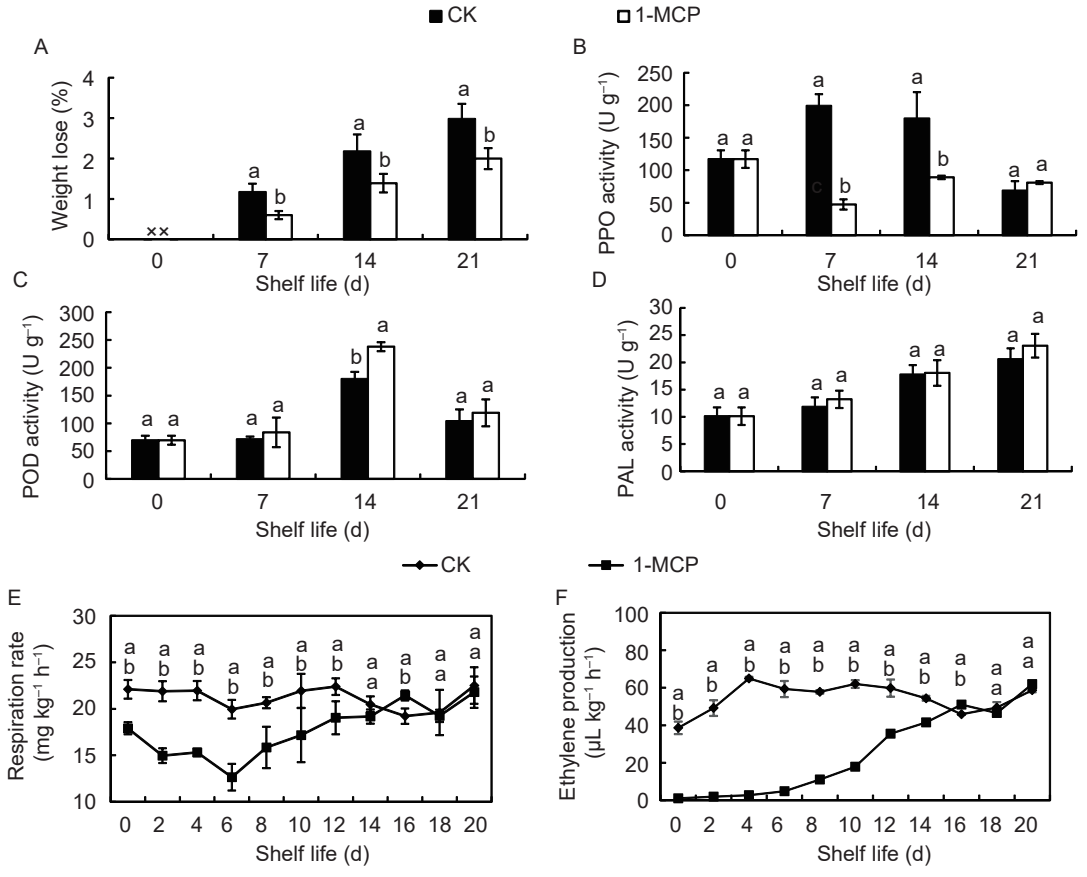

Fig. 5 Effects of 1-MCP treatment on physiological indicators of 'Yuluxiang' pear during storage at 20°C. A, weight loss. B, polyphenol oxidase (PPO). C, peroxidase (POD). D, phenylalanine ammonia-lyase (PAL). E, respiration rate. F, ethylene production. Error bars represent ±standard deviation (n=3). Letters above data points indicate significant differences at the level of P<0.05.

POD activity on d 14 (Fig. 5-C). Thus, our research demonstrates that treatment with 1-MCP effectively preserves desirable physiological characteristics of 'Yuluxiang' pear fruits during room temperature storage.

