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PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Optimization of process variables for drying of cashew nuts by superheated steam

Rashid Eang¹ and Nakorn Tippayawong^{1*}

Abstract: Cashew is an important economic crop in international market. Thermal processing of cashew nut is essentially an optimization problem. In this work, influence of drying of cashew kernels with testa using superheated steam on product color change and process energy consumption was simultaneously investigated and optimized using response surface methodology. Three independent process variables: temperature (120–140°C), velocity (1–3 m/s), and drying duration (5–30 min) were considered. Box–Behnken design of experiments was employed to obtain the optimum process conditions. It was shown that the second-order polynomials were adequate for the regression model. The coefficient of determination (R^2) for the color difference and energy consumption were found to be 0.964 and 0.864, respectively. The color difference and energy consumption were also observed to be a linear function of steam temperature, velocity, and drying duration. For superposition of maximum yield of kernel and other quality indices, optimum thermal processing condition of superheated steam drying was found at 30 min of drying duration, 4 m/s velocity and 115°C temperature of steam.

Subjects: Food Engineering; Industrial Engineering & Manufacturing; Heat Transfer

Keywords: agro-products; superheated steam; response surface methodology; food processing; postharvest technology

1. Introduction

Cashew (*Anacardium occidentale* L.) is one of the major economic crops in international market and extensively recognized as nutritious food product. It is widely distributed throughout the

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PUBLIC INTEREST STATEMENT

World production of cashew nut in 2000 was estimated at 2,000,000 tons of nuts in shell, with an overall estimated value exceeding 2 billion USD. Most of them contain large amount of initial moisture content and highly susceptible to rapid quality deterioration, or worse in the extent of spoilage, unless kept in thermally controlled storage facilities. Drying is a common process adopted to add value to cashew nut production. However, large amount of energy is a particular need in mechanization of thermal processing and conversion processes. Regarding effective drying technique for the commercial exploitation, there remains a need for emerging technologies that can be proven to combat escalating energy costs, stringent emissions standards and consumer demand for better product quality.

World tropical regions (Bart-Plange, Addo, Kumi, & Piegu, 2012). Cashew nut contains fat, proteins, and vitamins. Its thin reddish-brown skin between the inner lining and the outer shell known as testa holds a source of hydrolysable tannins with catechin and epicatechin as the major polyphenols (Jacob & Burri, 1996; Jekayinfa & Bamgboye, 2006). Cashew nut shell has high energy content which is an excellent feed stock for gasification (Tippayawong, Chaichana, Promwangkwa, & Rerkkriangkrai, 2011). Cashew kernels are thermally processed to ensure the product is available all year round. This drying is critical owing to the fact that improper drying can lead to damaged kernels. As white whole kernel holds a superior value for both domestic and international markets, drying operations are carefully conducted to maximize the yield (Hebbar & Ramesh, 2005). To carry out the desired operations and obtain high efficiencies, large amount of energy is needed for thermal processing. Inefficient use of energy will result in huge economic losses in the food and agricultural production (Jekayinfa & Bamgboye, 2006; Tippayawong, Tantakitti, Thavornun, & Peerawanitkul, 2009).

