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Combined effects of aqueous chlorine dioxide and ultrasonic treatments on postharvest storage quality of plum fruit (*Prunus salicina* L.)

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ABSTRACT

The individual and combined effects of aqueous chlorine dioxide (40 mg L^{-1} ClO_2 for 10 min) and ultrasonic (100 W ultrasound for 10 min) treatments on postharvest storage quality of plum fruit (*Prunus salicina* L.) were investigated. Two combination modes of these two treatments, treatment with ClO_2 solution accompanied by simultaneous ultrasonic waves (one-step mode) and applying them sequentially (two-step mode) were adopted. The effect of combined treatments on maintaining contents of total flavonoids, ascorbic acid, reducing sugars, and titratable acids were similar but were more beneficial than the individual treatments and the untreated control. The one-step mode was more effective in reducing the initial microflora and retaining sensory qualities of plum fruit than the two-step mode, and fruit shelf-life could be extended to 60 d compared to 35 d for the control. Moreover, there were no detectable chemical residues in the treated samples with the one-step mode. These results demonstrated that the combined treatments of ClO_2 and ultrasound could be a promising approach to maintain postharvest storage quality of plum fruit without significant risks to consumers.

1. Introduction

Plums are highly perishable and storage duration is limited due to the occurrence of physiological disorders. Various chemical and physical methods have been undertaken to maintain postharvest plum fruit quality, including 1-methylcyclopropene, nitric oxide, calcium, cold storage, heat treatments, and controlled atmospheres (Serrano et al., 2004; Menniti et al., 2006; Larrigaudière et al., 2009; Luo et al., 2009; Singh et al., 2009).

Chlorine dioxide (ClO_2), a powerful sanitizer that has broad and high biocidal activity, is more stable and has a higher oxidizing capacity than chlorine. Unlike chlorine, ClO_2 does not react with organic compounds to generate undesirable carcinogenic chemicals (Chen et al., 2010). This novel preservative, considered an alternative to chlorine in fruit and vegetable processing for its effectiveness and safety, therefore was used in this study on storage quality of plum fruit. ClO_2 is legally permitted in China and USA for sanitizing fruit and vegetables in water (Ministry of Health of the People's Republic of China, 2008; USFDA, 2010), though potable or clean water is still designated as the only decontamination agent for surface treatment of fresh produce in the European Union (EU, 2004).

Ultrasonic technology is mainly applied in medical diagnostics, and industrial processes and inspections (Mizrach, 2008). Currently however, ultrasound has attracted considerable interest in food science and technology due to its promising applications in the food industry. It has been used in extraction of bioactive compounds (Rodrigues et al., 2008) and in microbial inactivation (Huang et al., 2006), although there is insufficient information about the effect of ultrasonic treatments on storage quality of fresh produce. Cao et al. (2010) recently reported that ultrasound was effective in inhibiting decay incidence and preserving quality in strawberries, but more evidence is needed to prove the effects of ultrasound on fruit and vegetables to promote the application of this technique.

So far there have been no available reports studying the combined effects of ClO_2 and ultrasonic treatments on storage quality of fruit and vegetables. The present research was therefore designed to investigate their combined effects on the postharvest quality of plum fruit.

2. Materials and methods

2.1. Plant material and preparation

Plums (*P. salicina* L.) cv. 'Black Diamond' were harvested from a local orchard (Taian, China) at the commercial ripening stage. The fruit were transported to the laboratory and selected for uniformity

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of size (approx. 100 g) and color (purple black), with damaged fruit removed.

2.2. ClO_2 and ultrasonic treatments

In the first experiment, plums were treated with aqueous ClO_2 at 20, 40, and 60 mg L^{-1} for 5, 10, and 15 min. A commercially available brand of stabilized ClO_2 powder (Charmstar, Tianjin Charmstar Technology Development Co., Ltd., Tianjin, China) was dissolved in deionized water to prepare a stock solution (approx. 100 mg L^{-1}) according to the manufacturer's instructions. The concentration of ClO_2 was measured by a standard method using iodimetry immediately before use (APHA, 1998). Then the stock solution was diluted with deionized water to prepare solutions with desired concentrations. Plums were subsequently washed with ClO_2 solutions at different concentrations for different times with a ratio of 1 kg:5 L (fruit:ClO_2 solution) at 20 °C. Samples washed with potable tap water were used as controls to simulate commercial industrial processing. Following treatments, plums were rinsed in potable tap water for 1 min according to USFDA information (USFDA, 2010) and then air-dried. Control and ClO_2-treated samples were packaged into aseptic polyethylene bags (350 mm × 250 mm, 0.02 mm thick) and stored at 4 °C for 60 d. Properties of the bags were specified by the manufacturer (Zhongda, Nanjing Zhongda Package Material Co., Nanjing, China) as follows: O_2 permeability of 210–1615 mL m^{-2} h^{-1} MPa^{-1}) (23 °C, 0% RH) and CO_2 permeability of 1060–8075 mL m^{-2} h^{-1} MPa^{-1}) (23 °C, 0% RH). The bags were not completely sealed as the aim was not to create a modified atmosphere environment, but to avoid moisture loss and mechanical damage of the fruit.