'Yuluxiang' pears are climacteric fruits that exhibit robust respiration rates and ethylene production throughout storage at room temperature. However, our research findings indicate a deviation from the typical climacteric behavior in these fruits, although a prominent peak in ethylene production was observed. Notably, the control pear fruits displayed fluctuating respiration rates, with the lowest rate recorded on d 6 following treatment with 1-MCP (Fig. 5-E). Initially, the respiration rate of 1-MCP-treated fruits decreased during the first 6 d of storage but subsequently increased. Moreover, compared to the control group, applying 1-MCP significantly reduced the respiration rate of pear fruits up to 14 d of storage. The timing and intensity of ethylene production varied between treatments; untreated fruits peaked on d 4, while those treated with 1-MCP exhibited peak production on d 20. On d 0, negligible ethylene production was observed in pear fruits treated with 1-MCP, which gradually increased until d 6 and sharply rose on d 8 (Fig. 5-F). After storing for two weeks (14 d), all treatments showed slight fluctuations in respiratory intensity and ethylene production before stabilizing. Consequently, it can be concluded that the effect of applying 1-MCP treatment on 'Yuluxiang' pear fruits' respiration rate and ethylene production is time-dependent, lasting approximately two weeks.

3.7. Correlation between peel greasiness, wax composition, lipid metabolism parameters, and fruit physiological indicators

The correlation between changes in peel wax composition, peel greasiness score, total epidermal wax content, L*, weight loss rate, ethylene release rate, MDA content, and PPO, POD, PAL, KCS, LACS, and LOX activities were analyzed by generating correlation cluster heat maps. Based on the result from the heat map (Fig. 6), a strong positive correlation was observed among *cis*-9-hexadecenal, *α*-farnesene, weight loss, greasiness score, (Z)-9-tricosene, total wax content, (Z,Z)-9,12-octadecadienoic acid, (Z)-13-docosenoic acid, (Z)-9-octadecenal, (Z)-9-octadecen-1-ol, and (Z)-15-tetracosenoic acid. This correlation was represented by the largest area of red coloration in Fig. 6. The finding suggests a highly consistent trend in the change of those indicators during the 20°C shelf life. Additionally, a weak positive correlation was observed between LOX, PLD, KCS, MDA, and PPO with specific components of peel wax. This indicates that the changing trend of these substances during the 20°C shelf remains essentially consistent.

4. Discussion

4.1. Effects of 1-MCP treatment on fruit greasiness of 'Yuluxiang' pear during storage

Skin greasiness is a significant issue observed in fruits during storage. Specific apple and pear cultivars, such as 'Granny Smith', 'Royal Gala', and 'Korla' (Fan *et al.* 1999; Veraverbeke *et al.* 2001; Yang *et al.* 2023), are prone to developing greasiness as they ripen. Our study identified that a pear cultivar called 'Yuluxiang' also exhibits sensitivity towards becoming greasy. The presence of a greasy peel indicates an increasing brightness of the fruit surface with extended shelf life, accompanied by an intensification of the greasy sensation (Wang *et al.* 2014a, b). A previous investigation reported an increase in the L* value of the fruit and a rise in its level of greasiness (Jia *et al.* 2016). This finding aligns with our observations on 'Yuluxiang' pears stored at 20°C. According to our study, treatment with 1-MCP effectively inhibits the increase in L*, consistent with prior research on apple fruits (Du *et al.* 2021). Therefore, we can conclude that applying 1-MCP can effectively prevent fruit greasiness by inhibiting the increase in L* for 'Yuluxiang' pear fruits during storage at 20°C.

The increased greasiness can also be observed through SEM images, where wax crystals gradually dissolve and disappear over time (Yang *et al.* 2017). On d 0 of shelving, the microstructure of peel wax appeared flat. With extended shelf time, flake wax emerged and eventually melted and rearranged into block structures. However, as early as the 7th d of shelving, untreated fruit peel wax began to melt and aggregate into small lumpy wax structures. Therefore, by inhibiting the microstructural changes in the 'Yuluxiang' pear peel during storage at 20°C, 1-MCP can effectively delay the occurrence of greasy peel. During the later stages of fruit storage, as the microstructure of peel wax continues to dissolve, its composition undergoes constant changes, particularly in terms of its polar composition (Curry. 2008; Dong *et al.* 2012). Palmitic acid, (Z,Z)-9,12-octadecadienoic acid, and secondary alcohols such as nonacosan-10-ol and nonacosan-10-ketone constitute 60% of the polar wax composition associated with apple fruit greasiness (Belding *et al.* 1998; Dong *et al.* 2012). However, the combination treatment using 1-MCP and MAP can inhibit the accumulation of these components and delay the onset of greasy peel (Dong *et al.* 2013). Our research on 'Yuluxiang' pear also confirmed this

