Sulfur dioxide gasification and generators combined with controlled atmosphere on postharvest quality of 'Blue Ribbon' blueberries

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Abstract

Chile is the second-largest supplier of fresh blueberries in the Southern Hemisphere. Our blueberries are exported to distant markets such as North America, Europe, and Asia, and maintaining high quality standards is a significant challenge. This study evaluated the postharvest quality of the 'Blue Ribbon' cultivar treated with different technologies simulating cool shipping conditions. The fruits were treated with sulfur dioxide (SO_2) gasification at harvest, followed by cooling and packaging in perforated bags with SO_2 generators. The boxes were stored for 35 days at 0°C in cold storage chambers, under either normal air or controlled atmosphere (CA) of 6% O_2 and 14% CO_2. After storage, fruits were held for 2 days at 5°C and 2 days at 10°C to simulate commercial conditions. Evaluations included weight loss, firmness, total soluble solids (TSS), and titratable acidity (TA). The CA treatments resulted in weight loss of less than 1.5% and fruit appearance below 5% dehydration. Additionally, under CA conditions, firmness values were higher than 228 gf mm^{-1} (150 gf mm^{-1}: minimum export standard). The combination of gasification and CA completely inhibited decay in the fruits. Under these treatments, TSS values were slightly lower, reaching 11.3%, while acidity remained stable compared to the initial evaluation. In conclusion, the combination of SO_2 gasification and a controlled atmosphere of 6% O_2 and 14% CO_2 proved effective in maintaining 'Blue Ribbon' blueberries in optimal quality conditions after prolonged storage.

Keywords: controlled atmosphere, SO_2, refrigerated transport, decay, berries

INTRODUCTION

Blueberries are considered non-climacteric fruits with a relatively low respiration rate compared to other climacteric fruits, which contributes to their extended postharvest shelf life under proper storage conditions. Blueberries are sensitive to temperatures below -1°C, which can cause physical damage such as watery spots, internal browning, and soft texture. Their quality is defined by factors such as color, firmness, sweetness, and acidity balance, among others. Although there are several commercial cultivars with different postharvest behaviors, they all face similar challenges, such as susceptibility to decay and loss of firmness (Yahia et al., 2017). Despite their growing popularity, postharvest preservation remains a crucial challenge to ensure that blueberries reach distant markets in optimal condition. To avoid or reduce the incidence of these defects and disorders, strategies must be employed to prolong their storage period and preserve their quality characteristics that make them attractive to consumers. To achieve this purpose, the main tool used in postharvest is cold storage. The optimal storage temperature for blueberries is 0°C and a relative humidity of 90-95%, which allows minimizing dehydration and maintaining fruit quality during transport and storage (Gross et al., 2016). In addition, other complementary technologies to delay *Botrytis cinerea* growth in blueberry is sulfur dioxide (SO_2), which minimizes the prevalence of this fungus during storage and transportation (Kumar et al., 2018). Controlled atmosphere

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(CA) has been shown to be effective in controlling metabolic activity and reducing pathogen development, ensuring higher quality during storage and transport. Adjusting O_2 and CO_2 levels helps to reduce dehydration, respiration rate and prevent the incidence of rots at optimal temperature. Concentrations of about 10-15% CO_2 + 1-10% O_2 at or below 5°C are beneficial for the preservation of blueberries, maintaining firmness and total acidity, and decreasing decay, with a shelf life of up to 6 weeks.

Given this context, it is important to evaluate the effects of integrating sulfur dioxide (SO_2) fumigation, SO_2-generating pads, and controlled atmosphere storage on the quality attributes and postharvest life of 'Blue Ribbon' blueberries. The combined use of these technologies may contribute to maintaining fruit quality and minimizing postharvest losses during 35 days of refrigerated storage.

