Chlorine dioxide fumigation generated by a solid releasing agent enhanced the efficiency of 1-MCP treatment on the storage quality of strawberry

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Abstract The effect of 1-methylcyclopropene (1-MCP) and chlorine dioxide (ClO₂) on fruit quality during storage was investigated. Strawberries were treated with 1-MCP alone or in combination with ClO₂ gas generated by a releasing agent, and the quality, fruit decay, microbial inhibition, and enzyme activities [polyphenol oxidase (PPO), superoxide dismutase (SOD), ascorbate peroxidase (APX), and phenylalanine ammonia lyase (PAL)] at 4 °C were measured for 16 days. 1-MCP alone could maintain the fruit quality during storage but had little effect on microbial growth, resulting in quick decay during storage. ClO₂ treatment effectively inhibited microbial growth during storage and improved shelf life with no visual damage. Moreover, 1-MCP in combination with ClO₂ was superior in maintaining quality attributes as compared with 1-MCP alone, as significant differences were found in some indices. Furthermore, 1-MCP in combination with ClO₂ maintained higher SOD, APX, and PAL activities and lower PPO activity as compared with the control and 1-MCP alone. Overall, ClO₂ enhanced the effect of 1-MCP on strawberries during storage and shelf life, possibly

through the inhibition of microbial growth and regulation of enzyme activity. The combination of 1-MCP and ClO₂ may serve as a potential strategy with dual physiological and antimicrobial effects for the preservation of perishable products.

Keywords 1-MCP · Chlorine dioxide · Strawberry · Controlled ClO₂ generating · Composite bactericide

Introduction

Individual technologies used in the preservation and storage of fruits and vegetables are often insufficient in maintaining the quality or improving the shelf life of perishable products such as berries. To meet the demands of market and consumers, a combination of fresh-keeping technology is necessary and may become a trend in the future. Strawberries are high-value fruits that are susceptible to microbiological decay (Kim et al. 2010). After harvest, strawberries experience a sequence of physiological and biochemical changes which may decrease its firmness and change its color. The microorganisms present on its surface may further accelerate the firmness reduction and shorten the shelf life. Therefore, postharvest treatment is necessary for the elimination of microorganisms to extend the shelf life and retain the freshness of strawberries.

Several studies have reported that 1-methylcyclopropene (1-MCP) may maintain the quality attributes of strawberries (Sliva et al. 2012) with no effect on the overall fruit acceptability; however, 1-MCP may slightly increase rot development (Bower et al. 2003). Therefore, sterilization treatment was necessary for strawberry storage.

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Chlorine dioxide (ClO_2) is a powerful sanitizer that possesses broad and efficient biocidal activity for the reduction of pathogenic microorganisms related to food safety (Du et al. 2002; Wang et al. 2014). ClO_2 has been recently used in postharvest treatments of fruits and vegetables, such as bell pepper (Du et al. 2007), plum fruit (Chen and Zhu 2011), strawberry (Arango et al. 2016), blueberry (Xu et al. 2016), and was efficient for extending the shelf life and maintaining the quality of products. However, its performance was influenced by factors such as pH, concentration, exposure time (Zoffoli et al. 2005; Arango et al. 2016), temperature, and treatment modes (gas or aqueous). Extended treatment duration and higher concentrations may result in visual damage; for instance, strawberries treated with $5 \text{ mg } \text{ClO}_2 \text{ L}^{-1}$ for 7 min showed color changes in the calyx, discolored tissue parts, and were desiccated (Arango et al. 2016). In addition, the exposure burst of ClO_2 gas should be avoided with the use of a solid-releasing agent (Xiao et al. 2016) or controlled ClO_2 -generating instruments.

There are no reports on the effects of the combination of ClO_2 gas and 1-MCP on the storage quality of strawberries. The aim of our study was to evaluate the efficiency of ClO_2 gas generated using a solid-releasing agent in combination with 1-MCP for removing microorganisms and ensuring the quality of stored strawberries. We show that the combination treatment may be an effective method for the preservation and storage of strawberries.