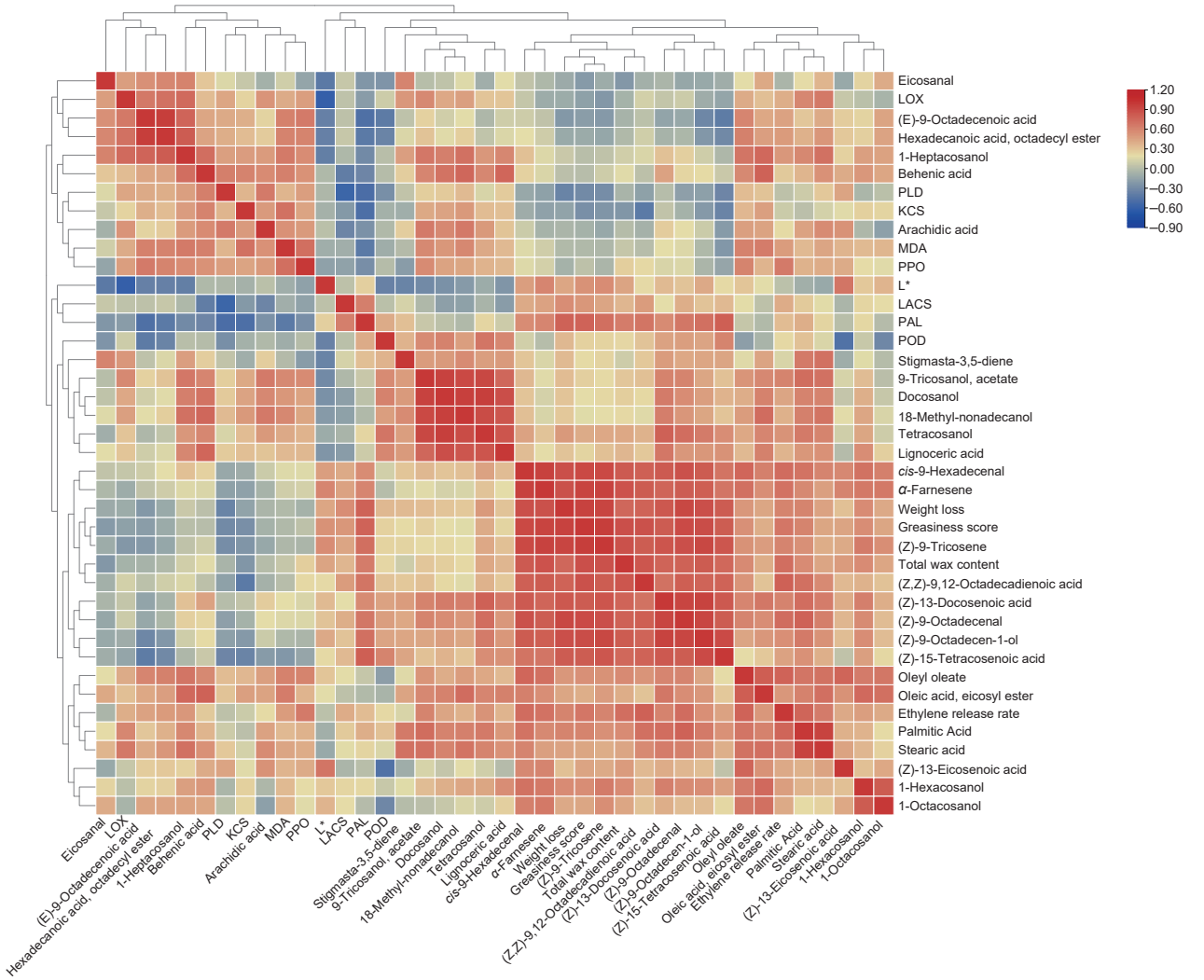

Fig. 6 Correlation analysis was conducted among peel greasiness, wax composition, lipid metabolism parameters, and fruit physiological indicators of 'Yuluxiang' pear during storage at 20°C. The data were analyzed using SPSS software with Pearson's coefficients. This figure was created using TBtools. The color bar from blue to red indicated negative to positive correlation coefficients.

effect when treated with 1-MCP. Furthermore, our study found that *α*-farnesene content was not detected during the first 7 d after shelf life for pears treated with 1-MCP compared to control samples. It is speculated that *α*-farnesene accumulation is one reason for increased 'Yuluxiang' peel greasiness. In addition to changes in fruit wax composition, the accumulation of total wax content also contributes to increased greasiness in 'Pink Lady' apples and 'Korla' pears (Wang *et al.* 2014a, b; Yang *et al.* 2023), which we also observed in our study on 'Yuluxiang'.

