Quality characteristics of Niagara grapes and their storage life as affected by 1-MCP combined with sulfur dioxide treatment and modified atmosphere packaging

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ABSTRACT
Skin of Niagara grapes is thin and light green, but browning and postharvest disease seriously shorten their storage life after harvest. In this study, we studied the effects of 1.0 μL L⁻¹ 1-methylcyclopropene (1-MCP) combined with 200 μL L⁻¹ SO₂ on the grape quality of Niagara grapes. It was stored in cold storage for 6 days after cold storage at low temperature and modified atmosphere packaging. 1-MCP combined with SO₂ can delay the consumption of nutrients and declined of textural characteristics by inhibiting the respiration rate and ethylene production rate. It also reduced the changes of antioxidant components and antioxidant enzyme activities to delay the decay, berry drop and browning, and to maintain a high marketable berry quality. In conclusion, postharvest 1-MCP combined with 200 μL L⁻¹ SO₂ treatment can effectively maintain the quality and prolonged the shelf life of Niagara grapes in modified atmosphere packaging.

Introduction
Niagara grape (Vitis labrusca, cv. Niagara grape) is a unique variety in Sandu County of Guizhou, which is planted in Guizhou. The berry is light green and translucent, crystal clear, has a unique aroma, thin skin, soft flesh, and a high moisture content. However, threshing, browning of berry and rachis, and diseases caused by Penicillium sp., Colletotrichum gloeosporioides and Alternaria sp occur during postharvest storage. Among them, browning mainly affects consumer acceptance, and disease rot causes economic loss, those also shorten storage period and shelf life.

Grapes are considered to be non-climacteric, but the rachis is climacteric. 1-MCP effectively delays rachis browning by inhibiting respiration and ethylene in the rachis and maintains postharvest quality of table grapes. Besides, 1-MCP can inhibit the rise of the weight loss rate, abscission rate and rotting incidence, and maintain flavor and postharvest quality. Modified atmosphere package (MAP) storage, a regular controlled atmosphere (6% O₂ + 10% CO₂) or a controlled atmosphere with an extreme CO₂ level (ECA; 4% O₂ + 30% CO₂) can maintain postharvest rachis quality by delaying degradation of green pigments and accumulation of brown compounds at the periderm and cortex tissues, and delaying softening and decay of harvested muscadine grapes. However, only 1-MCP or MAP does not control fungal diseases.

Sulfur dioxide (SO₂) is a classic grape preservative, SO₂ can inhibit microbial activities and kill various pathogenic bacteria. Fumigation, adding SO₂ to the environment or SO₂ release pads can effectively control the incidence of gray mold in grapes. SO₂ markedly activates defense responses associated with secondary metabolism and pathogenesis-related proteins for enhanced...
disease resistance at the transcriptional and post transcriptional levels, and delays decay of table grape cultivars caused by B. cinerea, and thus extends their storage life.\textsuperscript{20-22} In addition, SO\textsubscript{2} can inhibit chlorophyll decomposition and browning of grape stem and stalk, keep the content of soluble solid, titratable acid stable, and texture parameters, maintaining postharvest quality of grapes.\textsuperscript{23}

