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Combination of optimization techniques to find of processing optimal condition of postharvest broccoli by vacuum cooling process

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ABSTRACT. This study aimed to investigate the impact of each factor on the weight loss of postharvest broccoli and treatment efficacy, and also attempted to fix the optimal condition for vacuum cooling treatment on postharvest broccoli by response surface methodology combined with tabu search techniques. Fresh broccoli samples were harvested from a Chinese farm and the green heads of selected samples were cut into smaller ones with approximately 3~4 cm diameter, and sequentially equilibrated to room temperature. Pressure (200-600 Pa), broccoli weight (200-500 g), water volume (2-6 %, v v^{-1}) and time (20-40 min) were used as factors and weight loss, final temperature and cost as responses. A tabu search algorithm was developed to find the optimum condition for processing broccoli and its initial condition were from response surface methodology. Results demonstrates a good adjust of tabu search algorithm in simulation of the broccoli freezing process. From tabu list the best condition were found as follows: the broccoli weight between 273.5 and 278.0 g with a water volume of 3.0%, processed for 40.0 min and at 200 Pa, where the weight loss was 0.34 ± 0.01%, of end temperature was 2.0 ± 0.0°C and profit percent was 99.66 ± 0.01%.

Keywords: *Brassica oleracea* var; experimental design; tabu search; food preservation; the best condition.

Combinação de técnicas de otimização para encontrar a condição ótima para processar os brócolis por resfriamento à vácuo

RESUMO. Este trabalho objetivou estudar os impactos de cada fator sobre a perda de peso dos brócolis empacotados usando o sistema de resfriamento a vácuo por meio de uma otimização por análise de superfície de resposta (RSM) combinada com a busca tabu. As amostras de brócolis foram coletadas em fazendas chinesas e suas cabeças foram cortadas entre 3-4 cm de diâmetro e armazenadas em temperatura ambiente até o início do processo. Para a otimização foram utilizados, como fatores, a pressão (200-600 Pa), a massa (200-500 g), a umidade inicial (2-4%) e o tempo de processamento (20-40 min) dos brócolis e, como respostas, foram consideradas a perda de peso, a temperatura final das amostras de brócolis e o custo do processo. A partir dos dados experimentais, foram obtidas as superfícies de respostas baseadas na metodologia RSM, as quais geraram as condições iniciais de busca para o algoritmo de busca tabu. As melhores condições encontradas na lista tabu foram: 273,5 e 278,0 g de massa de brócolis, com um volume de água igual a 3%, processando a amostra por 40,0 min a uma pressão de 200 Pa. Sob estas condições, a perda de massa dos brócolis foi de 0,34 ± 0,01%, com uma temperatura final de 2,0 ± 0,0°C e uma porcentagem de lucro de 99,66 ± 0,01%.

Palavras chave: *Brassica oleracea* var.; planejamento de experimentos; busca tabu; conservação de alimentos; condição ótima.

Introduction

Vacuum cooling process in food preservation

Broccoli (*Brassica oleracea* var.) is rich in carbohydrates (4.4%), proteins (2.1%), saturated fats (0.1%), polyunsaturated fats (0.2%) and dietary fiber (3.4%). In addition, it contains vitamin C and riboflavin B2 and thiamin B1 and minerals important for human nutrition such as calcium, phosphorus, manganese, magnesium, lipids, iron, potassium, copper, zinc and sodium, which makes it a very appreciated food and indicated for the maintenance of human health (Ding et al., 2014; Hubbard et al., 2017). The main producers of broccoli in the world are China and India with 9.1 and 7.9 millions of ton per year, respectively; together they produce over 75% of world production of broccoli (Kirsh et al., 2007). However, like any vegetable, it undergoes enzyme action and insults during its processing and transportation, causing many losses before reaching the shelf (Ding et al., 2014).

The cool storage and the modified atmosphere packaging can be pointed out among the techniques used to delay the senescence and to promote the shelf life extension of food. One of the most recent techniques of the food preservation is the vacuum cooling (Carvalho & Clemente, 2004). The vacuum cooling is obtained through the very heat removal product by evaporation of water from its surface and pores connected to it (McDonald, Sun, & Kenny, 2000). The water evaporation is performed with the decrease of inner pressure of a chamber where the product is packaged. This technique is often used for cooling leafy vegetables such as lettuce, mushrooms and flowers after harvest.

