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Manipulation of ripening progress of different plum cultivars during shelf life by post-storage treatments with ethylene and 1-methylcyclopropene

Hanxu Pan, Rui Wang, Lili Li, Jiao Wang, Jiankang Cao*, Weibo Jiang

College of Food Science and Nutritional Engineering, China Agricultural University, 17 Qinghuadonglu Road, Beijing 100083, PR China

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ABSTRACT

In order to manipulate ripening progress and increase marketing acceptance, plum (*Prunus salicina* Lindl.) cultivars 'Gaixian', 'Yuhuang' and 'Aozhou 14' were treated with 500 $\mu L L^{-1}$ ethylene or 2.0 $\mu L L^{-1}$ 1-methylcyclopropene (1-MCP) for 24 h at 25 °C after removal from the cold storage at 0 °C for 8, 4 and 4 weeks, respectively. Different patterns of physiological progresses including color changes, softening and ethylene production were observed in these plum cultivars during cold storage. Upon removal, regardless of physiological patterns, a sharp increase of ethylene production was found in either plum cultivar during shelf life and the increase was stimulated by post-storage ethylene treatment but dramatically inhibited by post-storage 1-MCP treatment. Skin color changes of 'Gaixian' and 'Yuhuang' plums during shelf life were greatly enhanced by ethylene but significantly retarded by 1-MCP. Flesh reddening occurred easily in 'Aozhou 14' during cold storage and became more serious after removal, which was hastened by ethylene but significantly alleviated by 1-MCP. Firmness decline of plums during shelf life was not significantly influenced by ethylene but effectively delayed by 1-MCP. Post-storage ethylene treatment could 'recover' the inherent epidemic color of 'Gaixian' and 'Yuhuang' during shelf life, while post-storage 1-MCP treatment could maintain fruit firmness and alleviate flesh reddening of 'Aozhou 14'. Thus the manipulation of ripening progress of plums with post-storage ethylene or 1-MCP treatment would be practical for increasing fruit marketing acceptance, though it depends on cultivars.

1. Introduction

Plums are highly perishable and deteriorate quickly during shipping, storage and shelf life. Considerable postharvest losses of plums usually occur when supplied at a large scale on the market during harvest seasons. Commonly, plums are harvested at early mature stage before ripening or skin color change, stored at 0 °C for a period and then transferred to room temperature to increase the supply. However, plums are very susceptible to low temperature and the benefits of cold storage may be limited by the development of physiological disorders, such as internal browning, gel breakdown, reddening or bleeding, retarded softening after prolonged cold storage and/or after ripening at room temperature (Abdi et al., 1998; Crisosto et al., 1999, 2004; Candan et al., 2008, 2011; Larrigaudière et al., 2009; Khan et al., 2011; Minas et al., 2013; Fanning et al., 2014). Besides, the cold-stored plums usually exhibit a sharp increase in ethylene production after removal from 0 to 20 °C, though it was still contradictory on what effects of such sharply-increased ethylene may have, as it may accelerate ripening and softening of plums during shelf life, or result in physiological disorders of the fruit (Dong et al., 2001; Martiänez-Romero et al., 2003; Valero et al., 2004; Candan et al., 2008; Manganaris et al., 2008a,b; Khan et al., 2009, 2011; Larrigaudière et al., 2009; Özkaya et al., 2010; Bae et al., 2011). To date, very little is known with regards to the manipulation of ripening progress of plums during shelf life by regulating ethylene production of the fruit after removal from cold storage.

Plums are traditionally considered as climacteric fruit but some cultivars have been identified to be suppressed-climacteric in the past decades. Physiological and biochemical changes related to ripening progress of both climacteric and suppressed-climacteric plums can be triggered by ethylene, which is accumulated around or in the fruit during storage (Abdi et al., 1998; Martiänez-Romero et al., 2003; Manganaris et al., 2008b; Candan et al.,

* Corresponding author.
E-mail address: cjk@cau.edu.cn (J. Cao).

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2008). It has been extensively reported that application of 1-methylcyclopropene (1-MCP), which binds irreversibly to ethylene receptors of cells and thereby prevents ethylene action on plant tissues (Sisler and Serek, 1997), can suppress ethylene biosynthesis, delay ripening and softening, reduce chilling injury symptoms of various fruits (Blankenship and Dole, 2003; Watkins, 2008), including plums (Dong et al., 2001; Larrigaudière et al., 2009; Minas et al., 2013). However, effects of 1-MCP on physiological progresses of plums depends upon cultivars (Abdi et al., 1998; Martiänez-Romero et al., 2003; Menniti et al., 2004; Candan et al., 2008, 2011), the maturity stage at harvest (Özkaya et al., 2010; Lee et al., 2011; Sharma et al., 2012), concentration applied (Martiänez-Romero et al., 2003; Menniti et al., 2004; Khan and Singh, 2009; Khan et al., 2009; Özkaya et al., 2010), duration of exposure (Abdi et al., 1998; Menniti et al., 2004), method of 1-MCP application (Manganaris et al., 2007, 2008a; Minas et al., 2013), package or storage conditions (Valero et al., 2004; Bae et al., 2011; Singh and Singh, 2012). Previously, Dong et al. (2002) reported that the 1-MCP treatment applied post-storage than pre-storage could more effectively inhibit ethylene production, softening and internal flesh browning of apricots during the subsequent ripening at 20 °C and thereby further extended marketing life. But so far, no attempt has been made to inhibit ripening and softening of plums during shelf life with the post-storage application of 1-MCP.