Recently, superheated steam drying has gained great attention, because it is claimed to save process energy consumption and provide better product characteristics. Superheated steam is employed as a drying medium to provide thermal input to a product. Airless drying occurs from driving internal moisture out from the product at its boiling temperature with no diffusional resistance (Deventer and Heijmans, 2001). Use of hot steam above its boiling point as a process gas to take away the excess moisture from material is very fascinating. Since the evaporated vapor joins in as part of superheated steam, volatile matter of food component can be removed and readily condensed for other applications. Exhausted steam can be recycled in other unit operations (Ezhil, 2010; Tang & Cenkowski, 2000). It is of great interest to food processors since high production rate and integration of drying, and other steam processing steps such as blanching, pasteurization, and sterilization are possible, making the method very appealing for deployments in the snack food (Strumillo, 2009). Nonetheless, high steam temperature exceeding the saturation point could bring about challenges for temperature sensitive food materials. Browning reaction, discoloration, starch gelatinization, enzyme destruction, and protein denaturation may occur (Eang & Tippayawong, 2017; Khan, Beasley, & Alatas, 1991). It is essential to produce good quality dried food products and to prevent nutritional losses. It is also important to ensure low operation cost and high energy efficiency for thermal processing operation. It is known that agricultural product has low thermal conductivity, limiting heat transfer to the inner section of food (Tippayawong, Tantakitti, & Thavornun, 2008; Tirawanichakul, Saenaratana, Boonyakiat, & Tirawanichakul, 2011). Operations engaging time dependent heat and mass transfer together with physicochemical changes that may arise during superheated steam drying are complex, optimization is necessary in the search for the most suitable processing conditions. To the authors' knowledge, reported works on drying of cashew nuts with superheated steam together with optimization of process conditions remain relatively rare. It is therefore of great interest to explore development of this area.

Part of this work, especially, development of the dryer setup has been reported (Eang & Tippayawong, 2017). In the present work, further investigation of superheated steam drying for cashew kernels was carried out to include the effect of drying time and optimization of process variables. Optimization of process variables was achieved by optimizing combined factors affecting energy usage and a number of product quality indices. Contour plots were employed to identify common conditions where optimization may occur and confirmatory studies were also performed.

2. Material and methods

2.1. Raw materials

Cashew nuts with testa were purchased domestically from a local cashew processor. Their moisture content was evaluated (Cunniff and AOAC International., 1995). The mean value was

estimated to be approximately 10–11% dry basis. The mass of 100 cashew kernels with epispem layer was weighed. It was about 200 ± 5 g. A single batch of cashew kernels was used. For each test case, about 50 g of cashew nuts (~25 nuts) was used.