Until now, water-spraying method can reduce the weight loss caused by vacuum cooling treatment. However, it was still unclear how many spraying water is suitable to apply in vacuum cooling process. Besides, preliminary studies indicated that many other factors such as vacuum degree, weight of treated broccoli samples, and treatment time can also influence the weight loss of products significantly (Alibas & Koksal, 2014).

The vacuum cooling technique was applied to other types of vegetables like cauliflower, peppers, sweetcorn, onions, carrots (Alibas & Koksal, 2014). Fruits such as strawberry, gooseberry and melon, and vegetables such as cabbage, turnips, eggplant and cucumber, have also been objects of study for the application of vacuum cooling (McDonald et al., 2000).

Use of tabu search in process optimization

Tabu search is a metaheuristic search method employing local search methods used for mathematical optimization. Tabu search enhances the performance of local search by relaxing its basic rule. First, at each step 'worsening' moves can be accepted if no improving move is available (like when the search is stuck at a strict local minimum). In addition, 'prohibitions' (henceforth the term 'tabu') are introduced to discourage the search from coming back to previously-visited solutions. The implementation of tabu search uses memory structures that describe the visited solutions or user-provided sets of rules (Glover, 1989).

Since when it was developed by Glover (1989), the tabu search is widely used in logistics problems, with restrictions mainly on vehicle routing, as cited in the work of Chaves, Biajoli, Mine, and Souza (2007), Ma, Hao, and Wang (2017) and Silvestrin and Ritt (2017). However, because to its easy use, the tabu search has been applied in several fields, such as in the modeling of chemical reactions and polymerization of molecules in the area of chemistry (Anand, Rao, & Venkateswarlu, 2015; Nandi, McAnanama-Brereton, Waller, & Anoop, 2017), in obtaining of PID controller and Mimo systems in telecommunications (Ateş & Yeroglu, 2016; Karthikeyan & Saraswady, 2018), in the control of data flow in the computer science (Michalska, Zufferey, & Mattavelli, 2016), in product development and design in the industrial engineering (Bożejko, Gnatowski, Pempera, & Wodecki, 2017; Soto, Rosarius, Rieger, Chen, & Adey, 2017), in nuclear power management (Hill & Parks, 2015) and in the control of cash flow in the economic area (He, He, Liu, & Wang, 2017).

Recent works have not been found that have used tabu search in the optimization of food processes and engineering. However, several metaheuristic techniques have been applied in these fields of scientific knowledge. Among the metaheuristics we can mention the traveling salesman, the ant colony, general algebraic modeling system (Gams), the tabu search, the search tree, simulated annealing, genetic algorithm among others (Chaves et al., 2007; Benvenga, Librantz, Santana, & Tambourgi, 2016).

In general, metaheuristic techniques need to be combined with some modeling technique in order for their performance to be improved. As the work presented by Almeida et al. (2014) and Santana et al. (2018) which used simulated annealing and response surface methodology in standardization and optimization of the a wine production. Benvenga et al. (2016) have been combined the response surface methodology with genetic algorithm to study of the economic viability of alcohol production from Cassava root.

Therefore, this study aimed to investigate the impact of each factor on the weight loss of postharvest broccoli and treatment efficacy, and also attempted to fix the optimal condition for vacuum cooling treatment on postharvest broccoli by response surface methodology combined with tabu search techniques.

Material and methods

Sample preparation

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

Vacuum cooling treatments

The vacuum cooling treatment was implemented by a self-developed vacuum cooler with water-spraying unit connected with the water pipe and vacuum chamber. The water-spraying volume can be controlled by this system. In this study, the pressure in 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 (Alibas & Koksal, 2014). The weight was calculed by Equation 1.

$$W_{Loss} = 100 * \left(\frac{W_{initial} - W_{end}}{W_{initial}} \right) \tag{1}$$

Each experiment was conducted in duplicate and mean values ± standard errors (SD) were calculated for the analysis. Data were analyzed using Statistical Package for the Social Sciences, SPSS v18.0 of according to da Silva Padilha, Curvelo-Santana, Alegre & Tambourgi (2009) and de Almeida, Araújo & Santana (2012). Tukey's test was applied to determine the significance of difference (P = 0.05) .