In the second experiment, plums were subjected to ultrasonic waves of different strengths (80, 100, and 120 W) for different times (5, 10, and 15 min) at a constant frequency of 40 kHz. The experiments were carried out in an ultrasonic water bath (KQ3200DV, Kunshan Ultrasonic Instrument Co., Ltd., China; internal dimensions: 300 mm × 150 mm × 180 mm) with a ratio of 1 kg:5 L (fruit:water) at 20 °C. Fruit treated by potable tap water were used as the control. The fruit were then removed from the bath, air-dried, and stored at 4 °C for 60 d after being packaged.

From the above two experiments, the ideal treatment conditions for reducing respiration rates and maintaining firmness were selected to carry out the third experiment. This experimental design was inspired by the work of Allende et al. (2007), who studied the impact of combined UV-C light, gaseous O_3, and modified atmosphere on postharvest strawberries. In their experiments, the effects of UV-C light and gaseous O_3 on the respiration rate and overall visual quality were considered for the selection of the optimal doses, which were used for further research on the combined effects on more quality parameters.

In the third experiment, the ideal treatments from the first two experiments were used to test and compare their combined effects with their individual application. Moreover, two combination modes of the ClO_2 and ultrasonic treatment were utilized in order to evaluate synergistic effects between them. In the first combination mode (C1, one-step mode), plums were immersed into the ultrasonic chamber containing ClO_2 solution at 20 °C and subjected to simultaneous continuous ultrasound at 40 kHz. Our preliminary experiment indicated that ClO_2 concentration was not affected by ultrasonic waves under the strength, frequency, and treatment time selected in this study for the combined treatment. In the second mode (C2, two-step mode), samples were treated firstly by ClO_2 and then by ultrasound in a water bath at 20 °C. Following ClO_2 treatments in C1 and C2, samples were all rinsed with potable tap water for 1 min. After the combined treatments, fruit samples were air-dried, packaged, and stored at 4 °C for 60 d. Fruit treated with potable tap water were used as controls.

In the third experiment, the ideal treatment conditions for maintaining contents of flavonoids, ascorbic acid, reducing sugars, and titratable acids were selected to perform the shelf-life study. Subsequently, the most effective treatment in prolonging the shelf-life was adopted to carry out further analysis.

2.3. Respiration rate

Plums (approx. 500 g) were placed in a 3 L glass jar at 2 °C and 95% RH. Humidified air flow was continuously pumped into the jars to avoid dehydration and excessive CO_2 accumulation. Samples of 1 mL of headspace gas were taken from each glass jar and monitored using an infrared gas analyzer (GXH-1050, Beijing Junfang Chemical Institute of Technology, Beijing, China). The respiration rate was determined every 15 d for up to 60 d and expressed as mg kg^{-1} h^{-1} of CO_2 production.

2.4. Firmness

Firmness analysis was conducted every 15 d using a texture analyzer (TA-XT2i, Stable Micro Systems Ltd., Godalming, UK) with a 5 mm diameter cylindrical probe. Five fruit for each treatment were randomly selected and firmness was measured on the equatorial zone on two sides of each fruit, left and right side of the fruit suture. The penetration rate was 0.5 mm s^{-1} for a depth of 2 mm and results were expressed in N.

2.5. Contents of total flavonoids, ascorbic acid, reducing sugars, and titratable acids

Nutrients were analyzed from the whole edible parts of plum fruit. The total flavonoid contents were determined every 15 d using a colorimetric method described by Kim et al. (2003). The results were expressed as mg of catechin equivalents per 100 g of plum fruit. The ascorbic acid, reducing sugars, and titratable acid contents of fruit were determined every 15 d according to Li et al. (2009). Ascorbic acid was titrated using the 2,6-dichloroindophenol titration method and its content was expressed as mg per 100 g of plum fruit. The content of reducing sugars was determined by the Fehling's method and was calculated as g of glucose per 100 g of fruit. The content of titratable acids was obtained by titration with 0.1 mol L^{-1} sodium hydroxide to pH 8.2 and expressed as g of malic acid per 100 g of fruit.

2.6. Shelf-life

Plums were stored at 4 °C for 60 d for the shelf-life study. Samples washed with potable tap water were used as the controls. Fruit were taken for microbial growth assay and sensory quality evaluation on days 0, 35, 40, 55, and 60. Samples without treatment with potable tap water, ClO_2, or ultrasound were used to determine the inherent background microflora. The end of the shelf-life was defined as when the population of a microbial group reached an unacceptable level or the sensory quality evaluation panelists rejected the sample.

To measure microbial levels, most of the external part of the fruit (30 g) was homogenized using a Stomacher 400 Circulator (Steward Ltd., London, UK) for 2 min in 270 mL of sterile neutralizing phosphate buffer. Ten-fold dilution series were made in 0.1% peptone water for plating. The following media and conditions were used for microbial incubation: Plate Count Agar was incubated at 30 °C for 3 d for total aerobic mesophilic bacteria and also at 22 °C for 5 d for total aerobic psychrotrophic bacteria; de Man–Rogosa–Sharpe medium (0.14% sorbic acid) was incubated at 30 °C for 3 d for lactic acid bacteria; Rose Bengal Agar was incubated at 30 °C for 3 d for yeasts and moulds. Colonies were counted and results