Although single use of 1-MCP, SO\textsubscript{2} or MAP can maintain grape quality during storage, there are still some shortcomings. Such as 1-MCP or MAP cannot effectively control fungal decay,\textsuperscript{7,8} this can be improved with the SO\textsubscript{2}. However, high-concentration SO\textsubscript{2} treatment causes severe the berry abscission.\textsuperscript{16,19,24} Therefore, increasingly complex treatments have been used for grape storage. Such postharvest treatment with 1-MCP combined with SO\textsubscript{2} can slow down the change rate of berry softening, protopectin and respiratory intensity, prevent decay and deterioration effectively, maintain a high content of soluble solids and titratable acid, reduce sugar, and maintain a good quality of fruits.\textsuperscript{6,25} MAP combined with SO\textsubscript{2} controls fungal decay and stem browning, but is less effective in inhibiting fungal pathogens during the late storage period, whereas fumigation with 0.1 mL L\textsuperscript{-1} and 0.3 mL L\textsuperscript{-1} SO\textsubscript{2} for 30 min every 30 d can effectively maintain the quality of grapes during storage.\textsuperscript{26,27} Our previous study compared the effects of single or combined use of 1 μL L\textsuperscript{-1} 1-MCP or 200 or 400 μL L\textsuperscript{-1} SO\textsubscript{2} (from SO\textsubscript{2} release pods) under sustained release (CT-2 grape preservative, National Agricultural Products Processing Technology R&D Center, Tianjin, China) on the quality of Niagara grapes, and found that 1 μL L\textsuperscript{-1} 1-MCP combined with 200 μL L\textsuperscript{-1} SO\textsubscript{2} effectively maintains quality and delays the browning of Niagara grapes during storage at 0°C, but 4 tablets could increase the abscission and decay of Niagara grapes.\textsuperscript{11} This study investigates the effect of 1-MCP combined with 200 μL L\textsuperscript{-1} SO\textsubscript{2} treatment on the quality of Niagara grapes during cold storage and shelf life after cold storage under MAP.

Materials and methods

Plant Material and Treatment

The Niagara grapes were harvested from an orchard in Kaili City, Guizhou Province, China. Grapes in clusters were immediately transported to the laboratory of the Guizhou Engineering Research Center for Fruit Processing. To disperse the field heat, bagging was removed, and grape clusters without mechanical injury or disease and insect pests were selected for the experiment. All the grapes were randomly divided into two groups and packed in commercial polyethylene bags (Thickness: 30 μm; Air permeability: 6340 cm\textsuperscript{2} m\textsuperscript{-2} d\textsuperscript{-1} 0.1 MPa\textsuperscript{-1}, National Agricultural Products Processing Technology R&D Center, Tianjin, China) with a weight of 2.5 kg per bag, then transferred into 0 ± 0.5°C cold storage.

After precooling at 0 ± 0.5°C for 24 h, 1-MCP (SmartFresh\textsuperscript{TM}, AgroFresh Inc., USA) was added to a group at a concentration of 1.0 μL L\textsuperscript{-1}, and 200 μL L\textsuperscript{-1} SO\textsubscript{2} from 2 tablets SO\textsubscript{2} release pods were added, then quickly tie the bag, which is recorded as 1-MCP+SO\textsubscript{2}. The control group is directly tied to the bag, then stored at 0 ± 0.5°C. There were three replicates for each treatment, one bag for each replicate, and 30 bags per treatment. Six bags of each treatment were randomly removed from the cold storage every 15 d. Three bags were used at the end of cold storage, and the other three bags were used at 25 ± 0.5°C 6 d after cold storage.

Appearance quality

The weight of rotten, berry drop and browning grapes in each bag was measured according to the following formula: rot rate (\%) = 100 × rot berry weight/total berry weight. Berry drop rate (\%) = 100 × berry drop weight/total berry weight. Berry browning rate (\%) = 100 × berry browning weight/total berry weight, marketable fruits rate (\%) = 100- rot rate- berry drop rate.
**Respiration rate and ethylene production rate**

The respiration rate and ethylene production rate were measured referring to our previous method\(^{[28]}\) (Approximately 0.5 kg of berry in a 4.3 L sealed desiccator for 1 h at 25\(^\circ\)C). The concentrations of CO\(_2\) and ethylene were measured using a headspace CO\(_2\) analyzer (Model: 6600, Ollinois Tool Works Onc., Peoria, USA) and ethylene analyzer (Model: PGD3-C-C\(_2\)H\(_4\), Shenzhen Xins Technology Development Co., Ltd., Shenzhen, China). The respiration rate was expressed as mg CO\(_2\) kg\(^{-1}\) h\(^{-1}\). The ethylene production rate was expressed as mg C\(_2\)H\(_4\) kg\(^{-1}\) h\(^{-1}\).