MATERIALS AND METHODS

Raw materials and experimental location

Thirty-nine kilograms of 'Blue Ribbon' export-quality blueberries harvested and selected in Los Angeles (Chile) were used. The fruits were cooled by forced air and packed in 1.5 kg boxes with 12 clamshells of 125 g, arranged inside a perforated bag of 0.9% ventilated area, for a total of 26 boxes for the experiment. Fruit was then transported to the Center for Postharvest Studies (CEPOC) at the Faculty of Agronomic Sciences of the University of Chile, to carry out treatments and evaluations.

Treatments

At the start of the experiment, 19.5 kg of fruit were subjected to sulfur dioxide (SO_2) gasification in a chamber at a target dose of 180 ppm·h, whereas the remaining fruit served as untreated controls. Subsequently, all fruits were packed in boxes and pre-cooled. Two boxes, one subjected to SO_2 gasification and one untreated, were evaluated at the beginning of storage to characterize the fruit. Subsequently, 24 boxes were prepared to establish the eight treatments, with three replicate boxes per treatment. Half of the boxes were subjected to SO_2 gasification. SO_2-generating pads were placed inside the bags containing the clamshells in six boxes, regardless of whether the fruit had previously been treated with SO_2 gasification.

All boxes were stored at 0°C. Twelve boxes were maintained under regular atmosphere conditions, whereas the remaining 12 were stored in sealed cabinets to create controlled atmosphere conditions (Happy Volt, Santiago, Chile) with 6% O_2 and 14% CO_2 (Table 1). The storage period consisted of 35 days at 0°C to simulate shipment from the production area to a distant market, followed by 2 days at 5°C and 2 days at 10°C to simulate the marketing period (35 + 4 days).

Table 1. Treatments applied on blueberries in this trial. Studied factors: SO_2 gasification, SO_2 generators, and atmospheres (levels: with/without).

Code	Gasification SO_2	Generadores SO_2	Atmosphere	N° of boxes
Sga+Sge+Sac	without (S)	without	without	3
Sga+ Sge+Cac	without	without	with	3
Sga+Cge+Sac	without	with	without	3
Sga+Cge+Cac	without	with	with	3
Cga+Sge+Sac	with (C)	without	without	3
Cga+Sge+Cac	with	without	with	3
Cga+Cge+Sac	with	with	without	3
Cga+Cge+Cac	with	with	with	3

Sga: without SO_2 gasification, Cga: with SO_2 gasification, Sge: without SO_2 generator, Cge: with SO_2 generator, Sac: without controlled atmosphere, Cac: with controlled atmosphere.

Assessments

1. Weight loss.

Samples were weighed with an electronic balance (Ohaus, SC 6010, New Jersey, United States), considering 6 clamshells replicate^{-1} for each treatment, at the beginning and after 35 + 4 days. Weight loss was calculated as the quotient of the difference in weight between the final and initial weight of the clamshell. The results were expressed as percentage weight loss.

2. Decay.

A random sample of 100 fruits was taken per replicate to evaluate decay and/or presence of mycelium both in the initial evaluation, as well as after 35 + 4 days. Results were expressed as a percentage of fruit with rots.

3. Firmness with Baxlo.

Firmness was measured with a Baxlo durometer (Baxlo S.L., Barcelona, Spain) on 20 fruits replicate^{-1} on both equatorial sides with a 2.38 mm penetration cylinder, at a pulp temperature of 15±1°C. Subsequently, the average between both values expressed in shore units (°Ush) was calculated. This evaluation was carried out at the beginning of storage and after 35 + 4 days.

4. Firmness with FirmPro.

Firmness was measured with the FirmPro instrument (Happy volt, Santiago, Chile), using a compression plate (P/75 probe). This measurement considers the maximum force necessary to compress the berry 1 mm, at a speed of 1 mm s^{-1}. It was performed on 20 fruits replicate^{-1} at the beginning and after 35 + 4 days, at a pulp temperature of 15±1°C. The results were expressed in gf mm^{-1}, where higher values indicated greater fruit firmness.