Materials and methods

Strawberry

Experiments were conducted with commercially grown strawberries transported to the laboratory immediately after harvest. Only well-formed fruits with intact calyxes that were rot-free, uniformly matured, similar in size and color, and unblemished were selected. The selected fruits were pre-cooled at 5°C for 4 h prior to treatment to avoid condensation during treatment and maintained at a constant temperature inside a plastic box (10 L).

Preparation of solid ClO_2 -releasing agent

The solid ClO_2 -releasing agent used in this research was self-made in our laboratory. Firstly, the stable ClO_2 tablet (Beijing Golden Pool Scientific Co. Ltd, Beijing, China) was crushed into powder and mixed with β -cyclodextrin and β -zeolite, at a ratio of 1:3:1 (w/w). Then, the mixed powder was compressed into tablets (1 g weight), which was used in this experiment. The gas-releasing rate of tablets was measured by a standard iodimetry method at 2,

4, 6, 8, 10, 12, and 24 h, and subsequently every 12 h until 180 h at 4°C and 90% relative humidity (RH). The release curve is demonstrated in Fig. 1.

Fruit treatment

Strawberry fruits were divided randomly into three groups and placed in a vented clamshell punnet. Groups of four punnets, containing twenty fruits per punnet, were placed into each 10 L box. The three treatment groups were as follow: control (no treatment), 1-MCP treatment (1 mg L^{-1} of 1-MCP), and 1-MCP + ClO_2 treatment (combination of 1 mg L^{-1} of 1-MCP and 1 g ClO_2 tablets, which could release about $33 \mu\text{L L}^{-1}$ ClO_2 gas in the box). All fruits were stored at 4°C . Sampling for further analysis was conducted at 0, 4, 8, 12, and 16 days after treatment. The experiment was performed in triplicate.

Fruit decay and microbial inhibition

The decay incidence of strawberry at day 16 and its 1-day shelf life at 25°C was evaluated and calculated as follows: Decay incidence (%) = (number of decayed fruits/total number of fruits) $\times 100$.

The effect of 1-MCP and ClO_2 on the microbial population present on the strawberry surface was investigated. Prior to storage, five fruits were collected from each treatment group into sterile sealed plastic bags ($25 \text{ cm} \times 30 \text{ cm}$) and 150 mL sterile distilled water was added; the bags were shaken on a rotary shaker at 200 rpm for 15 min. After nine-fold dilutions for the determination of fungal population, 100 μL of solution from each dilution was plated on a petri dish containing potato dextrose agar (PDA) supplemented with $250 \mu\text{g L}^{-1}$ chloramphenicol

Fig. 1 The release curve of ClO_2 releasing agent. ClO_2 concentration was measured by a standard iodimetry method at 2, 4, 6, 8, 10, 12, 24, and every 12 h, until 180 h, at 4°C and 90% RH

(Sigma Chemical Co., St. Louis, MO, USA) to inhibit bacterial growth. The total microbial and bacterial populations were also detected using pure PDA and tryptic soy agar (TSA, Bacto, Sparks, MD, USA) supplemented with $200 \mu\text{g L}^{-1}$ cycloheximide (Applichem, Darmstadt, Germany). After 96 h of incubation at 24°C , the colonies were counted. The experiment was performed in triplicate for each dilution and populations were expressed as colony forming units (CFU) per fruit.

Quality attributes

The fruit firmness was evaluated by measuring the diameter of 10 fruits using a hand-held fruit firmness analyzer (GY-2, Tuopu, Zhejiang, China). Juice was prepared by manual extrusion and the total soluble solid (TSS) content was determined using a hand-held pocket refractometer (PAL-1, Atago, Tokyo, Japan). For the analysis of ascorbic acid content, 5 g of frozen fruit sample was homogenized in a 50 mL solution of 10 g L^{-1} oxalic acid and the supernatant was titrated using the 2,6-dichloroindophenol titration method; the result was expressed as mg kg^{-1} . Titratable acidity was determined by titration to a pH value of 8.2 with 0.4 M sodium hydroxide (NaOH). The volume of the titrant was recorded and the result was expressed as mmol H^+ per kilogram fruit sample. Total phenolic content (TPC) was measured used the Folin–Ciocalteu method (Chaven et al. 2012) and expressed as grams per kilogram fruit. The linear equation of the calibration curve was $y = 0.0476x - 0.0189$, with a correlation coefficient of $R^2 = 0.9923$.

