Simulation approach for optimal design of vacuum cooling on broccoli by simulated annealing technique

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Abstract: Water-spraying is regarded as an effective method to reduce the weight loss of product during vacuum cooling process. This study aimed to investigate the effect of vacuum cooling factors on the weight loss of postharvest broccoli, and attempted to optimize the treatment conditions by simulated annealing (SA) technique. An algorithm based on simulated annealing meta-heuristic technique was developed to identify the optimum condition for vacuum cooling treatment of broccoli. Results demonstrated that the SA algorithm could adjust well with the simulation of the broccoli cooling process. The best condition was at 200 Pa of pressure, 274 g broccoli, 6% of water volume and 40 min processing time. Under this condition, a product with only 0.35% of weight loss and 1.48°C final temperature was obtained. The developed method may help to effectively control the weight loss during vacuum cooling process and reducing the economic loss.

Keywords: broccoli, vacuum cooling, simulated annealing, optimization
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1 Introduction

Broccoli is a kind of very popular and healthy vegetable which is rich in vitamin C, dietary fiber, and also multiple nutrients with potent anti-cancer properties. It has been reported that a high intake of broccoli can reduce the risk of aggressive prostate cancer and heart disease[1]. However, broccoli has a short shelf life after harvest with the main concern of yellowing, wilting, shriveling, and corruption. For example, China produced 8 585 000 tonnes of broccoli in 2008[2], while the postharvest loss reached nearly 25% to 30% causing great financial loss and waste of resources. Postharvest loss is a worldwide subject and many efforts have been attempted, such as the application of cooling treatments[3,4], surfactant[5], different packaging methods[6], irradiation[7], hot water[8] etc. Therein, vacuum cooling has been reported as a high-efficiency method to extend the shelf life and enhance microbiological safety[9]. It can rapidly remove the field heat from a postharvest product through evaporating the

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water directly from the product[10]. However, just because of this principle, it may result in additional weight loss during the vacuum cooling process[11].

Until now, the water-spraying method was found to effectively reduce the weight loss caused by vacuum cooling treatment. However, it is still unclear how much spraying water would be suitable to apply in vacuum cooling process to gain optimum results. Besides, preliminary studies indicated that many other factors such as the degree of vacuum, weight of treated broccoli samples, and treatment time can also influence the weight loss of products significantly.

Meta-heuristics techniques consist of powerful tools for solving complex optimization problems in which the search spaces are too large to find the optimal solutions using deterministic methods with acceptable processing time. These techniques use information about the problem to produce quick and good quality solutions. Among the meta-heuristics that have emerged over the last decades, we can find well known techniques such as Genetic Algorithms[12-16], Tabu Search and Simulated Annealing[17,18]. The latter technique was used in this work, since it is considered a promising alternative for solving optimization problems. Benvenga et al[19] conducted the simulation and drying process optimization of corn malt by simulated annealing (SA) for estimation of temperature and time parameters in order to preserve maximum amylase activity. Therefore, this study aimed to investigate the impact of each factor on the weight loss of postharvest broccoli and treatment efficacy, and also to determine the optimal condition for vacuum cooling treatment on postharvest broccoli by simulated annealing techniques.

2 Materials and methods

2.1 Sample preparation

Fresh broccoli samples were harvested from a local farm in Hangzhou, Zhejiang Province, China. Only samples without mechanical damage, plant disease or insect damage were selected. Prior to tests, 200 g, 350 g, and 500 g broccoli were weighed according to the experimental design.

2.2 Vacuum cooling treatments

The vacuum cooling treatment was implemented by a self-developed vacuum cooler with water-spraying unit connected with water pipe and the vacuum chamber. The water-spraying volume was controlled by a pump of this system. In this study, the pressure in the vacuum chamber (200, 400, and 600 Pa), water-spraying volumes (3%, 4%, and 6%), and processing time (20, 30, and 40 min) were applied for the purpose of investigating their synthetic effects on the weight loss of broccoli during the vacuum cooling processing.

2.3 Weight loss

Weight loss for vacuum cooling of broccoli was calculated using the following equation:

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

where, W is the initial weight of the broccoli sample, and W_i is the weight after the vacuum cooling treatment.