Procedure for response surface metodology

An experimental design was used for the organization of the assays of this experiment. After the execution of the experiments (in duplicate), the Minimum Square Methodology was applied on experimental data to obtain the model, based in Equation 2. The fitting model was evaluated by variance analysis (ANOVA) (Benvenga et al., 2016; Ferreira, Santana, & Tambourgi, 2011). For both, the Statistica software 6.0 package was used, which was also responsible for generating the response surfaces. Factors were: pressure, P ($\boldsymbol{x_1}$), broccoli weight, W (x_2) water volume, V (x_3) and processing time, t (x_4), and two responses, the loss of weight (y_1), W_{Loss}, and final temperature (y_2), T_{End}. 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 pressure, P (200-600 Pa), broccoli weight, W (200-500 g), water volume, V (2-6%, v v^{-1}) and processing time, t (20-40 min) were coded and normalized as shows in Equation 3:

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

$$\begin{aligned} x_1 &= \frac{P_j - 400}{200} \\ x_2 &= \frac{W_j - 350}{150} \\ x_3 &= \frac{V_j - 4.5}{1.5} \\ x_4 &= \frac{t_j - 30}{10} \end{aligned} \tag{3}$$

where:
y is the response (W_{Loss} or T_{End}).

The evaluation of the empiric models was performed by variance analysis (ANOVA) and optimization by response surface methodology (RSM) in the program Statistics for Windows 6.0. The experimental design used to obtain the optimal condition for broccoli processing by vacuum cooler is shown in Table 1. All methodology are showed in Benvenga et al. (2016) and Ferreira et al. (2011).

Procedure to apply tabu search

On fitting model, the response surface methodology was applied to obtain the optimal areas on while the tabu search algorithm makes a hardness examination to reach the optimal condition. These areas will compose of ranges of pressure, weight, volume and time. Local condition will varied by tabu search until to obtain optimal conditions which the weight loss must be about zero and; end temperature between zero and two (0 and 2°C) because of it is the conventional range used in vacuum cooling process to increase the high shelf life of vegetables.

Table 1. Experimental design and results of this experiment.

Assay	Pressure (Pa)	Weight (g)	Water volume (%)	Time (min)	Weight loss (%)	Weight loss (%)	End temperature (°C)	End temperature (°C)
1	200	200	3.0	20	1.99	2.16	4.7	1.1
2	200	350	4.0	30	1.20	1.23	6.6	5.0
3	200	500	6.0	40	0.72	0.49	3.9	5.3
4	400	200	3.0	20	1.33	1.95	3.7	5.2
5	400	350	4.0	30	0.21	0.36	8.5	8.5
6	400	500	6.0	40	0.66	0.47	8.4	9.6
7	600	200	3.0	20	1.44	1.80	7.5	8.3
8	600	350	4.0	30	1.01	1.14	7.9	8.3
9	600	500	6.0	40	0.29	0.22	9.8	10.1

At optimal RSM areas, the tabu search algorithm will varied the processing pressure of 2.00 to 2.00 Pa, the sample weight of broccoli of 1.50 to 1.50 g, the processing time of 0.100 to 0.100 min, and the water volume of 0.150 to 0.150%, all variation of accordance to operational limit of equipment used. However, this would make in a search area of $1.6.10^9$ iterations, which increases the computation time. Thus, the response surface analysis method was applied firstly, to find initial conditions for tabu search and thus reduce the search time to find the best condition.

In this problem, the last square methodology 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 function, OF, of W_{Loss} and T_{End} had to be adjusted based on multiple regression as showed in Equation 2.

According to Carvalho and Clemente (2004) is usual in the vacuum cooling process that the end temperature is between 0 and 2°C and according to Alibas and Koksal (2014) the weight loss and time process should be minimal to reduce costs.

From the response surface analysis to determine the initial condition of starting the algorithm; which sought the minimum value to the W_{Loss} using the tabu conditions of T_{end} between 0 to 2°C and the OF should not exceed the value of 3.00 (Equation 4).

$$OF = \begin{cases} W_{Loss} + \cdot T_{End} \text{ , if } W_{Loss} \geq 0.00 \text{ and } 0.0 < T_{End} < 2.0 \\ 0.00 < OF < 3.00 \end{cases} \quad (4)$$

In Chine, the common price for broccoli is 4.0 US\$ kg^{-1} and for kW $hour^{-1}$ is 8 cents. These values were used to calculate of total profit of according to Equation 5, according to Alibas and Kuksal (2014). It is written as a percentage of the maximum value of profit (US\$ 4.00), in which the term inside the parenthesis is equivalent to the average energy consumption per unit time (0.006 kW $hour^{-1}$ min^{-1}) multiplied by its cost (8 cents kW^{-1} $hour^{-1}$) expressed as a percentage of total profit.