Enzyme activities

Five grams of strawberries were extracted for 10 min with 3 mL of 0.05 M sodium phosphate buffer (pH 7.8) containing some quartz sand at 4°C . The extracted solution was centrifuged for 30 min at $10,000\times g$ and the supernatant was collected as the enzyme solution.

Polyphenol oxidase (PPO, EC 1.10.3.1) was assayed as described by Galeazzi et al. (1981). The enzyme activity was measured by the increase in the absorbance at a wavelength of 410 nm. One unit of enzyme activity was defined as the increase in the absorbance of 0.01 per minute.

Superoxide dismutase (SOD, EC 1.15.1.1) was assayed following the method of Wang and Chen (2010). The absorbance was measured at 560 nm wavelength with 0.05 M sodium phosphate buffer (pH 7.8) as a control. One unit of enzyme activity was defined as the amount of enzyme that caused 50% inhibition of NBT reduction.

Ascorbate peroxidase (APX, EC 1.11.1.11) was assayed by the method described by Zhou et al. (2014). One unit of

APX activity was defined as the oxidation of 1 mol ascorbic acid per minute at a wavelength of 290 nm.

Phenylalanine ammonia lyase (PAL, EC 4.3.1.5) was assayed according to the methods of Martínez-Téllez and Lafuente (1997). One unit was defined as the amount of enzyme that caused an increase in the absorbance of 0.01 at a wavelength of 290 nm in 60 min.

Statistical analysis

We used SPSS 20.0 software for all data analyses. Analysis of variance (ANOVA) was performed to examine the treatment effects. Duncan's multiple range test was applied to determine statistically significant differences ($P < 0.05$) among treatments. In addition, graphs were prepared using Microsoft Excel 2016.

Results

Releasing curve of stabilized ClO_2 formulation

An appropriate level of gas disinfectants is necessary for the removal of microorganisms from the fruit surface and storage environment; however, improper treatment with ClO_2 may lead to visual damage of the fruit surface. As shown in Fig. 1, the releasing rate of ClO_2 rapidly increased in the initial period, with the maximum releasing rate ($3.56 \mu\text{L L}^{-1}$) reported at 10 h, followed by a decrease in the releasing rate. As previously reported by Arango et al. (2016), the exposure of fruits to high concentration of ClO_2 (5 mg L^{-1} or approximately $166 \mu\text{L L}^{-1}$ for 7 and 37 min and 1.26 mg L^{-1} or approximately $41.6 \mu\text{L L}^{-1}$ for 332 min) resulted in the discoloration of strawberries from red to pale yellow. In addition, the calyx dried and bleached, as evidenced by the change in its texture and color from fresh green to ashy yellow. The degree and area of bleaching increased with an increase in the concentration and/or time. However, no phytotoxic effects were observed on pear (cv. Packham's Triumph) at 1 mg L^{-1} (approximately $33 \mu\text{L L}^{-1}$) after 20-day exposure at 20°C (Zoffoli et al. 2005). In the present study, no visual damage of strawberry surface was observed and greener calyxes were reported for samples treated with ClO_2 , indicating that the solid ClO_2 -releasing formulation used was safe and effective for strawberries.

Fruit decay and microbial inhibition

Chlorine dioxide is an effective sanitizing agent against fungi and bacteria, while the direct effects of 1-MCP on the inhibition of microbial growth and survival are yet unknown; however, 1-MCP may strengthen the disease

resistance of fruit and vegetables by inhibiting the action of ethylene and delaying senescence. As shown in Table 1, a remarkable difference was observed in the appearance of strawberries treated with 1-MCP alone and combination of 1-MCP + ClO₂ as compared with the control. While the control group showed a decay incidence of 57.5% accompanied with tissue collapse and shrinkage, the decay incidence was 42.5 and 17.5% for 1-MCP and 1-MCP + ClO₂ group, respectively. However, the shelf-life evaluation for 1 day at 25 °C showed that the decay of strawberry from 1-MCP treatment rapidly increased to 75.0%, while that of strawberry from ClO₂ treatment group was 35.0%. Thus, ClO₂ efficiently reduced the decay caused by microorganisms. As shown in Table 1, ClO₂ killed more than 92% of microorganisms from the fruit surface, thereby reducing the microbial population. Although 1-MCP showed a relatively low decay incidence, its inhibitory effect on the microbial growth may be neglected, as no significant difference was observed between 1-MCP treatment and control group.