2.4 Procedure to apply simulated annealing

Simulated annealing (SA) technique reported by Pham and Pham[18] can be defined as a probabilistic version of the well known hill-climbing algorithm. The pseudocode applied in this study is shown in Figure 1. It consists of a meta-heuristic technique that imitates the annealing process of metals, in which the metal is heated to high temperatures and then systematically cooled in the same order to achieve an equilibrium characterized by an orderly and stable microstructure.

```
Procedure SA
Begin
    Let s0 the initial solution (randomly generated), s the solution represented by
    the current state, s' the solution represented by the successor of the current
    state, s* the best solution obtained until the moment, Iter the counter of
    iterations, Max_Iter the maximum number of iterations, ΔE the variation
    between s and s', P the probability of accepting worse solutions and Temp
    the temperature that controls the probability P.
    s ← s0
    s* ←s0
    Iter ← 1
    While (Iter ≤ Max_Iter) do
        Temp ← Max_Iter - Iter
        If Temp=0 then
            Return s*
        End if
        Generate successor s' {randomly}
        ΔE ← s'– s
        If ΔE > 0 then
            s ← s'
        Else
            P ← e^(-ΔE/Temp)
            s ← s' {only with certain probability P}
        End if
        If s > s* Then
            s* ← s
        End if
        Iter ← Iter + 1
    End while
End
```

Figure 1 Pseudocode of simulated annealing (SA)

In the SA algorithm, movements for states better than the current one is always accepted. If the movement is towards a worse state, whether it can be accepted depending on a probability, which is calculated by taking into account the quality of movement represented by ΔE that decreases according to the "temperature". Thus, in later iterations of the algorithm, only better solutions are accepted since the probability of accepting worse solutions is almost zero[17,18]. Because of the effect of inconsistencies caused during computations, it was necessary to normalize the variables ($x_i \in [-1, 1]$). This way, the variables including pressure, P (200-600 Pa), broccoli weight, W (200-500 g), water volume, V (2%-6%, v/v) and processing time, t (20-40 min) were coded and normalized.

In the problem considered in this work, SA technique was applied to determine the coefficients x_1, x_2, x_3 and x_4, with $x_i \in [-1, 1]$, assigned to loss of weight (W_{Loss}) and final temperature (T_{End}), that minimize the objective function (OF) described in Equation (3), representing a weighted composition of W_{Loss} and T_{End}. The objective functions of W_{Loss} and T_{End} had to be adjusted based on multiple regression as showed in Equation (2).

$$y = b_0 + \sum_{i=1}^{K} b_i x_i + \sum_{i=1}^{K} b_{ii} x_i^2 + \sum_{i=1} \sum_{j=i+1} b_{ij} x_i x_j \tag{2}$$

$$OF = \begin{cases} \dfrac{\alpha \cdot W_{Loss} + \beta \cdot T_{End}}{\alpha + \beta}, & \text{if } W_{Loss} \geq 0 \text{ and } T_{End} \geq 0 \\ \infty, & \text{other wise} \end{cases} \tag{3}$$

where, y is the response (W_{Loss} or T_{End}); b is the model parameter, and x_i are the coded variables (P, W, V and t) and α and β are weights associated to responses W_{Loss} and T_{End}, respectively.

2.5 Statistical analysis

Each experiment was conducted in duplicate and mean values ± standard errors (SD) were calculated for the analysis. Data were analyzed using SPSS v18.0 (Statistical Package for the Social Sciences, Chicago, IL, USA). Tukey's test was applied to determine the significance of difference (P = 0.05). The simulated annealing (SA) technique was implemented by software Matlab Release 2007®.

3 Results and discussion

Table 1 shows the weight loss of broccoli and its final temperature after vacuum cooling treatment with specific conditions of pressure, initial broccoli weight, water-spraying volume, and processing time. It was observed that weight loss of broccoli ranged from 0.21% to 2.16% and final temperature ranged from 1.10°C to 10.1°C. Obviously, the factors selected in this study could influence the performance of vacuum cooling. Compared with the previous studies, the weight loss of products in the current work was significantly lower due to the application of the water-spraying system. Similar findings were reported by Zhang and Sun[20] which indicated a 2.2% reduction in weight loss of cooked broccoli after vacuum cooling by use of the water-spraying method. This may be due to the evaporation of spray water on the surface of broccoli. However, it has some disadvantages. For instance, if too much evaporated water is derived from the spraying water, it may result in an unexpected final temperature and also unutilized superiority of the vacuum cooling. Hence, it is necessary to find the proper volume of spraying water with the consideration of other factors.

Table 1 Results of broccoli freezing process[a]

Assays	P/Pa	W/g	V/%, v/v	t/min	W_{Loss}/%, g/g	T_{End}/°C
1	200	200	3	20	2.12±0.057[e]	2.9±2.55[a]
2	200	350	4	30	1.23±0.007[cd]	5.8±1.13[abc]
3	200	500	6	40	0.55±0.085[ab]	4.6±0.99[ab]
4	400	200	4	40	1.80±0.219[e]	4.5±1.06[ab]
5	400	350	6	20	0.29±0.106[a]	8.5±0.00[bc]
6	400	500	3	30	0.57±0.134[ab]	9.0±0.85[c]
7	600	200	6	30	1.62±0.255[de]	7.9±0.57[bc]
8	600	350	3	40	1.08±0.092[bc]	8.1±0.28[bc]
9	600	500	4	20	0.26±0.050[a]	9.9±0.21[c]

Note: [a] P = pressure, W = broccoli weight, V = water-spraying volume, t = processing time.

