Comparison of different cooling methods for extending shelf life of postharvest broccoli

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Abstract: This study aimed to investigate and compare the effects of vacuum cooling, cooling water and cold room methods on the shelf life of broccoli. The experiments were divided into four groups: vacuum cooling (A), ice-water cooling (B), cold room cooling (C) and control. The cooling rate and changes of weight loss, respiratory rate, chlorophyll, vitamin C, reducing sugar content and sensory properties were measured at intervals of five days. The results indicated that vacuum cooling was the most effective method for extending the shelf life of postharvest broccoli in terms of cooling rate, respiration rate, chlorophyll, vitamin C, reducing sugar and sensory properties. Moreover, spraying the broccoli with water during the vacuum cooling process resulted in a significant reduction in weight compared with the other two cooling methods and did not reduce the quality of the broccoli. Consequently, vacuum cooling treatment can be applied to broccoli after harvest in the field to maintain quality during transportation and storage. Additionally, the application of water spraying during vacuum cooling can considerably reduce the negative influence caused by vacuum cooling.

Keywords: vacuum cooling, broccoli, shelf life, water spraying, postharvest

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1 Introduction

Broccoli is a very popular and healthy vegetable with high antioxidant contents. It is perishable, and floret yellowing is the main concern related to senescence[1]. The postharvest loss of fresh vegetables in China is as high as 25%-30% per year and is primarily caused by wilting, shriveling, decay, and mechanical injury, etc. Therefore, studies of postharvest physiological changes, postharvest senescence control, storage life extension and postharvest loss reduction in broccoli are highly important. To date, many techniques, such as refrigerated storage[2], modified atmosphere packaging[3,4], 1-methyleyclopropene[5,6], hot water[7,8], and irradiation[9], have been applied to broccoli for postharvest quality control.

The shelf life of fresh broccoli is suggested to be 2-3 days in 20°C air[10] but can be extended by refrigeration[6]. Hence rapid cooling of fresh broccoli is attractive to farmers and retailers because it is able to extend the shelf life and enhance the microbiological safety of the product,

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which may reduce production losses and result in additional economic benefits. In contrast to conventional cooling methods, such as cold rooms and water immersion cooling, vacuum cooling technology involves evaporating part of the moisture of the product under vacuum conditions and an exceptionally fast cooling rate[11,12]. Agricultural and food products containing free water can be cooled by subjecting them to a deep vacuum, which increases the efficiency of the moisture evaporation by reducing the pressure and decreasing the temperature at which water boils[13]. Vacuum cooling technology has been successfully used to cool vegetables since the 1950s[14,15] and is currently used as an effective cooling treatment to remove field heat and thus extend the shelf-life and improve the quality of many types of vegetables, including lettuce[16], mushrooms[17], spinach[18], green peppers[19], cucumbers[20] and Chinese cabbage[21].

However, vacuum cooling technology also has disadvantages when applied to fruits and vegetables due to its functional principles[22]. Vacuum-cooled products exhibit undesirable weight loss because considerably more moisture is evaporated in vacuum chambers compared with other conventional cooling methods[23]. This weight loss is the main defect of vacuum cooling technology because it can lead to increased economic losses when widely applied during the postharvest process. Zhang and Sun[24] attempted to use a water-spraying method during the vacuum cooling of cooked broccoli and carrot slices and achieved 2.2% and 7.5% reductions in weight loss, respectively, compared with normal vacuum cooling treatments. To date, there are few published reports on the effects of vacuum cooling treatments on the postharvest characteristics of broccoli. Therefore, this study aimed to develop a vacuum-cooler coupled with water-spraying system to reduce the water loss from postharvest broccoli. Meanwhile, it also investigated the effects of vacuum cooling on the quality parameters of broccoli during storage after harvest compared with other conventional cooling methods, such as the application of cold rooms and water immersion cooling.