$$Profit(\%) = (100 - W_{Loss}) - 100 * \left(\frac{4.8.10^{-4} * t(\min)}{4.00} \right) \quad (5)$$

Simulation was performed in a Software Matlab Release 2007® installed on an Intel CPU (Pentium Dual Core 2 Duo Intel with 1.86 GHz). To solve the problem of freezing process optimization of broccoli, we have configured the tabu list array equal to TL = [x_1, x_2, x_3, x_4, W_{loss}, T_{end}, Profit, Error] and the tabu search was configured as follows (Hill & Parks, 2015):

Step #1: Choose x to start the process.

Step #2: Find a neighbor x' of x such that the solution of x' is better than the solution of x.

Step #3: If no such x' can be found, x is the local optimum and the method stops.

Step #4: Otherwise, designate x' to be the new x and go to Step #2.

As a way to stop the algorithm assumed the square error of 10^{-4}, assuming the calculation only for weight loss, due to be the most important parameter, since it also influences the economic viability of the process. Square error was calculated according to Equation 6.

$$Error = (y_{1(i)} - y_{1(i+1)})^2 \quad (6)$$

where:

$y_{1(i)}$ *and* $y_{1(i+1)}$ are the weight loss calculated previously and currently.

Results and discussions

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 0.26 to 2.12% and final temperature ranged from 2.9 and 9.9°C. Obviously, the factors selected in this study could influence the performance of vacuum cooling. Compared with the previous studies showed in Ding et al. (2014), the weight loss of products in the current work was significantly lower due to the application of water-spraying system. It can be observed that an inverse behavior of weight loss with respect to final temperature is presented. It caused very difficult to optimize this process and a high range of possibility may be accepted as optimal conditions. Therefore, Tabu Search (TS) technique was employed to conduct the optimization in this study.

Equation 7 and 8 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 were considered to have good statistical fit with the experimental data and they were qualified to be used in the OF function (Equation 4) to the minimization multiple of the W_{Loss} and T_{End} values.

Figure 1 and 2 show the surfaces of responses obtained from Equation 7 and 8 to perform the optimization of vacuum cooler process of broccoli, obtained by combining two by two factors with each response. From a detailed analysis of the figures was possible to mount the following Table 2.

This table makes a summary of the combined effects of factors presented in each response surface to demonstrate how to arrive at the optimum condition via RSM methodology. Such as example: when we combine the Figure 1a, b and c, it can see that all reach the lower end temperatures when using the lower pressure values. However, when looking at Figure 2a and b, it notes that the pressure may be anywhere between -1 and +1 to achieve the lowest weight loss, but from Figure 2c only the extreme values (-1 or +1) is that reaches the low weight loss. This text is a translation of what is reported for the factor x_1 (pressure) in the table, which was extracted from the cited figures and similar analyzes were made to other factors.

From Table 2, it is observed that it can be extracted with certainty the best condition for the temperature (x_1) and water volume (x_3) only, as to be a best condition, the value must be repeated for all combinations of factors in both responses. The bold values are those who repeated that met for the x_1 and x_3 and both had an indication of best condition when they are in their lowest values (-1). After RSM applying the initial condition have been found, which are as follows: P (x_1) and V (x_3) set at 200 Pa and to 3.0%; other factors have been varied, which are as follows: for W steps were 1.50 and 1.50 g, total 201 steps and t steps were 0.100 and 0.100 min, also totaling 201 steps, which totaled a search area of 4.10^5 iterations.

Table 2. Summary of the combination effect of the factors.

Analyzed Response	Factor	Combination effect			
		x_1	x_2	x_3	x_4
End temperature	x_1		-1	-1	-1
Weight loss			-1 to +1	-1 to +1	-1 or +1
End temperature	x_2	-1		-1	-1
Weight loss		0 to +1		0 to +1	0 to +1
End temperature	x_3	-1	-1		-1 or +1
Weight loss		-1 or +1	-1 to +1		-1 to +1
End temperature	x_4	-1 to +1	-1 to +1	0 to -1	
Weight loss		+1 to -1	-1 to +1	+1 to -1	

Figure 3 shows the variation of error to iteration values; which allows us to analyze the performance of tabu search algorithm used in this work. There is a high drop error until 3,000 iterations, is accentuating after that and only from 10,000 iterations was the error of weight loss fell to 10^{-4}, converging to the optimum condition. The total search space is 4.10^4, and then we can be said that the best condition has achieved in only 25% of the total estimated time for searches. If considering the total search space including the portion removed from RSM optimization, the total space is $1.6.10^9$ iterations. From this, we estimate that the best condition was achieved in only $6.1.10^{-4}$% of the total estimated time for searches, ie, the contribution of RSM methodology was of great value to the reduction of processing time used in tabu search.