Quality attributes

Firmness

Firmness change is one of the most important features of fruit ripening and senescence and may reduce the shelf life, facilitate pathogen infection, and limit transportation. As shown in Table 2, a decrease in firmness was observed during storage; in particular, a greater reduction in firmness was observed after day 12. Treatment with 1-MCP alone and in combination with ClO₂ was effective in maintaining the relatively high firmness of strawberries as compared with the control ($P < 0.05$). Strawberries treated with 1-MCP + ClO₂ showed the highest firmness; however, no significant difference was observed between 1-MCP + ClO₂ and 1-MCP group ($P > 0.05$). This result was in agreement with the previous reports, wherein both 1-MCP and ClO₂ had the ability to maintain the firmness of fruits such strawberry (Sliva et al. 2012), nectarine (Ziliotto et al. 2008), and plum (Chen and Zhu 2011), and a better

effect on firmness retention was observed with their combination as compared with their single treatment.

Total soluble solids

As shown in Table 2, a decreasing trend in TSS of strawberries was observed and no significant difference was found between the three treatment groups ($P > 0.05$). 1-MCP or ClO₂ had no apparent effects on TSS, although 1-MCP and ClO₂ showed a small reduction in TSS. Studies with apples (Zanella 2003) showed that 1-MCP exerted little effects on TSS.

Ascorbic acid content

As shown in Table 2, the ascorbic acid content of strawberries remained steady before day 4 of storage and declined thereafter. 1-MCP treatment was found to be effective in preserving ascorbic acid content and the effect was enhanced in the presence of ClO₂; however, no significant difference was observed between 1-MCP and 1-MCP + ClO₂ group ($P > 0.05$). This result was consistent with the previous reports, wherein 1-MCP treatment reduced the decrease in ascorbic acid content from pineapples (Selvarajah et al. 2011) and was effective in combination with ClO₂ in strawberry (Chen 2015). Certain chlorides (Cl₂, HOCl, ClO₂) may reduce the loss of vitamins from food (Fennema 1991).

Titrate acidity content

As shown in Table 2, the titratable acidity of strawberry decreased by more than 50% during the first 8 days, increased rapidly from day 8 to 12, and then decreased during the last 4 days. 1-MCP was found to be effective in preserving titratable acidity and its effects were weakened in combination with ClO₂; however, no significant difference was observed between the three groups ($P > 0.05$). This result is in agreement with the reports, wherein 1-MCP inhibited the loss in titratable acidity of green tomatoes (Wills and Ku 2002) throughout the storage

Table 1 The efficacy of 1-MCP and chlorine dioxide on decay incidence, microorganism population on fruit surface

Treatment	Decay (%)		Microorganism population (10 ⁵ cfu/fruit) at 4 °C		
	16 d at 4 °C	1 d at 25 °C	TM ^a	Fungi	Bacteria
Control	57.5 ± 6.33a	100a	4.2 ± 0.18a	5.1 ± 0.26a	0.22 ± 0.01a
1-MCP	42.5 ± 5.00b	75.0 ± 4.50b	4.1 ± 0.15a	4.9 ± 0.21a	0.21 ± 0.02a
1-MCP + ClO ₂	17.5 ± 3.50c	35.0 ± 3.00c	0.35 ± 0.02b	0.42 ± 0.02b	0.012 ± 0.003b

Each value represents mean ± standard deviation of three replicates, different letters in the same line mean significant difference ($P < 0.05$)

^aTotal microorganisms grown in PDA medium

Table 2 Effect of 1-MCP and chlorine dioxide treatment on the quality attributes of strawberry stored at 4 °C for 16 d