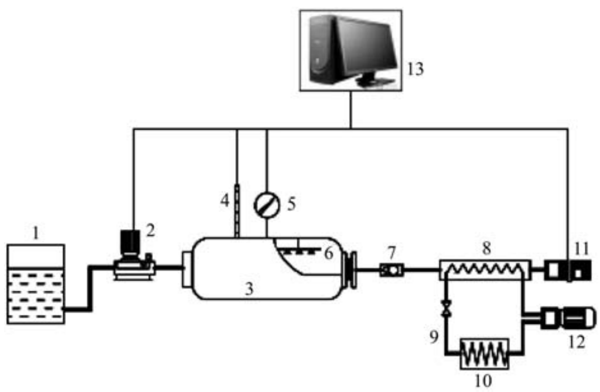
2 Materials and methods

2.1 Sample preparation

Fresh broccoli samples of similar size were harvested from a local farm in Hangzhou, Zhejiang Province, China. Broccoli that had been damaged by mechanical factors, disease or insects was discarded. Prior to the experiments, the temperatures of the selected samples were equilibrated to room temperature.

2.2 Cooling treatments

Vacuum cooling treatment (Group A) was implemented with a self-developed vacuum cooler. A schematic diagram is presented in Figure 1. A water-spraying unit was connected to a water pipe and vacuum chamber, and the pressure, temperature, and water flow velocity data were collected by sensors and transmitted to a computer. Relevant software was developed to form a central processing unit with the computer to analyze the data and automatically control the vacuum pump. Aside from vacuum cooling, two conventional cooling methods were investigated in terms of their effectiveness in extending the shelf life of fresh broccoli. Ice-water cooling treatment (Group B) was implemented by immersing the broccoli samples into a water bath filled with an ice-water mixture. Cold room cooling (Group C) was carried out using a refrigerator with an average temperature of 0°C-3°C. Prior to storage at (5±1)°C for the shelf life test, the broccoli samples from the different treatments were cooled to approximately 5°C and then packaged with 0.025 mm polyethylene bags, whereas the untreated samples were used as controls.



Note: 1. Water tank 2. Water pump 3. Vacuum chamber 4. Thermometer 5. Piezometer 6. Water sprayer 7. Check valve 8. Steam condenser 9. Throttle valve 10. Condenser 11. Vacuum pump 12. Compressor 13. Computer

Figure 1 Schematic diagram of the self-developed vacuum cooler

2.3 Weight loss

An electronic scale (JA 2003, Shanghai, China) was used to weigh the samples with a precision of ±0.1 g. Weight loss is expressed as a percentage of the initial weight (Equation (1)).

$$\text{Weight loss} = \frac{W - W_i}{W} \times 100\% \qquad (1)$$

where, W is the initial weight of the broccoli sample, g; W_i is the weight of the sample at the time of testing, g.

2.4 Respiratory rate

The tested broccoli samples were placed in a drier, and a Petri dish with a 0.4 mol/L NaOH solution was placed at the bottom to absorb the CO_2. After 1 h of sealed storage, the solution was transferred from the Petri dish to a triangular flask with 5 mL of $BaCl_2$ saturated solution and two drops of phenolphthalein indicator. Subsequently, oxalic acid was titrated into the solution in 0.1 mol/L drops until the red color disappeared. The method previously proposed by Wei et al.[25], with slight modifications, was used calculate the respiratory rate during the shelf life study.

2.5 Chlorophyll

Chlorophyll was extracted from 5 g broccoli samples by homogenization in 50 mL of 80% acetone using a high-speed tissue homogenizer (DS-1, Shanghai, China). The homogenate was filtered through four layers of cheesecloth and centrifuged at 10 000×g for 10 min, and the absorbance was then read at 645 nm and 663 nm utilizing a recording spectrophotometer (UV-2550, Shimadzu, Kyoto, Japan)[26]. Total chlorophyll content was calculated in mg/g using the Arnon formula[27]: 20.29 A_{663}+8.05 A_{645}.