Figure 4 shows the behaviour of objective fuction (OF) during the iteration performed by tabu search algorithm. As shows, this curve is similar to the behavior expected for the sum of the functions representing the weight loss to the end temperature, represented by Equation 7 and 8, respectively. Moreover, its value in great condition did not waver beyond 2.5 points, such as expected.

Figure 5 shows the variation of the weight loss, the end temperature and profits. This figure shows the tabu list update with the best results during the iterations performed. As noted, from 3,000 iterations temperature had a high growth rate and linear with the Iterations, however, the weight loss showed shows a linear and sharp decrease to the first 3,000 iterations and after that a linear and decreasing behavior with the iterations. The profit had an inverted behavior weight loss, what was expected, because it is a dependent function on the inverse of weight loss.

From tabu list met the following condition as the optimum process conditions the following values: 200.0 Pa of pressure, between 273.5 and 278.0 g for the broccoli weight, 3.0% of water volume and between 39.9 and 40.0 min for processing time, where the 10^{-4} error of weight loss values not exceeded to the best condition. In this list, the average values of weight loss was 0.34 ± 0.01%, of end temperature was 2.0 ± 0.0°C and of profit was 99.66 ± 0.01%.

According to McDonald et al. (2000) this is due to the packaging at low weights to leave the broccoli in thin layers, and in these cases, the surface is more exposed to facilitating mass transfer. This corroborates the results obtained in this work, because when we use the lower weight broccoli also got the less weight loss.

$$W_{Loss} = 0.9619 - 0.2756x_1 - 0.9195x_2 + 0.2786x_1^2 + 0.4936x_2^2 - 0.6914x_4^2 - 0.7725x_1 \cdot x_3 + 0.5807x_1 \cdot x_2 \cdot x_3 \cdot x_4 \quad (7)$$

$$T_{End} = 8.9690 + 2.0083 \cdot x_1 + 1.8834 \cdot x_2 + 0.7714 \cdot x_3 - 0.8750 \cdot x_1^2 - 1.1000 \cdot x_2^2 - 1.2500 \cdot x_4^2 + 1.8000 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \quad (8)$$