**Instrumental textural characteristics**

The texture characteristics were analyzed by methods previously described.\(^{[29,30]}\) The force-time curves were determined by using a P/36 R of TA. XT Plus texture profile analyzer (Stable Micro System Ltd., UK). The force was measured with the following instrumental settings: 2 mm s\(^{-1}\) of test speed, 1 mm s\(^{-1}\) of posttest speed, and auto-force trigger of 5.0 g. Each fruit was compressed and deformed to 30%. Thirty replicates with the same size of berry were conducted for each treatment. The firmness, springiness, cohesiveness, gumminess, chewiness, and resilience were determined based on the force-time curve.

**Physicochemical properties**

The contents of total soluble solid (TSS) and titratable acid (TA) were analyzed by a previously described method,\(^{[31,32]}\) and the results were expressed as %. Ascorbic acid content was determined according to a previously described method\(^{[33]}\) and expressed as g kg\(^{-1}\). Reducing sugar content was determined by DNS method,\(^{[34]}\) and expressed as %. Glutathione (GSH) content was determined by a colorimetric method,\(^{[35]}\) and expressed as g kg\(^{-1}\). Total polyphenols content was quantified by the Folin-Ciocalteu’s\(^{[36]}\) and expressed as g kg\(^{-1}\).

**Enzyme assays**

POD activities were estimated using a previously described method,\(^{[37]}\) where 1 unit was defined as an increase of 0.001 ∆OD\(_{470}\) min\(^{-1}\), and expressed as U g\(^{-1}\). PPO activities were estimated according to the method of Tian et al,\(^{[38]}\) where 1 unit was defined as increase of 0.01 ∆OD\(_{470}\) min\(^{-1}\), and expressed as U g\(^{-1}\).

**Statistical analysis**

Each treatment was implemented three replicates, and the results were reported as the mean ± standard error. Statistical tests were performed using IBM SPSS Statistics 25 (International Business Machines Corporation, Armonk, New York, USA). Significant differences between control and 1-MCP combined with SO\(_2\) on the same day of storage were performed by Duncan’s multiple tests at the 95% level of probability (\(P < .05\)).

**Results and discussion**

**Rot rate, berry drop rate, browning rate and marketable fruits rate**

Niagara grapes are crystal clear, with high water and sugar content and a thin skin, which make them easily brown, berry drop and rot within 2–3 days of postharvest storage at room temperature, which lose commercial value.\(^{[1,2,39]}\) Our previous study found that the combination of 1.0 μL L\(^{-1}\) 1-MCP and 200 μL L\(^{-1}\) SO\(_2\) effectively maintains quality and delays browning of Niagara grapes during cold storage.\(^{[1]}\) However, the berry browning is rapid during the shelf life after cold storage. Our results
found that the rot rate, berry drop rate and browning rate of Niagara grapes increased gradually during cold storage and at 6 d of shelf life after cold storage, while the marketable berry rate decreased rapidly. The rot rate of the control was more than 50% at 6 d of shelf life after 30 d of cold storage, and loss the commercial value. 1-MCP or SO\textsubscript{2} can effectively inhibit rachis browning, berry drop and rot of grape berry.\textsuperscript{[5,7,8,23]} SO\textsubscript{2} without or with MAP is also effective in inhibiting fungal pathogens.\textsuperscript{[16,18,27]} Previous reports showed that 1-MCP combined with SO\textsubscript{2} could significantly inhibit browning of Munake grapes and maintain its postharvest quality.\textsuperscript{[25]} The berry drop rate and browning rate of 1-MCP combined with SO\textsubscript{2} treatment were significantly lower than those of the control after 30 days of cold storage (\(P < .05\)), and significantly inhibited their increase at 6 days after cold storage (\(P < .05\)). Our results found that 1-MCP combined with SO\textsubscript{2} treatment significantly inhibited the rapid changes of the rot rate and marketable berry rate of Niagara grapes after 30 days of cold storage and shelf life after cold storage (Figure 1A and D Supplement Fig. S1). These results showed that 1-MCP combined with low concentration SO\textsubscript{2} could effectively inhibit the browning of undertint grapes and maintain their edible quality.