Quality index	Storage time (d)	Treatment		
		Control	1-MCP	1-MCP + ClO ₂
Firmness (N)	0	2.72 ± 0.26a	2.72 ± 0.26a	2.72 ± 0.26a
	4	2.06 ± 0.23a	2.19 ± 0.24a	2.15 ± 0.34a
	8	1.84 ± 0.16a	2.11 ± 0.19a	2.01 ± 0.10a
	12	1.72 ± 0.06a	1.80 ± 0.09a	1.86 ± 0.07b
	16	1.18 ± 0.06a	1.69 ± 0.09b	1.80 ± 0.06b
Total soluble solid (%)	0	9.60 ± 0.40a	9.60 ± 0.40a	9.60 ± 0.40a
	4	9.42 ± 0.36a	9.32 ± 0.41a	9.49 ± 0.54a
	8	8.65 ± 0.25a	8.78 ± 0.36a	8.95 ± 0.15a
	12	8.10 ± 0.18a	8.50 ± 0.50a	8.75 ± 0.45a
	16	7.90 ± 0.19a	8.30 ± 0.35a	8.43 ± 0.23a
Ascorbic acid (mg kg ⁻¹)	0	480.4 ± 5.6a	480.4 ± 5.6a	480.4 ± 5.6a
	4	667.2 ± 46.2a	653.3 ± 18.0a	64.0 ± 0.90a
	8	480.4 ± 12.9a	510.2 ± 12.1b	561.0 ± 13.8c
	12	400.0 ± 32.0a	440.4 ± 28.3b	483.4 ± 22.6b
	16	360.4 ± 24.8a	416.2 ± 20.4b	434.2 ± 26.0b
Titratable acidity (mmol kg ⁻¹)	0	44.0 ± 0.16a	44.0 ± 0.16a	44.0 ± 0.16a
	4	22.7 ± 2.95a	25.3 ± 1.45a	25.0 ± 0.09a
	8	26.1 ± 2.83a	28.9 ± 1.40a	31.0 ± 1.44b
	12	31.5 ± 2.11a	36.0 ± 1.41b	35.0 ± 2.83b
	16	28.5 ± 0.95a	3.30 ± 0.11b	30.9 ± 0.85a
Total phenolic content (g kg ⁻¹)	0	0.244 ± 0.01a	0.244 ± 0.01a	0.244 ± 0.01a
	4	0.230 ± 0.01a	0.237 ± 0.01a	0.234 ± 0.01a
	8	0.224 ± 0.01a	0.229 ± 0.01a	0.230 ± 0.01a
	12	0.216 ± 0.01a	0.224 ± 0.01a	0.222 ± 0.02a
	16	0.206 ± 0.01a	0.214 ± 0.01a	0.211 ± 0.01a

Each value represents mean ± standard deviation of three replicates, different letters in the same line meant significant difference in the same day during storage ($P < 0.05$)

period and ClO₂ treatment maintained the relatively high titratable acidity of strawberry (Chen 2015).

Total phenolic content (TPC)

As showed in Table 2, little fluctuation in the TPC of strawberries was observed during storage. No remarkable effects were observed following treatment with 1-MCP alone or in combination with ClO₂ ($P > 0.05$), although 1-MCP treatment maintained the highest content of total phenolics. This result was in agreement with that reported in blueberries (Pantelidis et al. 2010). However, ClO₂ gas decreased the content of TPC in carrots (Vandekinderen et al. 2008).

Related enzyme activity

Oxidative stress may induce significant cellular damage due to the accumulation of superoxide radical, hydroxyl radical, and hydrogen peroxide. A balance among PPO,

SOD, APX, and PAL activities in the tissue is vital for cell survival during storage (Sala and Lafuente 2004).

PPO activity

As shown in Fig. 2a, PPO activity decreased during the first 4 days and then rapidly increased, especially for the control group. PPO activity was lower for 1-MCP and 1-MCP + ClO₂ treatment groups and a significant difference was observed between these two groups and control ($P < 0.05$). In addition, the combination of 1-MCP and ClO₂ resulted in the lowest PPO activity, indicating that 1-MCP suppressed the increase in PPO activity while ClO₂ enhanced this effect. In addition, ClO₂ at 80 and 120 mg L⁻¹ concentration was shown to significantly inhibit PPO activity in litchi fruit (Wu et al. 2011).