Currently, there is limited research on the physiological mechanisms underlying greasy peel. According to a recent study by Jiang *et al.* (2022), MDA has been identified as a membrane lipid metabolite, and its elevated levels contribute to excessive greasiness of the fruit peel. Our findings also demonstrate that 1-MCP exerts a significant inhibitory effect on the increase in MDA content, thereby reducing fruit greasiness. Previous literature lacks reports on the impact of PLD, LOX, LACS, and KCS activities on fruit greasiness. However, it is known that PLD catalyzes the hydrolysis of phosphodiester bonds in glycerophospholipids, producing phosphatidic acid and soluble choline (Zhang *et al.* 2023). LOX is widely distributed in plants and primarily acts upon polyunsaturated fatty acids from the plasma membranes, such as linoleic acid, methyl-oleic acid, linolenic acid, and arachidonic acid (Gorst-Allman and Spiteller 1988; Regdel *et al.* 1994; Tsitsigiannis *et al.* 2005). KCS facilitates the catalytic synthesis of very long-chain fatty acids. LACS plays a crucial role in lipid synthesis by converting

free fatty acid into acyl-CoA sulfide (Joyard and Stumpf 1981; Todd *et al.* 1999). Based on their involvement in lipid anabolic reactions observed previously, our study investigated their activities, which initially increased before declining with peak levels reached at d 7 during shelf life. However, LACS enzyme activity remained consistently elevated throughout the entire shelf life. Furthermore, treatment with 1-MCP significantly suppressed the aforementioned increased enzyme activities. Thus, it can be inferred that 1-MCP modulates peel wax anabolic reactions by inhibiting the upregulation of enzyme activity to mitigate greasiness. Nevertheless, due to the intricate nature of lipid metabolism, further investigations are warranted to elucidate its underlying mechanisms.

4.2. Effects of 1-MCP treatment on fruit quality of 'Yuluxiang' pear during storage

Weight loss in fruit refers to the loss of water, which contributes to rapid deterioration (Plainsirichai *et al.* 2010). Previous studies have demonstrated the effective reduction of weight loss in 'Berlepsch' apples, 'Lateblue' blueberries, and Japanese palms (Lippert 2006; Chiabrando and Giacalone 2011; Uysal *et al.* 2023) through the application of 1-MCP. Furthermore, our study reveals that a concentration of 1.0 μL L^{-1} of 1-MCP can effectively preserve firmness and maintain optimal TSS and TA content levels in 'Yuluxiang' pears. The measurement of TSS and TA levels serves as an indicator for assessing the quality and senescence progression during storage. According to a study conducted by Tomala *et al.* (2023), applying 1-MCP, both preharvest and postharvest, enables the attainment of consistently stable firmness and TSS levels throughout the shelf life. Our research has demonstrated that applying 1-MCP did not adversely affect the quality indicators of these fruits during storage at 20°C. Additionally, treatment with 1-MCP effectively suppressed the decline in vitamin C content during the storage of 'Yuluxiang' pears. This finding is consistent with the previous study conducted by Ma *et al.* (2019). In comparison, fruits treated with 1-MCP exhibited reduced respiration rates and ethylene production during the initial 14-d storage period. Our findings align with previous studies conducted by Bai *et al.* (2005) and Gago *et al.* (2022). The storability of fruit is correlated with its antioxidant capacity; thus, we also assessed the activity of PPO, POD, and PAL enzymes to investigate the impact of 1-MCP on fruit storability. Increased PAL activity leads to the synthesis of additional antioxidant substances, which contribute to forming potent antioxidants in fruits (Niu *et al.* 2023). Our study validates that treatment with 1-MCP maintains PAL activity while promoting the growth of POD activity and inhibiting PPO activity. The rapid interaction between PPO and phenolic compounds can lead to the development of black or brown pigments, significantly impacting fruit storage quality (Holderbaum *et al.* 2010; Peng *et al.* 2013). Higher POD activity mitigates lipid degradation and oxidation, enhancing fruit resistance during storage. Consequently, regulating these enzyme activities through 1-MCP treatment could improve the storage quality of 'Yuluxiang' pears.