2.6 Determination of Vitamin C

Vitamin C was determined with the 2,6-dichloroindophenol titrimetric method[28]. Homogenized broccoli samples (10 g) were mixed thoroughly with 20 g/L oxalic acid and were then transferred into a 100 mL volumetric flask. After measuring the volume and centrifuging at 1000×g for 20 min, 10 mL of the extracted solution was pipetted into a 50 mL triangular flask. Subsequently, standardized 2,6-dichloroindophenol solution was used for titration until the solution turned pink and the color did not fade within 15 s. Vitamin C (Vc) content was calculated by the following Equation 2:

$$X = \frac{(V - V_0) \times T}{W} \times 100 \qquad (2)$$

where, X is the Vc content in each 100 g sample, mg/100 g; T is the amount of ascorbic acid standard solution, mg/mL, equivalent to 1 mL of dye solution; V is the volume of the dye solution used to titrate the filtrate, mL; V_0 is the volume of the dye solution used to titrate the control, mL; W is the amount of the sample in the tested filtrate, g.

2.7 Reducing sugar

Broccoli samples (1 g) were completely ground with 5 mL of distilled water in a mortar. The homogenate was transferred into a 25 mL graduated test tube, and distilled water was added to reach 25 mL before the sample was placed in a thermostatic water bath at 80°C for 30 min. After cooling down, the sample was leached twice to obtain the reducing sugar extracting solution. Subsequently, 2 mL of extracting solution and 1.5 mL of 3,5-dinitrosalicylic acid solution were mixed in a 25 mL graduated test tube, and the optical density was tested at 540 nm. The method proposed by Chen[29], with slight modification, was applied to calculate the reducing sugar content.

2.8 Sensory studies

The sensory qualities of the broccoli samples (fresh, withering rate, rotting rate, etc.) were evaluated by panelists. A 5-point scoring method was applied in which five indicated excellent (green, no withering and rot), four indicated very good (less than 10% withering rate and no rot), three indicated good (less than 30% withering rate and slight rot), two indicated fair (less than 50% withering rate and obvious rot), and one indicated poor (more than 50% withering rate and serious rot). All samples were served in Petri dishes and were used for further chemical analysis. The sensory evaluations were performed on day 0 and repeated at 6-day intervals for up to 30 days of storage.

2.9 Statistical analysis

Each experiment involved three replications, and the mean values were used in the analyses. Data were analyzed using SPSS, v18.0 (Statistical Package for the

Social Sciences, Chicago, IL, USA). Tukey's tests were used to determine the significances of the differences at the level of 0.05.

3 Results and discussion

3.1 Cooling rate

Figure 2 illustrates the temperature variations of broccoli samples during different treatment periods according to the vacuum cooling (A), cooling water (B), and cold room (C) treatments. This figure illustrates that the temperature decrease rates of the three different cooling methods were significantly different and that the vacuum cooling method resulted in the lowest final broccoli temperature. Vacuum cooling has previously been proven to be a rapid cooling method. In contrast to conventional refrigeration methods, such as immersion in cool water and blowing of cold air, vacuum cooling directly evaporates the water from the product directly, which makes it faster and more efficient[30,31]. Ozturk and Ozturk[32] observed that vacuum cooling of iceberg lettuce is approximately 13 times faster than refrigerator cooling at 6°C. Our study supports this conclusion and demonstrated that vacuum cooling resulted in a broccoli temperature of 5.5°C after 30 min of treatment, whereas water cooling and the use of a cold room achieved temperatures of only 10.0°C and 11.8°C, respectively. Similar trends have been reported by Chen et al.[23] who examined asparagus cooling.