Fig. 2 Effects of 1-MCP alone or in combination with ClO_2 on the activity of PPO (a), SOD (b), APX (c) and PAL (d) of strawberries during storage. Each value represents mean $\pm$ standard deviation of three replicates

SOD activity

As shown in Fig. 2b, SOD activity increased rapidly within the first 4 days of storage for the control group and 8 days of storage for 1-MCP and ClO_2 treatment groups; SOD activity decreased thereafter. 1-MCP treatment maintained higher SOD activity as compared with the control group; the combination of 1-MCP and ClO_2 demonstrated highest SOD activity, which peaked to $192.6 \text{ U g}^{-1} \text{ FW}$; significant differences were observed between all treatments ($P < 0.05$). This observation was in agreement with that reported in blueberries, wherein aqueous ClO_2 could maintain higher SOD activity and enhance the peak value as compared with the control (Xu et al. 2016).

APX activity

As shown in Fig. 2c, the APX activity level in strawberries increased from days 0 to 4 or 8 and declined thereafter, similar to the change in SOD activity. The peak value of APX activity in 1-MCP treatment was

$105.8 \mu\text{mol min}^{-1} \text{ g}^{-1}$, which was 26.1 and 10.6% greater than that of the control and 1-MCP + ClO_2 treatment, respectively. At day 16, APX activity in the combination treatment group was similar to that reported for the 1-MCP treatment group ($P > 0.05$).

PAL activity

Studies have shown an upregulation in PAL activity, secondary metabolism, lignin synthesis, and oxidation resistance as a defense mechanism in response to pathogenic invasion of the fruit tissue (Yang et al. 2015). As shown in Fig. 2d, PAL activity increased during the first 8 and 12 days for control and other two treatment groups, respectively, and decreased thereafter. Samples from 1-MCP + ClO_2 treatment group showed higher PAL activity as compared with other groups between day 12 and 16, suggesting that ClO_2 treatment strengthened the defense system against microbial invasion, although 1-MCP showed similar effects. These observations were similar to those previously reported, wherein ClO_2 at 80

and 120 mg L⁻¹ concentration significantly increased PAL activity of litchi fruit (Wu et al. 2011).

Discussion

While several studies have reported the antifungal activity of ClO₂, its activity in postharvest fruits is relatively less studied. Most fruits are cleaned and washed before storage to remove soil particles, dust, or microbial contaminants, which may cause fruit decay. It is inappropriate to wash some fruits such as berries with water due to their biological properties. The fruit skin may be easily damaged during washing and the fruit may absorb water. The free water on the surface may induce germination of pathogen spores and color degradation. The most efficient way to treat such fruits is through fumigation or fogging using an appropriate disinfectant to reduce the number of microbes present. The results of this study indicate that fungus and bacteria growing on the fruit surface may be efficiently inactivated by ClO₂ fumigation (Table 1), without any side effects related to surface color and quality attributes (Table 2). Although 1-MCP alone could maintain the good quality of the strawberries as compared with the untreated control, it failed to exert any direct effect on microbial growth (Table 1). The combination of 1-MCP and ClO₂ achieved this dual effect.

Some reports have shown that ClO₂ may play a positive role in maintaining the quality of fruits such as green pepper (Du et al. 2007) and plum (Chen and Zhu 2011) possibly by reducing respiration and ethylene synthesis (Guo et al. 2013, 2014). In the present study, fruit quality was maintained by the combination of 1-MCP and ClO₂, which was better than the effect observed with 1-MCP alone. Furthermore, 1-MCP maintained the relatively high activity of enzymes related to the antioxidant system of the fruit and suppressed PPO activity, while it enhanced these effects in combination with ClO₂, suggesting that ClO₂ may strengthen the defense system of fruit tissues.

Very little has been reported on the combined used of 1-MCP and ClO₂ for increasing the storage period of fresh products. For green walnut kernel, the combination of 1-MCP and ClO₂ retained the fatty acid and phenolic content as compared with control and 1-MCP treatment alone, whereas 1-MCP exerted a negative effect on decay control (Jiang et al. 2015). In this study, the combination treatment showed better effects on fruit quality and removal of microorganisms as compared with the effects observed with 1-MCP alone. These results suggest a new strategy with dual physiological and antimicrobial effects for the preservation of perishable products.