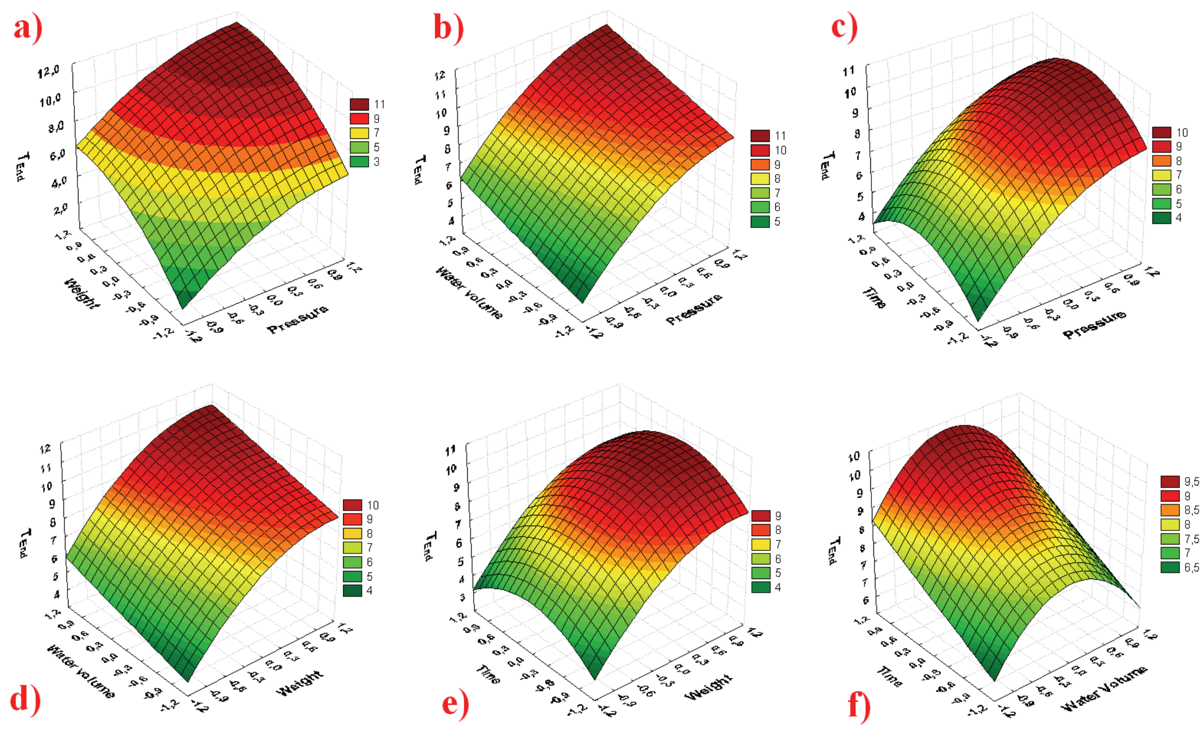

Figure 1. Response surfaces to evaluate the effects of factors on the end temperature of broccoli.

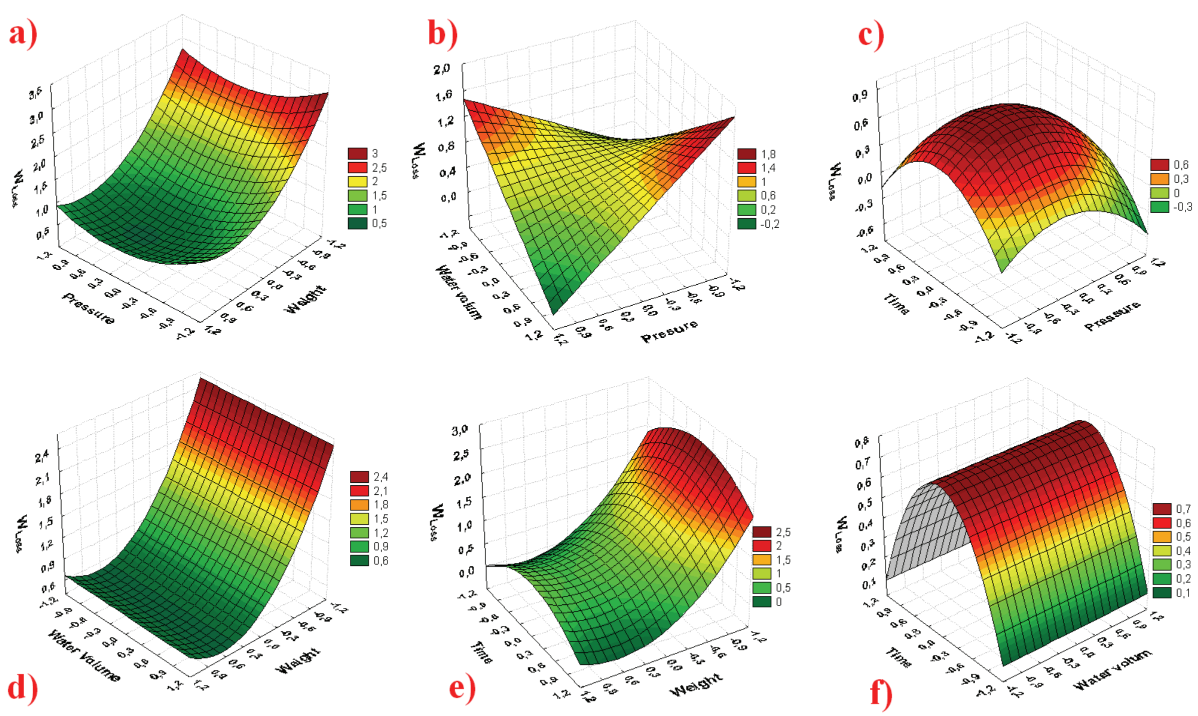

Figure 2. Response surfaces to evaluate the effects of factors on the weight loss of broccoli.