According to the correlation heat map, a strong positive correlation was observed between weight loss and the contents of specific fruit wax components. Weight loss serves as a significant quality indicator during fruit storage. Previous studies have demonstrated that a decrease in very long-chain wax biosynthesis can result in rapid water loss and size reduction of fruits (Leide *et al.* 2007; Wang *et al.* 2021). Furthermore, it has been reported that weight loss during storage is positively correlated with specific wax components such as fatty acids and alcohol (Wang *et al.* 2014a, b). Our study also revealed a weak positive correlation between ethylene production, LOX, KCS, PLD, PPO activities, and some wax components. Curry (2008) suggested that elevated levels of environmental ethylene could modify the production of surface lipids, as fruit greasiness is associated with early ripening. Therefore, we can conclude that besides fruit wax components and lipid metabolism enzymes, some indicators of fruit storage quality may also impact peel greasiness.

5. Conclusion

This study comprehensively analyzed the effects of 1-MCP on the greasy peel and storage quality of 'Yuluxiang' pear during storage at 20°C, with a focus on fruit appearance, the microstructure, and components of peel wax, enzymatic activity related to lipid metabolism, lipid metabolism product, storage quality, and physiological characteristics. The results demonstrated that 1-MCP inhibited greasiness in the peel by delaying changes in microstructure and specific components of the wax layer. It also affected enzymatic activity related to lipid metabolism and prevented an increase in lipid metabolism product within the membrane to delay the occurrence of greasy peel. Additionally, treatment with 1-MCP did not hurt fruit quality; it reduced the weight loss rate and inhibited vitamin C decline. Furthermore, respiration intensity and ethylene production were significantly suppressed by 1-MCP. Therefore, we conclude that 1-MCP can delay greasiness in 'Yuluxiang' pear during storage at 20°C while maintaining overall fruit quality. This study provides important insights into the effects of 1-MCP treatment on pear greasiness and storage quality.

These findings will assist further work toward novel inhibitors of pear fruit greasiness.

Acknowledgements

This work was supported by the Agricultural Science and Technology Innovation Program of Chinese Academy of Agricultural Sciences (CAAS-ASTIP-RIP), the earmarked fund for the China Agriculture Research System (CARS-28), and the Natural Science Foundation of Liaoning Province, China (2021-MS-036).

Declaration of competing interest

The authors declare that they have no conflict of interest.

References

Bai J, Baldwin E A, Goodner K L, Mattheis J P, Brecht J K. 2005. Response of four apple cultivars to 1-methylcyclopropene treatment and controlled atmosphere storage. *Horticultural Science*, **40**, 1534–1538.

Belding R D, Blankenship S M, Young E, Leidy R B. 1998. Composition and variability of epicuticular waxes in apple cultivars. *Journal of the American Society for Horticultural Science*, **123**, 348–356.

Chiabrando V, Giacalone G. 2011. Shelf-life extension of highbush blueberry using 1-methylcyclopropene stored under air and controlled atmosphere. *Food Chemistry*, **126**, 1812–1816.

Christeller J T, Roughan P G. 2016. The novel esters farnesyl oleate and farnesyl linoleate are prominent in the surface wax of greasy apple fruit. *New Zealand Journal of Crop and Horticultural Science*, **44**, 164–170.

Curry E. 2008. Effects of 1-MCP applied postharvest on epicuticular wax of apples (*Malus domestica* Borkh.) during storage. *Journal of the Science of Food and Agricultur*e, **88**, 996–1006.

Dadzie B K, Banks N H, Hewett E W, Cleland D J. 1995. Reduced greasiness of 'Granny Smith' apples washed in Tween 20 solution. *New Zealand Journal of Crop and Horticultural Science*, **23**, 219–222.