Conclusion

1-MCP alone maintained strawberry quality during storage. However, exerted very little microbial inhibition. 1-MCP, in combination with ClO₂ gas, was superior in maintaining the quality attributes as compared with 1-MCP alone and the control, as significant differences were found between some indices. Overall, ClO₂ enhanced the efficiency of 1-MCP during fruit storage and shelf life examination possibly through microbial inhibition and enzyme activity regulation. The combination of 1-MCP and ClO₂ may serve as a new strategy with dual physiological and antimicrobial effects for the preservation of perishable products.

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References

- Arango J, Rubino M, Auras R, Gillett J, Schilder A, Grzesiak AL (2016) Evaluation of chlorine dioxide as an antimicrobial against *Botrytis cinerea* in California strawberries. *Food Packag Shelf Life* 9:45–54
- Bower JH, Biasi WV, Mitcham EJ (2003) Effects of ethylene and 1-MCP on the quality and storage life of strawberries. *Postharvest Biol Technol* 28(3):417–423
- Chaven JJ, Jagtap UB, Gaikward NB, Dixit GB, Bapat VA (2012) Total phenolics, flavonoids and antioxidant activity of saparangi (*salacia chinensis* L.) fruit pulp. *J Plant Biochem Biotechnol* 22(4):109–413
- Chen Z (2015) Development of a preservation technique for strawberry fruit (*fragaria ananassa* Duch.) by using aqueous chlorine dioxide. *J Microbiol Food Sci* 15(1):45–51
- Chen Z, Zhu CH (2011) Combined effects of aqueous chlorine dioxide and ultrasonic treatments on postharvest storage quality of plum fruit (*Prunus salicina* L.). *Postharvest Biol Technol* 61(2–3):117–123
- Du JH, Han YC, Linton RH (2002) Inactivation by chlorine dioxide gas (ClO₂) of *Listeria monocytogenes* spotted onto different apple surfaces. *Food Microbiol* 19(5):481–490
- Du JH, Fu MR, Li MM, Xia W (2007) Effects of chlorine dioxide gas on postharvest physiology and storage quality of green bell pepper (*Capsicum frutescens* L. var. Longrum). *Agric Sci China* 6(2):214–219
- Fennema OR (1991) *Food Chemistry*, 3rd edn. Translated by Wang Z, Xu SY, Jiang B, Yang RJ, Zhong F, Ma IG. Light Industry Press in China, Beijing
- Galeazzi MAM, Sgarbieri VC, Constantinides SM (1981) Isolation, purification and physicochemical characterization of polyphenoloxidases (PPO) from a dwarf variety of banana (*Musa cavendishii*, L.). *J Food Sci* 46(1):150–155
- Guo Q, Lv X, Xu F, Zhang YL, Wang JD, Lin HH, Wu B (2013) Chlorine dioxide treatment decreases respiration and ethylene synthesis in fresh-cut ‘Hami’ melon fruit. *Int J Food Sci Technol* 48(9):1775–1782
- Guo Q, Wu B, Peng XY, Wang JD, Li QP, Jin J, Ha YM (2014) Effects of chlorine dioxide treatment on respiration rate and