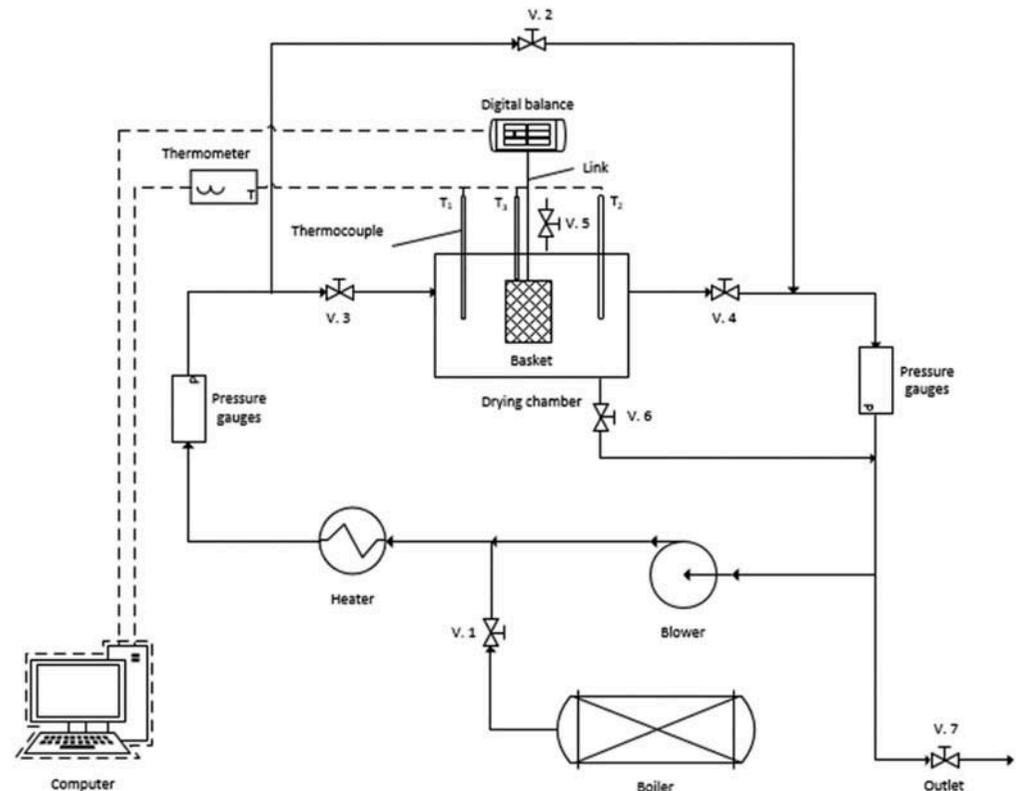
2.2. Experimental setup

Figure 1 illustrates schematically the superheated steam drying system. The main components were an electric heater (15 kW), a centrifugal fan (1.9 kW), a drying chamber (300 × 300 × 100 mm) connected together by pressure gauges, valves, and pipes. The dryer setup was operated in an exceedingly closed-loop system at a pressure slightly higher than gas pressure. Hot air at desired set point temperature was initially heated up before steam feeding into the system. The heating tapes were installed to prevent heat losses and potential internal condensation in the pipelines. The drying process was first started with discharging of saturated steam from the boiler at roughly 1 bar, heated to a superheated state through electric heating. The food sample was then put into a basket (60 × 80 × 100 mm in size) connected to a digital balance (± 0.01 g accuracy) in the test chamber, and linked to a computer to enable continuous weight monitoring. Once the door was closed and the test system was sealed, superheated steam was introduced into the drying chamber. Recirculation of superheated steam was done by a blower. The superheated steam flowrate was adjusted by a frequency controller to regulate the specified value. The pressure within the system was kept constant by venting the excess steam. Type-k thermocouples were positioned at different points along the pipes and in the chamber.

2.3. Experimental procedure and analysis

The drying experimental campaign was carried out with superheated steam at different thermal conditions. Temperature (120, 130, and 140°C), velocity (1.0, 2.0, and 3.0 m/s) and drying duration (5, 17.5, and 30 min) were varied. Lower operating range was not possible due to condensation of

Figure 1. Schematic diagram of dryer setup with superheated steam.



steam in the drying chamber. The test cashew nuts were randomly sampled from the chamber, and then left to cool down in a desiccator for about 24 h to prevent moisture from the atmosphere to be re-absorbed. Visual inspection and further analyses were conducted, for changes from each thermal condition.

2.3.1. Moisture content

A standard method was adopted to determine the moisture content of the sample. The sample weight was determined and then dried in a vacuum oven at 75°C for 16 h (Hebbar & Rastogi, 2001). The moisture content was given as percentage of water per dry solid:

$$MC = \frac{m_t - m_d}{m_d} \times 100, \quad (1)$$

where m_t is the total mass of sample (g) and m_d is the mass of dry-matter (g)

2.3.2. Peeling acceptability

Removal of the epidermis layer or testa from the dried nuts was carried out manually using stainless steel knife similar to that usually practiced in industry. The experiments were replicated for at least three times and percentage of peeling acceptability was defined as:

$$PA = \frac{n_k - n_r}{n_k} \times 100, \quad (2)$$

where n_k , n_r are the number of whole dried kernels and unpeeled, dried kernels before and after testa removal, respectively. Only whole peeled kernels were accounted for as premium kernels. The broken or split kernels were separated and classified as minor ones.