Dhindsa R S, Plumb-Dhindsa P, Thorpe T A. 1981. Leaf senescence: Correlated with increased levels of membrane permeability and lipid peroxidation, and decreased levels of superoxide dismutase and catalase. *Journal of Experimental Botany*, **32**, 93–101.

Dias C, Ribeiro T, Rodrigues A C, Ferrante A, Vasconcelos M W, Pintado M. 2021. Improving the ripening process after 1-MCP application: Implications and strategies. *Trends in Food Science & Technology*, **113**, 382–396.

Dong X Q, Rao J P, Huber D J, Chang X X, Xin F C. 2012. Wax composition of 'Red Fuji' apple fruit during development and during storage after 1-methylcyclopropene treatment. *Horticulture*, *Environment*, *and Biotechnology*, **53**, 288–297.

Dong X Q, Rao J P, Zhu S L, Yang Q Z. 2013. Combination of modified atmosphere packaging and 1-methylcyclopropene treatment suppress decreasing of wax composition of apples during cold storage. *Transactions of the Chinese Society of Agricultural Engineering*, **29**, 269–277. (in Chinese)

Du M J, Yan Y M, Liu Z Y, Fan X J, Zhang X T, Li H D, Li X H, Wang L Y. 2021. Effect of pre-harvest exogenous phytohormone and post-harvest 1-MCP treatment on storage quality of sugar-core apples. *Journal of Food Science and Technology*, **39**, 151–159. (in Chinese)

Fan X, Mattheis J P, Blankenship S. 1999. Development of apple superficial scald, soft scald, core flush, and greasiness is reduced by MCP. *Journal of Agricultural and Food Chemistry*, **47**, 3063–3068.

Gago C, Guerreiro A, Cruz S, Martins N, Cabrita M J, Miguel M G, Faleiro M L, Antunes M D. 2022. 1-Methylcyclopropene and lemongrass essential oil nanocoatings effect on the preservation of cold stored 'Rocha' pear. *Postharvest Biology and Technology*, **192**, 111992.

Gorst-allman C P, Spiteller G. 1988. Investigation of lipoxygenase-like activity in strawberry homogenates. *Zeitschrifttfr Lebensmittel-Untersuchung und-Forschung*, **187**, 330–333.

Holderbaum D F, Kon T, Kudo T, Guerra M P. 2010. Enzymatic browning, polyphenol oxidase activity, and polyphenols in four apple cultivars: Dynamics during fruit development. *Horticultural Science*, **45**, 1150–1154.

Hu B X, Sun D W, Pu H B, Wei Q Y. 2019. Recent advances in detecting and regulating ethylene concentrations for shelf-life extension and maturity control of fruit: A review. *Trends in Food Science & Technology*, **91**, 66–82.

Huang S A, Lin X, Zhang Q, Chen H, Zhu S L, Ma Y H, Dong X Q. 2022. Comparison of wax structure and composition of plum peel from three varieties. *Journal of Nuclear Agricultural Sciences*, **36**, 1155–1165. (in Chinese)

Hyodo H. 1971. Phenylalanine ammonia-lyase in strawberry fruits. *Plant and Cell Physiology*, **12**, 989–991.

Jia X H, Wang W H, Jiang Y B, Wang Z H, Du Y M, Tong W. 2016. Effects of harvest maturity on fruit quality and storage life of 'Yuluxiang' pears. *Journal of Fruit Science*, **33**, 594–603. (in Chinese)

Jia X H, Zhang X N, Liu B L, Ma F L, Du Y M, Wang W H. 2022. Effects of low oxygen/high carbon dioxide controlled atmosphere combined with 1-methylcyclopropene on quality of Yuluxiang pear during cold storage. *Scientia Agricultura Sinica*, **55**, 4717–4727. (in Chinese)

Jiang Z T, Ding Y D, Liu J, Yin W J, Qi Y, Yang Y W, Ren X L. 2022. The *MdFAD27* and *MdFAD28* play critical roles in the development of greasiness disorder in postharvest apples. *Postharvest Biology and Technology*, **191**, 111990.

Joyard J, Stumpf P K. 1981. Synthesis of long-chain acyl-CoA in chloroplast envelope membranes. *Plant Physiology*, **67**, 250–256.