An inverse relationship between weight loss and final temperature was observed as shown in Table 1, which caused difficulty in optimizing this process. Table 2 and 3 present the variance analysis for the model as a function of weight loss and final temperature, with 95% of confidence level. The calculated F1 is smaller than the tabulated F1 which indicates that the model is statistically significant, and the calculated F_2 is smaller than the tabulated F_2 indicating that the model fits the data well. Thus it can be seen that the models are adjusted and can be used to predict the vacuum cooling process of the broccoli.

Equations (4) and (5) present the fitting functions to the experimental data of weight loss (W_{Loss}) and final temperature (T_{End}), respectively with the obtained correlation coefficients (R) of 0.9760 and 0.9459. It indicated that the models had good statistical fit with the experimental data and were qualified to be used in the OF function (Equation (3)) to the minimization multiple of the W_{Loss} and T_{End} values.

$$T_{End} = 8.7500 + 2.1083x_1 + 2.0830x_2 + 0.8667x_3 - 0.7750x_1^2 - 1.0000x_2^2 - 1.1500x_4^2 + 2.1000x_1x_2x_3x_4 \quad (4)$$

$$T_{End} = 8.7500 + 2.1083x_1 + 2.0830x_2 + 0.8667x_3 - 0.7750x_1^2 - 1.0000x_2^2 - 1.1500x_4^2 + 2.1000x_1x_2x_3x_4 \quad (5)$$

Figure 2 shows the simulated annealing performance to obtain the optimum condition of the vacuum cooling process. From this illustration, the state s is represented by four pairs of real values representing x_1, x_2, x_3 and x_4 of Equations (3) and (4). In addition, we adopted the value 130 000 for Max_Iter, since in the experiments there was no change in the best solution from iteration 125 000 as shown in Figure 2. At the end of iterations a low value of error was observed[17,18] which demonstrated a good adjustment of simulate annealing algorithm used to simulate the vacuum cooling process of broccoli, on the condition adopted in this work.

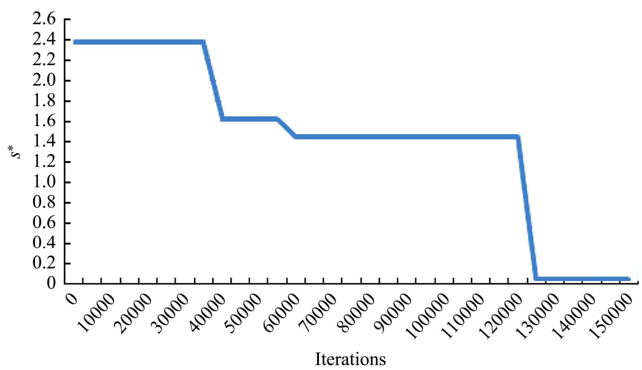

Figure 2 Evolution of best solution (s^*) found by SA during the iterations

The weights α and β were varied between 1.0000 and 10.000, and the x_1, x_2, x_3 and x_4 were varied between -1.0000 and 1.0000 which caused ten thousands iterations for each weight combinations. In all, the iterations exceed hundreds of billions. This proved that the SA had a high power to seek the optimal conditions within a large set of possible chances, as observed by Benvenga et al[19] in the corn malt drying process. Figure 3 shows a small part of all iteration performed by SA algorithm proposed in this work. It can be noted that the reduction in the FO values carried out to an optimum condition of two responses (weight loss and final temperature). The best condition found within the range that allowed the process was obtained at the pressure of 200 Pa, broccoli weight of 274 g, water-spraying volume of 6% and processing time of 40 min. In this case, weight loss of 0.35% and final temperature of 1.48°C were obtained after the vacuum cooling treatment of postharvest broccoli.