2.3.3. Colors

The color value was generally employed to standardize characteristics of the product by means of the total color difference (ΔE) and browning index (BI). These can be applied to the dried cashew nuts with the testa removed (Hebbar & Ramesh, 2005). The color values of original and dried products were evaluated by a colorimeter (Hunter Associates Laboratory, Inc., model MiniScan XE Plus, Reston, Virginia, USA). ΔE and BI can be determined from:

$$\Delta E = \sqrt{(L_0 - L_f)^2 + (a_0 - a_f)^2 + (b_0 - b_f)^2}, \quad (3)$$

$$BI = \frac{x - 0.31}{0.17} \times 100, \quad (4)$$

$$x = \frac{a + 1.75L}{5.646L + a - 3.012b}, \quad (5)$$

where L_0 , a_0 , and b_0 values are the initial brightness, redness, and yellowness while L_f , a_f , and b_f values indicate the final brightness, redness and yellowness of the sample, respectively. The evaluations were conducted for five nuts at three different points for each sample. About 55 measurements of each color parameter (L^* , a^* , b^*) were taken into account, and mean values were reported.

2.3.4. Energy consumption

The process energy use was expressed by the overall energy consumed in each unit operation of the superheated steam drying system. The total energy consumption was defined as:

$$TEC = E_{heater} + E_{boiler} + E_{blower}, \quad (6)$$

where E_{heater} , E_{boiler} , and E_{blower} are the electrical energy consumed (kWh) for a given operation on each experimental run by heater, boiler, and blower, respectively.

2.3.5. Design of experiments

Response surface methodology (RSM) is a set of statistical techniques that are of great value for tackling a problem in which a response of interest is dependent on a number of factors and the objective is to maximize this response (Hossain, Mansour, & Sultana, 2017). In this study, Box–Behnken design of experiments with three factors was chosen to examine the response pattern and to establish the optimum combination of these factors. To obtain a feasible relationship between dried product quality and total energy consumed as a function of steam temperature, velocity, and reaction time; a mathematical function $y = f(T, V, D)$, where T (temperature), V (velocity), and D (duration) are three independent variables, were assumed. The variance for each variable was assessed into linear, quadratic and interactive components and the relationship was represented using the second-order polynomial relationship as follow:

$$y = \beta_o + \sum_N^{i=1} \beta_i X_i + \sum_N \sum_N^{i=1, j=1} \beta_{ij} X_i X_j, \tag{7}$$

where β_o (intercept term), β_i (linear coefficient), β_{ii} (quadratic coefficient), and β_{ij} (interactive coefficient) are constant coefficients to the response error. X_i is the coded independent variables. The significance of all terms in the polynomial functions were evaluated statistically using F -value at a probability (p) of 0.05. The regression coefficients were used to produce contours from the regression model. Based on the Box–Behnken design, a total of 15 combinations including three replicates at the center point were carried out systematically for three independent variables. Each independent variable had three levels which were -1 , 0 , and $+1$. The actual and the corresponding coded values of independent variables used in developing the experimental design were shown in Table 1. The two responses, total color difference (y_1) and total energy consumption (y_2), were determined for cashew nuts processed under different combinations of temperature, velocity and time as defined in the design. Optimization was carried out together with the fitted models to generate the counterplots using Mini Tab-15 (Mini Tab Inc., State College, Pennsylvania, USA). Superimposition of optimum region was performed by contour plot for two independent factors while keeping the other factor fixed at a coded level, resulting in overlap regions of interest for total color difference and total energy consumption.

3. Results and discussion

The experimental results and analysis of variance for the two response variables, i.e. total color difference and total energy consumption under different processing conditions were analyzed using ANOVA and the data are presented in Tables 2 and 3, respectively. The lack-of-fit was found to be statistically insignificant at $p > 0.05$, making developed model approximated the response surfaces at any other values of the factors within the experimental domain.