Carvalho and Clemente (2004) using a range of 240 to 360 g broccoli in a vacuum cooling process, they observed that the best conditions to retain vitamin C, have low weight loss, low peroxidase activity and low turbidity were those that used smaller masses of broccoli.

In this study, the time below 40 min showed a high final temperature, although smaller loss of weight, indicating that 40 min of contact time was sufficient to transfer heat in the cooling process without water weight loss occur the product. Of according to most of the study, the vegetable processing by vacuum cooling occurs for hours. Such as processing of cauliflower that lasted between 1 and 3 hours (Alibas & Koksal, 2014). In contrast, Deng, Song, and Li (2011) have observed similar results where rapid vacuum cooling of steamed stuffed bun for 15 min led to a weight loss of 6-8% and the end temperature was close to 7°C.

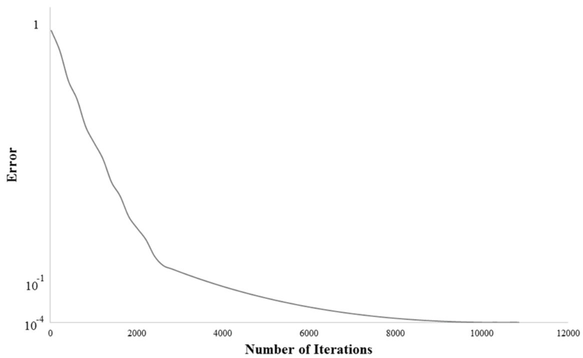

Figure 3. Error behavior with the variation of the best results found by the tabu search algorithm.

Figure 4. Variation of objective fuction (OF) with the best results found by the tabu search algorithm.

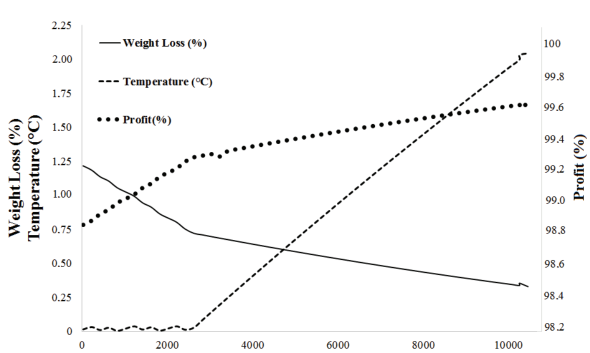

Figure 5. Varying of functions with the change of the best results found by the tabu search algorithm.

Figure 6 shows the search for the optimum condition made by the tabu search algorithm, when the beginning the search process by x_2 instead of x_4 using the same starting point from RSM. It shows that this new choice of starting point reduced to less than 50 iterations is same as $3.1.10^{-6}$% of total search area, which proves that tabu search is very depending on the point chosen for the start of the search. By observing the change generated in choosing the starting point shown in Figure 5, it is proven that the response surface methodology helps a lot in choosing the best starting point for the tabu search algorithm, even when choosing the beginning of the search was not ideal. Thus, it is highly desirable to use a simple method to reduce search time, computer time, processing time and computational costs, as shown by other authors (Benvenga et al., 2016).

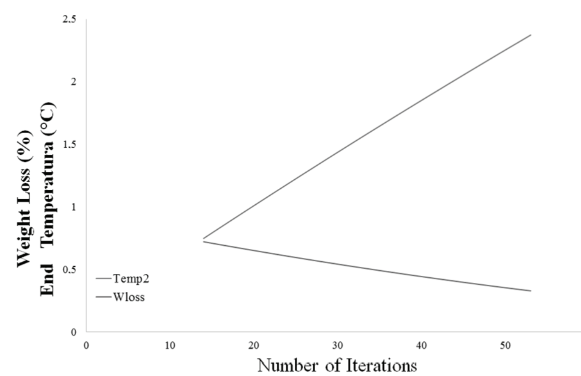

Figure 6. Varying the amount of iterations with changing initial variable used in tabu search.

Conclusion

This work proved that the amount of iterations made by tabu search suffer a large reduction when applying the response surface analysis methodology to provide begging conditions for the tabu search algorithm. The results suggested an optimal combined condition as follows: the broccoli weight between 273.5 and 278.0 g with a water volume of 3.0%, processed for 40.0 min and at 200 Pa, where the weight loss was 0.34 ± 0.01%, of end temperature was 2.0 ± 0.0°C and of percent of profit was 99.66 ± 0.01%.

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