- ethylene synthesis of postharvest tomato fruit. *Postharvest Biol Technol* 93:9–14
- Jiang LQ, Feng WY, Li F, Xu JY, Ma YP, Ma HL (2015) Effect of one-methylcyclopropene (1-MCP) and chlorine dioxide (ClO₂) on preservation of green walnut fruit and kernel traits. *J Food Sci Technol* 52(1):267–275
- Kim JY, Kim HJ, Lim GO, Jang SA, Song KB (2010) The effects of aqueous chlorine dioxide or fumaric acid treatment combined with UV-C on postharvest quality of 'marhyang' strawberries. *Postharvest Biol Technol* 56(3):254–256
- Martínez-Téllez MA, Lafuente MT (1997) Effect of high temperature conditioning on ethylene, phenylalanine ammonia-lyase, peroxidase and polyphenol oxidase activities in flavedo of chilled "Fortune" mandarin fruit. *J Plant Physiol* 150(6):674–678
- Pantelidis G, Vasilakakis M, Manganaris GA, Costa G (2010) Effect of 1-methylcyclopropene and retain on quality attributes of 'Kristali' pears after short or long term cold storage. *Acta Hort* 884:323–330
- Sala JM, Lafuente MT (2004) Antioxidant enzymes activities and rind-staining in 'Naveline' oranges as affected by storage relative humidity and ethylene conditioning. *Postharvest Biol Technol* 31(3):277–285
- Selvarajah S, Bauchot AD, John P (2011) Internal browning in cold-storage pineapples is suppressed by a postharvest application of 1-methylcyclopropene. *Postharvest Biol Technol* 23(2):302–307
- Sliva PA, de Abreu MP, Rezende Queiroz E, Corrêa AD, dos Santos CD (2012) Storage of strawberries (*Fragaria ananassa* L.) cv. 'Oso Grande' subjected to 1-MCP. *Acta Sci Technol* 34(3):353–358
- Vandekinderen J, Van Camp J, Devlieghere F, Veramme K, Denon Q, Ragaert P, De Meulenaer B (2008) Effect of decontamination agents on the microbial population, sensorial quality and nutrient content of grated carrots (*Daucus carota* L.). *J Agric Food Chem* 56(14):5723–5731
- Wang SY, Chen CT (2010) Effect of allyl isothiocyanate on antioxidant enzyme activities, flavonoids and post-harvest fruit quality of blueberries (*Vaccinium corymbosum* L., cv. Duke). *Food Chem* 4:1153–1158
- Wang Z, Narciso J, Biotteau A, Plotto A, Baldwin E, Bai J (2014) Improving storability of fresh strawberries with controlled release chlorine dioxide in perforated clamshell packaging. *Food Bioprocess Technol* 7(12):3516–3524
- Wills R, Ku V (2002) Use of 1-MCP to extend the time to ripen of green tomatoes and postharvest life of ripe tomatoes. *Postharvest Biol Technol* 26(1):85–90
- Wu B, Li XP, Hu HG, Chen WX (2011) Effect of chlorine dioxide on the control of postharvest diseases and quality of litchi fruit. *Afr J Biotechnol* 10(32):6030–6039
- Xiao SL, Liu YX, Li C, Wang GY, Zhang QL (2016) Optimization of the formulation of preservative coating used in slow-releasing ClO₂ preservative paper. *Food Sci* 37(8):248–254
- Xu FX, Wang SH, Xu J, Liu SY, Li GD (2016) Effects of combined aqueous chlorine dioxide and UV-C on shelf-life quality of blueberries. *Postharvest Biol Technol* 117:125–131
- Yang HQ, Zheng JY, Huang CQ, Zhao XF, Chen HY, Sun ZD (2015) Effects of combined aqueous chlorine dioxide and chitosan coatings on microbial growth and quality maintenance of fresh-cut bamboo shoots (*Phyllostachys praecox* f. *prevernalis*) during storage. *Food Bioprocess Technol* 5:1011–1019
- Zanella A (2003) Control of apple superficial scald and ripening- a comparison between 1-methylcyclopropene and diphenylamine postharvest treatments, initial low oxygen stress and ultra low oxygen storage. *Postharvest Biol Technol* 27(1):69–78
- Zhou Q, Ma C, Cheng SC, Wei BD, Liu XY, Ji SJ (2014) Changes in antioxidative metabolism accompanying pitting development in stored blueberry fruit. *Postharvest Biol Technol* 88:88–95
- Ziliotto F, Begheldo M, Rasori A, Bonghi C, Pietro P (2008) Transcriptome profiling of ripening nectarine (*Prunus persica* L. Batsny) fruit treated with 1-MCP. *J Exp Bot* 59(10):2781–2791
- Zoffoli JP, Latorre BA, Daire N, Viertel S (2005) Effectiveness of chlorine dioxide as influenced by concentration, pH, and exposure time on spore germination of *Botrytis cinerea*, *Penicillium expansum* and *Rhizopus stolonifera*. *Cienc Investig Agrar* 32(3):142–148