Historically, harvested immature plums of some cultivars were packed with ethephon by orchardists in China and the plums were allowed to ripen during transportation to get better marketing acceptance. Still, little is reported on manipulating marketing quality of plums in shelf life. Accordingly, the present work was undertaken to study patterns of changes of commercial quality and ethylene production of three plum cultivars during cold storage at 0 °C, and the manipulation of their ripening progress after removal from the cold storage with post-storage ethylene or 1-MCP application was further investigated.

2. Materials and methods

2.1. Fruit materials and storage

Three plum cultivars (*Prunus salicina* Lindl.) including 'Gaixian', 'Yuhuang' and 'Aozhou 14' were harvested at a firm mature stage from a commercial orchard in Beijing, China, respectively. 'Gaixian' and 'Yuhuang' had green peel but 'Aozhou 14' had dark purple–black peel at harvest. Plums were transported to the laboratory immediately after harvest and selected according to their uniformity of shape, color and size. Those with physical injuries or infections were discarded.

After pre-cooling in air at 10 °C overnight to release field heat according to Minas et al. (2013), plums were placed into plastic baskets (600 × 420 × 145 mm), packed with 30-μm-thick perforated low density polyethylene (LDPE) bags, and stored at 0 ± 0.5 °C, 85–95% relative humidity (RH). Fruit color changes, flesh firmness and ethylene production were measured at certain intervals during cold storage.

2.2. Post-storage treatments

Ethylene was purchased from Huayuan Gas Industry Co. Ltd. Beijing, China. 1-Methylcyclopropene (1-MCP) powder formulation [SmartFresh™ 3.3% (w/w) a.i.] was supplied by AgroFresh Inc. (Rohm and Haas China, Inc., Beijing, China). The powder can generate the active ingredient in the gas form after addition of warm water (35 ~ 40 °C).

'Gaixian', 'Yuhuang' and 'Aozhou 14' plums were removed to shelf life at 25 °C for 6 h for warming-up after stored at 0 °C for 8, 4 and 4 weeks, respectively. Then, approximately 600 fruit containing three replicates were hermetically sealed in 150-L stainless steel containers for ethylene or 1-MCP treatment. Dishes containing 500 mL 1 mol L^{-1} KOH were placed in containers to absorb CO_2 produced from respiration of the fruit during treatment.

Ethylene treatment: a certain volume ethylene was injected into a 150-L container via a rubber stopper using a plastic syringe to reach a concentration at 500 μL L^{-1} in the atmosphere inside the container.

1-MCP treatment: the weighed amount of SmartFresh™ powder (equivalent to 2.0 μL L^{-1} 1-MCP gas in the container) was dissolved in 5 mL warm distilled water and immediately injected into the container to release 1-MCP.

After the fruit were exposed to ethylene or 1-MCP for 24 h, containers were opened and ventilated and plums were transferred into shelf rooms at 25 °C, 80–90% RH. Plums incubated similarly but without ethylene or 1-MCP were used as controls.

2.3. Evaluation of skin color change

Evaluation of skin color change of plums (300 fruit in each treatment consisting of three replicates) was performed according to ripening progress of each cultivar, according to the method described by Candan et al. (2011) with some modifications. Skin color change was estimated visually as the percentage of color-changed area compared to the total surface area on a ripening scale where: 0 = no change (green); 1 = less than 10%; 2 = 10–25%; 3 = 25–50%; 4 = 50–75%; and 5 = more than 75% (turning red for 'Gaixian', yellow for 'Yuhuang' or dark black for 'Aozhou 14'). The skin color change index was calculated using the following formula: skin color change index = $\sum$(color scale × number of the fruit within the scale)/(total number of fruit × the highest scale) × 100.

2.4. Evaluation of flesh color change

Plums (180 fruit in each treatment consisting of three replicates) were longitudinally cut into halves for the evaluation of flesh color change according to Manganaris et al. (2008b) and Candan et al. (2011) with some modifications. Flesh color change was estimated visually as the percentage of color-changed area compared to the total surface area of each section on a ripening scale where: 0 = no change (light green); 1 = less than 10%; 2 = 10–25%; 3 = 25–50%; 4 = 50–75%; and 5 = more than 75% (turning white in 'Gaixian' or 'Yuhuang', but red in 'Aozhou 14'). The flesh color change index was calculated using the following formula: flesh color change index = $\sum$(color scale × number of the fruit within the scale)/(total number of fruit × the highest scale) × 100.

2.5. Measurement of fruit firmness

Thirty plums were used for measurement of flesh firmness. The measurement were performed on three separated but equidistant peeled sites on the equator of each fruit using a penetrometer (model GY-B, Mudanjiang Mechanical Institute, Heilongjiang, China) equipped with a flat probe (3 mm diameter). Firmness was expressed as the maximum force (N) attained during the penetration.

2.6. Measurement of ethylene production

Eight plums representing a replicate were placed in a 2-L hermetically sealed glass container at 25 °C for 60 min. One milliliter of headspace gas sample withdrawn from the container was injected into a gas chromatograph (Model 7890F; Tianmei Co., Shanghai, China) to measure the concentration of ethylene according to the method of Cao et al. (2015). The gas chromatograph equipped with