Ju Z G, Bramlage W J. 2001. Developmental changes of

cuticular constituents and their association with ethylene during fruit ripening in 'Delicious' apples. *Postharvest Biology and Technology*, **3**, 257–263.

Kochba J, Lavee S, Spiegel-Roy P. 1977. Differences in peroxidase activity and isoenzymes in embryogenic ane non-embryogenic 'Shamouti' orange ovular callus lines. *Plant and Cell Physiology*, **18**, 463–467.

Krupa T, Kistechok A, Tomala K. 2023 Estimating the physicochemical and antioxidant properties of Hardy Kiwi (*Actinidia arguta*) treated with 1-methylcyclopropene during storage. *Agriculture*, **13**, 1665.

Leide J, Hildebrandt U, Reussing K, Riederer M, Vogg G. 2007. The developmental pattern of tomato fruit wax accumulation and its Impact on cuticular transpiration barrier properties: Effects of a deficiency in a *β*-ketoacyl-coenzyme A synthase (LeCER6). *Plant Physiology*, **144**, 1667–1679.

Lippert F. 2006. 1-MCP reduces superficial scald and improves storability of cv. 'Berlepsch' apples. *Erwerbs-Obstbau*, **48**, 69–77. (in German)

Luo X F, Tian Y T, Yao H J. 1999. Polyphenol oxidase activities and phenol contents in tissue culture. *Journal of Beijing Forestry University*, **21**, 4. (in Chinese)

Ma F L, Du Y M, Wang Y, Tong W, Liu B L, Wang W H, Jia X H. 2019. Effect of 1-methylcyclopropene (1-MCP) on quality and chlorophyll maintenance of postharvest 'Yuluxiang' pear. *Acta Horticulturae Sinica*, **46**, 2299–2308. (in Chinese)

Mubarok S, Rahman M I, Kamaluddin N N, Solihin E. 2022. Impact of 1-methylcyclopropene combined with chitosan on postharvest quality of tropical banana 'Lady Finger'. *International Journal of Food Properties*, **25**, 1171–1185.

Niu Y X, Ye L X, Wang Y, Shi Y B, Liu Y J, Luo A W. 2023. Improvement of storage quality of 'Hayward' kiwifruit by MeJA combined with SA treatment through activation of phenylpropane metabolism. *Scientia Horticulturae*, **321**, 112354.

Nock J F, Watkins C B. 2013. Repeated treatment of apple fruit with 1-methylcyclopropene (1-MCP) prior to controlled atmosphere storage. *Postharvest Biology and Technology*, **79**, 73–79.

Peng Y, Huang B R, Xu L X, Li Z. 2013. Heat stress effects on osmotic potential, membrane fatty acid composition and lipid peroxidation content of two kentucky blue grass cultivars differing in drought tolerance. *Horticulture Plant Journal*, **40**, 971–980.

Plainsirichai M, Trinok U, Turner D W. 2010. 1-methylcyclopropene (1-MCP) reduces water loss and extends shelf life of fruits of Rose apple (*Syzygium jambos* Alston) cv. Tabtim Chan. *Fruits*, **65**, 133–140.

Regdel D, Kühn H, Schewe T. 1994. On the reaction specificity of the lipoxygenase from tomato fruits. *Biochimica et Biophysica Acta-Lipids and Lipid Metabolism*, **1210**, 297–302.

Shi H, Zhou W H, Xu Y Y, He X E, He F Y, Wang Y. 2023. Effect of calcium spray at flowering combined with post-harvest 1-MCP treatment on the preservation of grapes. *Heliyon*, **9**, e19918.

Thewes F R, Argenta L C, Anese R D O, Stanger M C, Freitas S D T. 2023. The response of 'Monalisa' apples to high CO_2 storage conditions, harvest maturity and 1-MCP treatment. *Scientia Horticulturae*, **317**, 112038.

Todd J, Post-Beittenmiller D, Jaworski J G. 1999. *KCS1* encodes a fatty acid elongase 3-ketoacyl-CoA synthase affecting wax biosynthesis in *Arabidopsis thaliana*. *Plant Journal*, **17**, 119–130.