5. Total soluble solids (TSS).

It was determined from three juice subsamples filtered from 6 fruits replicate^{-1}, using a compensated temperature digital refractometer (ATC -1E 0-32%, Atago, Japan). TSS were analyzed at the beginning and after 35 + 4 days of storage. The results were expressed as TSS percentage.

6. Titratable acidity (TA).

An aliquot of the extract used for TSS was used for this measurement. TA was measured in a solution with 5 mL of juice in 150 mL of distilled water, to which 0.1 N NaOH was added until a pH of 8.2-8.3. TA was analyzed at the beginning and after 35 + 4 days of storage. The results were expressed as a percentage of TA.

7. Statistical analysis.

The trial design was completely randomized with a 2×2×2 factorial structure. The factors corresponded to gasification, generator, and controlled atmosphere, all with 2 levels (with/without). The data were analyzed using InfoStat statistical software, and significant differences observed in the interaction or the factors independently were performed by a Fisher LSD test ($p \leq 0.05$).

RESULTS AND DISCUSSION

No significant differences in weight loss were observed among the individual treatments. However, significant effects were detected for the atmosphere and SO_2 generator factors when analyzed independently. For the atmosphere factor, fruit stored under regular air conditions (Sac) exhibited the greatest weight loss, reaching 2.34% after 35 days at 0°C and 2.74% after the complete storage and marketing period (35 + 4 days). In contrast, fruit stored under controlled atmosphere conditions showed the lowest weight loss, with values of 1.16% after 35 days at 0°C and 1.49% after 35 + 4 days.

For the SO_2 generator factor, after 2 days at 5°C, fruit stored with SO_2-generating pads

(Sge) exhibited greater weight loss (0.15%) than fruit stored without generators (Cge), which showed a weight loss of 0.11% (Table 2).

Table 2. Percent weight losses in 'Blue Ribbon' after 35 + 4 days, as a function of the gasification, generator, and atmosphere factors analyzed independently.

Factors	35d 0°C	2d 5°C	2d 10°C	35+4d
Gasification (Ga)				
Sga	1.90±1.00	0.13±0.06	0.26±0.46	2.24±1.08
Cga	1.70±0.70	0.12±0.10	0.22±0.39	2.01±0.87
Significance	ns	ns	ns	ns
Generator (Ge)				
Sge	1.75±0.86	0.15±0.10a	0.28±0.41	2.17±0.96
Cge	1.77±0.79	0.11±0.05b	0.21±0.44	2.07±0.92
Significance	ns	*	ns	ns
Atmosphere (Ac)				
Sac	2.34±0.70a	0.11±0.05b	0.29±0.59	2.74±0.89a
Cac	1.16±0.40b	0.15±0.10a	0.19±0.12	1.49±0.45b
Significance	*	*	ns	*

Sga: without SO_2 gasification, Cga: with SO_2 gasification, Sge: without SO_2 generator, Cge: with SO_2 generator, Sac: without controlled atmosphere, Cac: with controlled atmosphere.

Different vertical letters indicate significant differences according to Fisher's LSD test (p-value <0.05). ns: not significant. Data are mean ± standard deviation.

Previous studies have reported reduced weight loss in blueberries stored under controlled atmosphere conditions compared with regular air storage. In the present study, the lower weight loss observed under controlled atmosphere may be attributed to the static gas environment within the sealed cabinets, which likely reduced moisture loss relative to the ventilated bags stored in conventional cold rooms. Similarly, Duarte et al. (2009) reported lower weight loss in blueberries stored at 0°C under 5% O_2 and 15% CO_2 compared with fruit stored in air.

The isolated effect of the SO_2-generating pads observed after 2 days at 5°C is less clear. Since fruit in both treatments were packed in perforated bags, additional studies are needed to better understand the interactions between bag ventilation characteristics and SO_2 generator performance.