**Respiratory rate and ethylene production rate**

1-MCP has different effects on the ethylene production rate of different grape varieties. For example, 1-MCP significantly inhibits the ethylene production rate of ‘Hanxiangmi’ seedless grapes, but has no effect on ‘Thompson Seedless’ grapes.\textsuperscript{[5,7]} Previously showed that the combination of 1-MCP and SO\textsubscript{2} could significantly inhibit the respiration rate and ethylene production rate in Red Globe and Munake grapes.\textsuperscript{[1,6,25]} The respiration rate and ethylene production rate of Niagara grapes during shelf life after cold storage were significantly higher than that during cold storage, and increased during cold storage, while increased first and then decreased at 6 d of shelf life after cold storage (Figure 2). Our results show that the combination of 1-MCP and SO\textsubscript{2} significantly suppressed the respiration rate and ethylene production rate of Niagara grapes during postharvest storage (\(P < .05\)), this may be consistent with the effect of other grape varieties.
Textural characteristics

The decrease of firmness and softening of grapes berry affects the eating quality during postharvest storage.\(^1\)\(^,\)\(^2\)\(^,\)\(^3\)\(^,\)\(^6\)\(^,\)\(^7\)\(^,\)\(^8\)\(^,\)\(^9\)\(^,\)\(^11\)\(^,\)\(^23\) Previously showed that 1-MCP, SO\(_2\), MAP alone or in combination significantly inhibits the decline in firmness of grapes berry.\(^1\)\(^,\)\(^6\)\(^,\)\(^8\)\(^,\)\(^11\)\(^,\)\(^23\) Our results found that the gumminess, chewiness, adhesiveness, and firmness in the pericarp and flesh of Niagara grapes gradually decreased during postharvest storage. The combination of 1-MCP and SO\(_2\) significantly inhibited the decrease of gumminess, chewiness and adhesiveness (\(P < .05\)) (Figure 3A, C, D and Supplement Fig. S2A and B), consistent with our previous results.\(^1\)\(^,\)\(^6\)\(^,\)\(^7\) The springiness of Niagara grapes increased first and then decreased during postharvest storage and was effectively maintained by the combined treatment of 1-MCP and SO\(_2\) (Figure 3B). However, the cohesiveness and resilience of Niagara grapes decreased first and then increased during cold storage and shelf life after cold storage, but the effect of 1-MCP combined with SO\(_2\) treatment was not significant (\(P > .05\)) (Supplement Fig. S2C and S2D). These results showed that the textural characteristics of Niagara grapes showed various trends during postharvest storage, and the effects of treatment were also different.

Nutrients

TSS and reducing sugar content of Niagara grapes decreased significantly during cold storage, which is consistent with our previous results.\(^1\)\(^,\)\(^2\)\(^,\)\(^3\)\(^,\)\(^9\)\(^,\)\(^23\) We also found that TSS increased first and then decreased during shelf life after cold storage (Figure 4A and C). The content of ascorbic acid content increased continuously during cold storage and increased first at the 6 d of shelf life after early cold storage and then decreased (Figure 4B), this change may be due to immaturity at harvest and continued synthesis during postharvest storage. The contents of titratable acids and total polyphenols content increased at first and then decreased during cold storage and shelf life after cold storage (Figure 4D and E). The content of glutathione decreased first and then increased during cold storage, while it decreased continuously during shelf life after cold storage (Figure 4F). Previous reports showed 1-MCP and SO\(_2\) alone or in combination can effectively maintain the higher content of soluble solids, reducing sugar and titratable acid in table grapes.\(^6\)\(^–\)\(^9\)\(^,\)\(^23\)\(^,\)\(^25\) Our results indicated that the combined treatment of 1-MCP and SO\(_2\) significantly inhibited the changes of TSS, reducing sugar, ascorbic acid, total polyphenols and glutathione contents of Niagara grapes during postharvest storage (\(P < .05\)) (Figure 4). These results suggest that the combination of 1-MCP and SO\(_2\) can effectively maintain the nutrients of crystal grapes during postharvest storage.