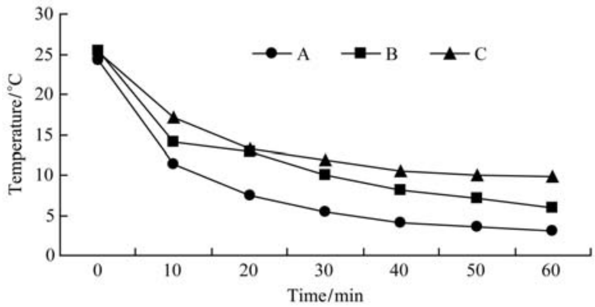


Figure 2 The temperature profiles of broccoli as a function of treatment time according to the vacuum cooling (A), cooling water (B), and cold room (C) treatments

3.2 Respiration rate

Broccoli is a floral vegetable with a high respiration rate after harvest. Controlling the respiration of broccoli is very important for delaying senescence as indicated by, for example, the softening and yellowing of the florets and leaves. Temperature is considered to be the factor with the greatest influence on the respiration rate of broccoli[33]. Therefore, it is necessary to remove field heat from postharvest broccoli, and vacuum cooling technology has been satisfactorily applied to horticultural products with high efficacy in the US[34]. As shown in Figure 3, the changes in the broccoli respiration rates during storage are graphically described according to the different cooling treatments and compared with the control. The respiration rate of the untreated broccoli samples reached 315.84 mg/(kg·h) within several hours, whereas Groups A, B, and C, i.e., showed significantly lower respiration rates of 227.36 mg/(kg·h), 254.65 mg/(kg·h), and 235.97 mg/(kg·h), respectively after different precooling treatments. During storage, the respiration rate of the vacuum cooled broccoli after was well controlled and significantly reduced compared with the other cooling methods within 24 days. This finding indicated that the vacuum cooling method more effectively decreased the respiration rate of broccoli after harvest.

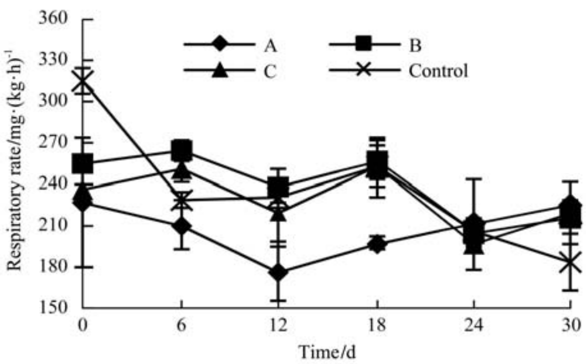


Figure 3 Respiration rates of broccolis stored in MAP following vacuum cooling (A), cooling water (B), and cold room (C) treatments. Broccoli without cooling treatment or MAP was used as a control

3.3 Weight loss

The average weight loss percentages of the broccolis with and without the different cooling treatments during storage are presented in Figure 4. This figure clearly demonstrates that the percentages of weight loss increased with storage duration. The control showed rapid and significant weight loss (p<0.05) compared with the other treatment groups in the modified atmosphere packaging (MAP). After 30 days of storage, a weight loss of 15.38% was observed in the control, whereas the weight losses in the other three groups were below 6%. There were no significant differences in the weight losses of the broccolis treated by vacuum cooling, cooling water and a cold room (p<0.05). Although vacuum cooling resulted in a weight loss of 1.47%, this was not much different than the losses caused by the cooling water (0.72%) and cold room treatments (1.27%), which may have been due to the water spraying. As Zhang and Sun[24] reported, some of the water that evaporated during the vacuum cooling process was derived from the surfaces of vegetables and supplied by water spraying, which decreased the evaporation of water in the void space and thereby reduced weight loss.

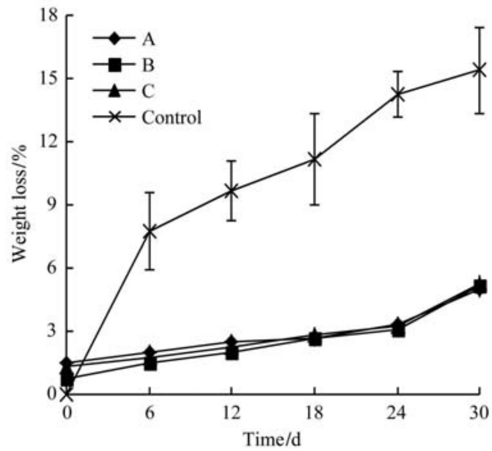


Figure 4 Weight losses of the broccolis stored in MAP after treatment with vacuum cooling (A), cooling water (B), and a cold room (C). Broccoli without cooling treatments or MAP was used as a control