No decay was observed at the beginning of storage. After 35 + 4 days, an interaction was found between gasification and atmosphere. The treatments Sga + Sca presented the highest percentages of decay, with 12.7% incidence, while the treatments Cga + Ca did not show any decay, and Sga + Ca resulted in 0.5% (Table 3). This highlights the positive effect of CA (15% CO_2) decreasing rots postharvest. Despite this, the use of SO_2-generating pads alone also contributed to reducing decay incidence, maintaining values below 1.5% compared with treatments that did not include generators. These findings are consistent with previous reports demonstrating the effectiveness of SO_2 generators in controlling postharvest decay in blueberries (Rodríguez Beraud et al., 2015). Overall, the results indicate that SO_2 gasification and controlled atmosphere storage, both individually and in combination, are highly effective strategies for reducing or virtually eliminating postharvest decay.

At the beginning of storage, the Sga treatment presented significantly higher firmness (83 °Ush) compared to Cga (80 °Ush), all being higher than the reference value considered as minimum for export in Chile (70 °Ush). After 35 + 4 days, significant differences were found among treatments. The highest values were observed in Sga + Cge + Cac (93 °Ush) and Sga + Sge + Cac (91 °Ush), respectively, and the lowest in Cga + Cge + Cac (84 °Ush) and Sga + Sge + Sac (86 °Ush), respectively (Table 4). In general, after 35 + 4 days, values were higher than at the beginning of storage.

Table 3. Decay incidence in 'Blue Ribbon' under different treatments, as a function of the gasification and atmosphere factors (35+4d).

Factors	Decay (%)
Gasification (Ga)	
Sga	6.6±6.5
Cga	0.8±0.7
Significance	ns
Atmosphere (Ac)	
Sac	7.1±5.9
Cac	0.3±0.5
Significance	ns
Ga × Ac	
Sga + Sac	12.7±1.8a
Cga + Sac	1.5±1.1b
Sga + Cac	0.5±0.4c
Cga + Cac	0.0±0.0c
Significance	*

[a]Sga: without SO_2 gasification, Cga: with SO_2 gasification, Sac: without controlled atmosphere, Cac: with controlled atmosphere.

Different vertical letters indicate significant differences among treatments, according to Fisher's LSD test (p-value <0.05). ns: not significant. Data are mean ± standard deviation.

Table 4. Firmness by Baxlo in 'Blue Ribbon' among the different treatments after 35 + 4 days.

Treatments	Firmness (°Ush)
Sga+Sge+Sac	86±6d
Sga+ Sge+Cac	91±5ab
Sga+Cge+Sac	88±7c
Sga+Cge+Cac	93±5a
Cga+Sge+Sac	90±5bc
Cga+Sge+Cac	90±7b
Cga+Cge+Sac	90±7b
Cga+Cge+Cac	84±6d
Significance	*

Sga: without SO_2 gasification, Cga: with SO_2 gasification, Sge: without SO_2 generator, Cge: with SO_2 generator, Sac: without controlled atmosphere, Cac: with controlled atmosphere.

Different vertical letters indicate significant differences, according to Fisher's LSD test (p-value <0.05). Data are mean ± standard deviation.

At the beginning of storage, firmness measured with FirmPro showed no significant differences between the Sga and Cga treatments, presenting an average value of 209 gf mm^{-1}. After 35 + 4 days, there was a significant interaction between SO_2 gasification and atmosphere factors. The highest value was obtained in Sga + Cac (233 gf mm^{-1}), and the lowest in Sga + Sac (195 gf m^{-1}) and Cga + Sac (202 gf mm^{-1}) (Table 5). After 35 + 4 days, CA showed higher firmness than at the beginning of storage, and all reached values above the minimum limit for export (150 gf mm^{-1}). These results clearly show the positive effect of the controlled atmosphere in maintaining the firmness of blueberries, as occurred in other studies (Falagán et al., 2020).

At the beginning of storage, total soluble solids (TSS) were similar between SO_2-gassed and non-gassed fruit, ranging from 12.6 to 12.9%. After the storage and marketing period (35 + 4 days), a significant interaction was observed between the gasification and atmosphere factors. The highest TSS values were recorded in Cga + Sac (12.1%), Sga + Cac (12.0%), and

Sga + Sac (11.8%), whereas the lowest value was found in Cga + Cac (11.3%).