Tomala K, Guzek D, Głąbska D, Małachowska M, Widłak A, Krupa T, Gutkowska K. 2023. Assessment of the quality of 'Red Jonaprince' apples during storage after delayed harvesting and 1-methylcyclopropene (1-MCP) preharvest and postharvest treatment. *Agronomy*, **13**, 1730.

Tsitsigiannis D I, Kunze S, Willis D K, Feussner I, Keller N P. 2005. Aspergillus infection inhibits the expression of peanut 13S-HPODE-forming seed lipoxygenases. *Molecular Plant-Microbe Interactions*, **18**, 1081–1089.

Uysal G, Eroğul D, Dayıoğlu A, Şen F, Oğuz 0. 2023. Effects of modified atmosphere packaging and 1-methylcyclopropene treatment on quality properties of japanese plum fruit (*Prunus salicina* Lindl. cv. 'Angeleno') during cold storage. *Erwerbs-Obstbau*, **65**, 1383–1391.

Veraverbeke E A, Lammertyn J, Saevels S, Nicolai B M. 2001. Changes in chemical wax composition of three different apple (*Malus domestica* Borkh.) cultivars during storage. *Postharvest Biology and Technology*, **23**, 197–208.

Wan R, Song J H, Lv Z Y, Qi X C, Feng Z L, Yang Z F, Cao X Y, Shi J L, Jian Z H, Tong R R, Hu Q X, Chen Y H. 2023. Effects of 1-MCP treatment on postharvest fruit of five pomegranate varieties during low-temperature storage. *Horticulturae*, **9**, 1031.

Wang X F, Ren X L, Yang Y Q, Kang J, Fan L, Yu J N. 2014a. Study on epicuticular wax greasiness of 'Pink Lady' apple fruits. *Journal of Fruit Science*, **31**, 201–205. (in Chinese)

Wang X F, Yang Y Q, Ren X L, Sun H T, Xiang C Y, Sun W S. 2014b. Effects of 1-MCP on postharvest physiology and quality of 'Pink Lady' apple fruits. *Food Science*, **35**, 219–223. (in Chinese)

Wang Y, Mao H J, Lv Y H, Chen G G, Jiang Y. 2021. Comparative analysis of total wax content, chemical composition and crystal morphology of cuticular wax in Korla pear under different relative humidity of storage. *Food Chemistry*, **339**, 128097.

Yan D, Liu Y L, Ren X L, Li R, Wang C, Qi Y W, Xu J, Liu Z D, Ding Y D, Liu C H. 2022. Integration of morphological, physiological and multi-omics analysis reveals a comprehensive mechanism for cuticular wax during development of greasiness in postharvest apples. *Food Research International*, **157**, 111429.

Yan D, Yang Y Q, Wang C, Qi Y W, Liu C H, Zhou B, Ren X L. 2018. Effects of epigallocatechin-3-gallate (EGCG) on skin greasiness and related gene expression in 'Jonagold' apple fruit during ambient storage. *Postharvest Biology and Technology*, **143**, 28–34.

Yang Y Q, Zhang M Z, Ren X L, Cheng Y J, Peng X Y, Tian

S W, Wang X S, Xu L, Zhang Y, Li C, Sun C C, Zhang W, Gong H S. 2023. Chemical and thermodynamic analyses of the surface waxes of 'Korla' pears: Relationships between the surface waxes and skin greasiness. *Postharvest Biology and Technology*, **196**, 112156.

Yang Y Q, Zhou B, Wang C, Lv Y R, Liu C H, Zhu X B, Ren X L. 2017. Analysis of the inhibitory effect of 1-methylcyclopropene on skin greasiness in postharvest apples by revealing the changes of wax constituents and gene expression. *Postharvest Biology and Technology*, **134**, 87–97.

Zhang P, Gong J S, Xie Z H, Su C, Zhang X M, Rao Z M, Xu Z H, Shi J S. 2023. Efficient secretory expression of phospholipase D for the high-yield production of phosphatidylserine and phospholipid derivates from soybean lecithin. *Synthetic and Systems Biotechnology*, **8**, 273–280.

Zhao X M, Yang Y R, Li J K, Yuan F, Cheng J J, Li X W. 2015. Effect of 1-MCP treatment on postharvest changes in epicuticular wax of korle fragrant pear fruits during ambient temperature storage. *Food Science*, **36**, 262–266. (in Chinese)