3.4 Chlorophyll content

The degradation of chlorophyll is the main reason for the use of chlorine treatments and yellowing and can determine the shelf life of broccoli[35]. As shown in Figure 5, the chlorophyll contents decreased during storage, and the loss percentages in the control reached as much as 40.08%; ultimately, only 6.99 mg/100 g remained after 30 days. The cooling treatments and MAP significantly postponed the degradation of chlorophyll in broccoli. Specifically, vacuum cooling resulted in the maintenance of a chlorophyll content of 11.28 mg/100 g, which was significantly greater than those observed after the cooling water and cold room treatments. These findings indicated that vacuum cooling technology effectively reduced the loss of the chlorophyll contents of broccoli samples during storage.

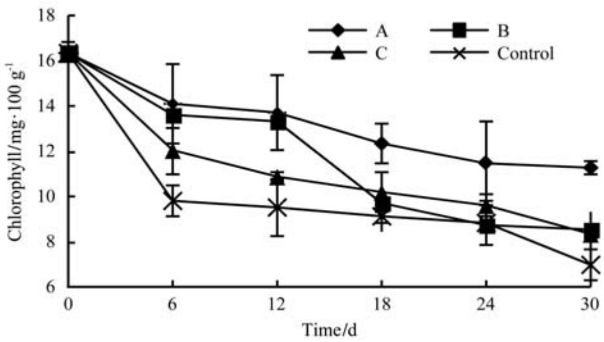


Figure 5 Chlorophyll contents of broccolis stored in MAP after vacuum cooling (A), cooling water (B), and cold room (C) treatments. Broccoli without cooling treatments or MAP was used as a control.

3.5 Vitamin C content

Broccoli is rich in vitamin C (Vc), which is an important antioxidant. Vc is a main nutritional constituent of broccoli and is also considered as a primary quality index of broccoli during storage. Figure 6 illustrates the decreases in Vc in the control and broccoli samples subjected to cooling treatments. After 30 days, the Vc content in the control was only 16.63 g/100 g, which equated to a reduction of 59.64%, whereas reductions of only 41.87%, 32.48% and 45.68% were observed in the vacuum cooling, cooling water, and cold room treatments, respectively. Although the final Vc content of the vacuum-cooled broccoli was lower than that of the cooling water-treated broccoli, vacuum cooling technology maintained a high level of Vc after 24 days of storage and more effectively inhibited Vc loss than the other two cooling methods.

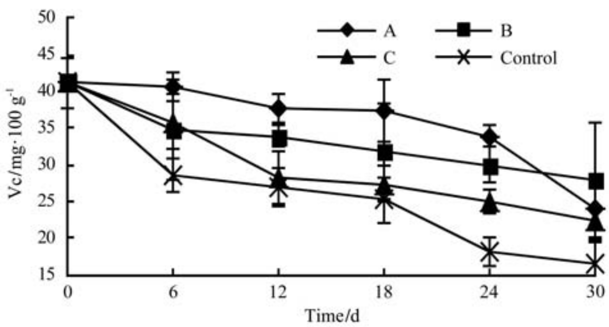


Figure 6 Vitamin C contents of the broccolis stored in MAP after vacuum cooling (A), cooling water (B), and cold room (C) treatments. Broccoli without cooling treatments or MAP was used as a control.

3.6 Reducing sugar content

Sugar is the essential energy source of vegetables and is also the main substrate for vegetable respiration. Therefore, reducing sugars are thought be closely related to the physiological and biochemical properties of vegetables. The reducing sugar contents of the control broccoli and the broccolis subjected to vacuum cooling, cooling water, and cold room treatments during the shelf life test are illustrated in Figure 7.