A significant interaction was also detected between the SO_2 generator and atmosphere factors. The highest TSS value was observed in the Sge + Sac treatment (12.3%), while the remaining treatment combinations showed TSS values ranging from 11.6 to 11.7% (Table 6).

Table 5. Firmness measured with FirmPro (gf mm^{-1}) in 'Blue Ribbon' as a function of the gasification and atmosphere factors after 35 + 4 days.

Factors	Firmness (gf mm^{-1})
Gasification (Ga)	
Sga	214±46
Cga	212±42
Significance	ns
Atmosphere (Ac)	
Sac	198±38
Cac	228±45
Significance	ns
Ga × Ac	
Sga + Sac	195±38c
Cga + Sac	202±37c
Sga + Cac	233±45a
Cga + Cac	221±45b
Significance	*

Sga: without SO_2 gasification, Cga: with SO_2 gasification, Sac: without controlled atmosphere, Cac: with controlled atmosphere.

Different vertical letters indicate significant differences among treatments, according to Fisher's LSD test (p-value <0.05). ns: not significant. Data are mean ± standard deviation.

Table 6. Total soluble solids (TSS) in 'Blue Ribbon' according to the interaction between gasification and atmosphere (Ga × Ac), and generators and atmosphere (Ge × Ac) factors after 35 + 4 days.

Factors	TSS (%)
Ga × Ac	
Sga × Sac	11.8±0.7a
Cga × Sac	12.1±0.4a
Sga × Cac	12.0±0.3a
Cga × Cac	11.3±0.4b
Significance	*
Ge × Ac	
Sge × Sac	12.3±0.4a
Cge × Sac	11.6±0.3b
Sge × Cac	11.6±0.6b
Cge × Cac	11.7±0.8b
Significance	*

*Sga: without SO_2 gasification, Cga: with SO_2 gasification, Sge: without SO_2 generator, Cge: with SO_2 generator, Sac: without controlled atmosphere, Cac: with controlled atmosphere.

Different vertical letters represent significant differences within each interaction according to Fisher's LSD test (p-value <0.05). Data are mean ± standard deviation.

Titratable acidity (TA) did not differ significantly at the beginning of storage, averaging 0.6%. After 35 + 4 days, significant differences were detected among treatments, with the highest TA value observed in Cga + Sge + Sac (0.7%) and the lowest in Cga + Cge + Sac (0.5%)

(Table 7). However, no consistent trend or clear effect attributable to any of the postharvest treatments evaluated in this study was evident for either TSS or TA.

Table 7. Titratable acidity (TA) in 'Blue Ribbon after 35 + 4 days.

Treatments	TA (%)
Sga+Sge+Sac	0.61±0.02bc
Sga+ Sge+Cac	0.57±0.03cd
Sga+Cge+Sac	0.64±0.02abc
Sga+Cge+Cac	0.64±0.00abc
Cga+Sge+Sac	0.72±0.07a
Cga+Sge+Cac	0.61±0.09bc
Cga+Cge+Sac	0.52±0.08d
Cga+Cge+Cac	0.67±0.01abc
Significance	*

Sga: without SO_2 gasification, Cga: with SO_2 gasification, Sge: without SO_2 generator, Cge: with SO_2 generator, Sac: without controlled atmosphere, Cac: with controlled atmosphere.

Different vertical letters represent significant differences among treatments according to Fisher's LSD test (p-value <0.05). Data are mean±standard deviation.

CONCLUSIONS

The use of SO_2 gasification in combination with controlled atmosphere storage proved effective in reducing weight loss, preserving firmness, and minimizing decay in 'Blue Ribbon' blueberries. Overall, the results indicate that storage under 6% O_2 and 14% CO_2 can successfully maintain fruit quality and marketability for at least 35 days at 0°C, plus an additional marketing period.

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