![Figure 2. Respiratory rate and ethylene production rate of Niagara grapes with or without 1-MCP combined with SO\(_2\) treatment during storage in the modified atmosphere.](https://example.com/figure2.png)
Antioxidant enzyme

Disease resistance decreases and the pathogens increase during postharvest storage, which promotes the disease occurrence of grapes. Preliminary study showed that SO₂ treatment enhances activity of PAL and PPO at the transcriptional and post transcriptional levels, and resists pathogen infection.²⁰–²² POD activity of Niagara grapes increased first and then decreased (Figure 5A). Previous reports showed that 1-MCP, SO₂ alone or combined suppressed the activities of POD and PPO.¹,⁶,⁷ Our results indicated that PPO activity of Niagara grapes decreased first and then increased during cold storage, while it increased first and then decreased during shelf life after cold storage (P < .05) (Figure 5B). Activities of POD and PPO were significantly inhibited by the combined treatment of 1-MCP and SO₂ during postharvest storage (P < .05).

Correlation analysis

Correlation analysis showed that the marketable berry rate of Niagara grapes decreased with the increase of rot rate, berry drop rate, browning rate, respiration rate, ethylene production rate and ascorbic acid content, and decreased with the decrease of reducing sugar and total phenol content during cold storage, indicating that the content of reducing sugar, total polyphenols and ascorbic acid content played an important role in berry drop, browning and rot of Niagara grapes. Texture parameters, including firmness in the pericarp and flesh, chewiness, gumminess and adhesiveness decreased with the decrease of reducing sugar content during cold storage (Figure 6A). Rot and browning were the main factors affecting the marketable berry rate. With the increase of respiration rate, the content of reducing sugar and total phenol decreased, and the chewiness, stickiness and adhesiveness of the fruit decreased, which promoted the increase of rot and berry drop rate during shelf life after cold storage (Figure 6B). The contents of reducing sugar and ascorbic acid showed a high correlation with physiological characteristics and texture parameters, indicating that reducing sugar and ascorbic acid contents may be important...
**Figure 4.** TSS, ascorbic acid, reducing sugar, total polyphenols, titratable acid and glutathione content of Niagara grapes with or without 1-MCP coupled with SO₂ treatment during storage in the modified atmosphere.

**Figure 5.** POD and PPO activity of Niagara grapes with or without 1-MCP coupled with SO₂ treatment during storage in the modified atmosphere.
indicators affecting quality and texture changes. These results showed that the postharvest decay of Niagara grapes was the result of the joint action of internal and external factors. The combined treatment of 1-MCP and SO₂ affected the changes of various indexes of Niagara grapes and maintained its quality.

**Conclusion**

The combined treatment of 1-MCP and SO₂ inhibited the respiration rate and ethylene production rate of Niagara grapes, delayed the decrease of TSS, reducing sugar, total polyphenols and glutathione content, maintained the gumminess, springiness, chewiness and adhesiveness, inhibited the increase of...
ascorbic acid content and activity of POD and PPO, inhibited the increase of berry drop rate and browning rate, and thus inhibited its rot and maintained a marketable fruit rate. Therefore, the combined treatment of 1-MCP and SO₂ can effectively maintain the quality of Niagara grapes during cold storage and during shelf life after cold storage under a modified atmosphere and prolong its storage life.

**Disclosure statement**

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