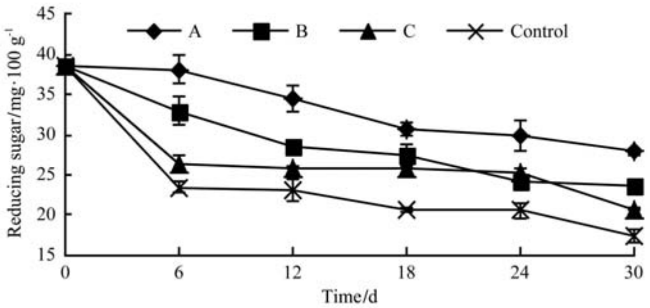


Figure 7 Reducing sugar contents of the broccolis stored in MAP after vacuum cooling (A), cooling water (B), and cold room (C) treatments. Broccoli without cooling treatments or MAP was used as a control

Vacuum cooling treatment prevented respiration and metabolism by promptly removing field heat from the broccoli after harvest. Therefore, the reducing sugar content of the vacuum cooled broccoli decreased slowly and was still 27.88 mg/100 g after 30 days. We observed sharp reductions in the reducing sugar contents of the cooling water and cold room treatment groups within the first 6 days that may have been due to slower cooling rates. Regarding the control, it exhibited the fastest rate of reducing sugar loss and a content of 17.41 mg/100 g after 30 days.

3.7 Sensory evaluation

Table 1 presents the effects of the different cooling methods on the sensory properties of broccoli during the shelf life test. After 30 days of storage, the qualities of the broccolis subjected to the cooling treatments were significantly better than those of the control. Specifically, the control broccoli became yellow and wilted and had no edible value after 24 days, which indicated that the cooling treatments helped to maintain the sensory qualities and extend the shelf life of broccoli during storage. Although there were no significant differences between the sensory properties of the samples subjected to the cooling methods, vacuum cooling treatment elicited the highest sensory scores throughout the shelf life test.

Within the same column, the values not followed by the same letter are significantly different (p<0.05).

Table 1 Effects of pre-cooling methods on the sensory qualities of broccoli

	Sensory score*					
	0 d	6 d	12 d	18 d	24 d	30 d
Vacuum cooling	5.00±0.00^{a}	4.91±0.03^{a}	4.78±0.22^{a}	4.14±0.14^{a}	3.70±0.26^{a}	2.8±0.42^{a}
Cooling water	5.00±0.00^{a}	4.70±0.22^{a}	4.64±0.19^{a}	3.85±0.42^{ab}	3.53±0.22^{a}	2.73±0.36^{a}
Cold room	5.00±0.00^{a}	4.70±0.23^{a}	4.58±0.20^{a}	3.81±0.10^{ab}	3.43±0.27^{a}	2.51±0.36^{a}
Control	5.00±0.00^{a}	4.66±0.09^{a}	4.26±0.13^{b}	3.56±0.21^{b}	2.84±0.12^{b}	1.95±0.15^{b}

4 Conclusions

In this study, the effects of vacuum cooling, cooling water, and cold room treatments broccoli quality during storage were investigated. We found that vacuum cooling technology greatly shortened cooling time. Examinations of the respiration rates, chlorophyll, vitamin C, and reducing sugar contents, and sensory properties of the broccoli over 30 days of storage revealed that vacuum cooling was the most effective method for maintaining the quality of postharvest broccoli during the shelf life tests. Additionally, our self-developed vacuum cooler with a water-spraying system was applied, and the water-spraying treatment considerably reduced weight loss. Based on our preliminary experiments, we found that many factors can influence broccoli weight loss during the vacuum cooling process, e.g., the magnitude of the applied vacuum, the weight of the treated broccoli samples, the amount of water sprayed, and the treatment time. Investigations of the influences of each of these factors on sample weight loss and treatment efficacy are strongly needed, and the optimal condition should be identified. Furthermore, the wide application of vacuum cooling technology in the postharvest area requires the development and improvement of a more convenient vacuum cooler with an intelligent water-spraying system.

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