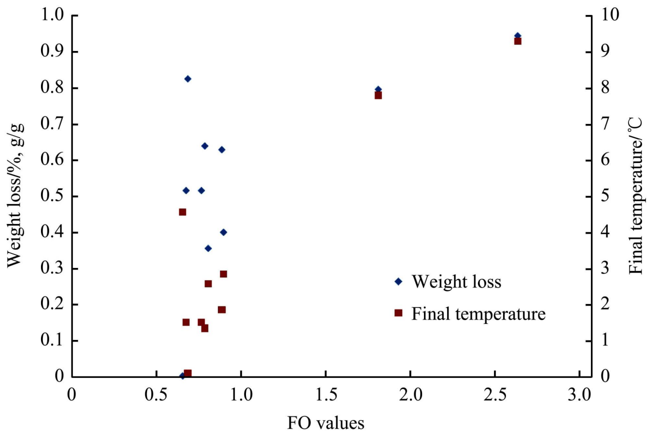

Figure 3 Behavior of responses with FO variation

4 Conclusions

In conclusion, it was found that the pressure in the vacuum chamber, product weight, water-spraying volume and processing time could affect the weight loss and final temperature of the product when vacuum cooling technique was applied. Especially, the water-spraying method was able to effectively reduce the product's weight loss and it has been proved to be a supplementary mean to minimize the drawback of vacuum cooling technique. However, the amount of spraying water should be controlled since it may have adverse effect on the final temperature of the treated product. Compared to common optimization methods, simulated annealing technique runs with high efficacy and is less constrained by the initial conditions. Therefore, SA technique is considered as a very promising tool for the use in food process optimization due to its power of search spaces for optimal solutions, with good accuracy and low computational processing time. Based on the results of this study, the optimized conditions could be applied in the vacuum cooling process of postharvest broccolis to reduce weight loss, and the SA technique has the potential to be used in other process optimization studies in the future.

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[References]

[1] Kirsh V A, Peters U, Mayne S T, Subar A F, Chatterjee N, Johnson C C, Hayes R B. Prospective study of fruit and vegetable intake and risk of prostate cancer. Journal of the National Cancer Institute, 2007; 99: 1200–1209.

[2] Food and Agricultural Organization of United Nations: Economic and Social Department: The Statistical Division. 2008. Available at http://faostat.fao.org/site/567/Desktop Default.aspx?PageID=567#ancor. Accessed on [2012-05-06].

[3] Li Z G, Gao X. The effects of storage temperatures on the qualities of broccoli. China Vegetables, 2000; 4: 6-9.

[4] Zhang Z H, Sun D W. Effect of cooling methods on the cooling efficiencies and qualities of cooked broccoli and carrot slices. Journal of Food Engineering, 2006; 77: 320–326.

[5] Fan X T, Mattheis J P. Yellowing of broccoli in storage is reduced by 1-Methylcyclopropene. Hort Science, 2000; 35: 885–887.

[6] DeEll J R, Toivenen P M A, Vigneault C. Postharvest dips to control black speck and scar discoloration in stored broccoli. Journal of Food Quality, 2001; 24: 575-584.

[7] Zhuang R F, Hu W Y, Lin G R, Cai L X. Effects of irradiation on preservation and physiological-biochemical index of brassica oleracea. Subtropical Plant Science, 2002; 31: 16–18.

[8] Tian M S. Color, ethylene production, respiration and compositional changes in broccoli dipped in hot water. Journal of the American Society for Horticultural Science, 1997; 122: 112–116.

[9] Sun D W, Zheng L Y. Vacuum cooling technology for the agri-food industry: Past, present and future. Journal of Food Engineering, 2006; 77: 203–214.

[10] Brosnan T, Sun D W. Precooling techniques and applications for horticultural products- a review. International Journal of Refrigeration, 2001; 24: 154–170.

[11] Haas E, Gur G. Factors affecting the cooling rate of lettuce in vacuum cooling installations. International Journal of Refrigeration, 1987; 10: 82–86.

[12] Chaves A A, Biajoli F L, Mine O M, Souza M J F. Hybrid metaheuristics for solving the prize collecting traveling salesman problem. Produção, 2007; 17: 263–272.

[13] Curvelo Santana J C, Araújo S A, Librantz A F H, Tambourgi E B. Optimization of corn drying by use of a genetic algorithm. Dry Technology, 2010; 28: 1236-1244.

[14] Goldberg D E. Genetic algorithms in search, optimization, and machine learning. Massachusetts: Addison-Wesley Pub, 1989.

[15] Thyagarajan T, Shanmugamm J, Ponnavaikko M, Panda R C. Hybrid intelligent control scheme for air heating system using fuzzy logic and genetic algorithm. Dry Technology, 2000; 18: 165–184.

[16] Zhang C, Lu Y. The improved ant colony algorithm based on immunity system genetic algorithm and application. In: IEEE International Conference Cognitive Informatics, 2006; 2: 726–731.

[17] Kirkpatrick S, Gelatt C D, Vecchi M P. Optimization by simulated annealing. Science, 1983; 220: 671–680.

[18] Pham D T, Pham P T N. Artificial intelligence in engineering. International Journal of Machine Tools & Manufacture, 1999; 39: 937–949.

[19] Benvenga M A C, Araújo S A, Librantz A F H, Santana J C C, Tambourgi E B. Application of simulated annealing in simulation and optimization of drying process of Zea mays malt. Engineering Agriculture, 2011; 31: 940–954.

[20] Zhang Z H, Sun D W. Effect of cooling methods on the cooling efficiencies and qualities of cooked broccoli and carrot slices. Journal of Food Engineering, 2006; 77: 320–326.