Factors	Symbols		Levels	
	Uncoded	Coded	Uncoded	Coded
Temperature (°C)	T	X_T	140	1
			130	0
			120	-1
Velocity (m s ⁻¹)	V	X_V	3	1
			2	0
			1	-1
Duration (min)	D	X_D	30	1
			17.5	0
			5	-1

Table 2. Box–Behnken design of experiments and response in terms of total color difference and total energy consumption

Tests	Factors			Response	
	X_T (°C)	X_V (m s ⁻¹)	X_D (min)	Y_1 (color)	Y_2 (kWh)
1	1	0	-1	4.20	1.43
2	-1	0	-1	4.18	0.91
3	0	1	1	22.48	3.77
4	0	1	0	4.84	0.92
5	0	0	0	13.70	1.91
6	1	1	0	22.66	2.55
7	1	-1	0	15.67	5.53
8	1	0	1	28.14	4.1
9	-1	1	0	9.49	2.34
10	0	0	0	11.64	2.11
11	-1	0	1	14.09	3.77
12	0	0	0	12.71	2.42
13	0	-1	-1	5.04	0.71
14	0	-1	1	17.94	4.35
15	-1	-1	0	5.76	2.03

Table 3. Analysis of variance for fitted second-order polynomial model and lack-of-fit for total color difference and total energy consumption under different combination of independent variances

Analysis of variance	DF	Adj SS	Adj MS	F-Value	p-Value
Regression model: Y_1 (color)					
Model	4	768.27	192.06	66.93	0.00
Linear	3	719.11	239.7	83.53	0.00
2-Way interaction	1	49.16	49.16	17.13	0.00
Error	10	28.69	2.87		
Lack-of-fit	8	26.58	3.32	3.15	0.26
Pure error	2	2.11	1.05		
Total	14	796.97			
Regression model: Y_2 (kWh)					
Model	4	31.09	7.77	17.95	0.00
Linear	3	28.53	9.51	21.96	0.00
2-Way interaction	1	2.56	2.56	5.91	0.04
Error	10	4.33	0.43		
Lack-of-fit	8	4.14	0.51	5.55	0.16
Pure error	2	0.18	0.09		
Total	14	35.42			

3.1. Effects on total color difference

The response surface for total color difference was created using a second-order polynomial. The coefficient of determination (R^2) and the standard error were found to be 96.40% and 1.69, respectively, indicated the adequacy of applied model (Das, Shah, & Kumar, 2014). The

statistical analysis of the coefficients of the model showed that linear and interaction terms were significant, as shown in Figure 2. It was inferred that independent variables not only influenced the response variable individually but also had the interaction effect. The total color difference was found to be a linear function of steam temperature, velocity, and duration. These three independent variables were found to have positive effect for the response function of total color difference. The degradation of pigment and browning reaction mainly gave rise to the color changes of high sugar content products which occurs during thermal treatment. Millard reaction and caramelization are the two possible browning reaction that is generally found for fruit color deterioration (Sehrawat, Nema, & Kaur, 2016). Interestingly, drying duration was found to be the dominant factor among these three independent variables. It could be implied that increase in total color difference depended strongly on the duration of drying much more than steam temperature and velocity. However, there was also a significant interaction effect between steam temperature and drying duration as the function of total color difference. In comparison with steam temperature and drying time, this interaction effect had less influence on the total color change, but stronger if it was compared to the effect of steam velocity. The overall changes in color are reported in Figure 3. It seemed to provide compelling evidence that the total color difference of dried kernels underwent a significant change when both steam temperature and drying duration were increased. Long time exposure to high steam temperature of the product highly promotes the value of redness and yellowness but lowers the value of lightness due to the occurrence of non-enzymatic browning reaction when superheated steam is used as the drying medium (Jamradloedluk, Nathakaranakule, Soponronnarit, & Prachayawarakorn, 2007). Obviously, it can be seen that all three color parameters (L^* , a^* , and b^*) altered during dehydration process, leading to a swing in the product color toward the darker regime. The increase in total color difference of dried kernel was found when high steam temperature coupled with long drying duration was applied.

3.2. Effects on total energy consumption

Similar to total color difference, a second-order polynomial was used to generate the response surface of the total energy consumption. The R^2 of 86.35% and standard error of 0.62 were obtained from the fit of the model, indicated the goodness of the fit and confirmed the adequacy of the regression model (Muhammad & Feng, 2014). The standardized effects of

Figure 2. Pareto chart of standardized effects for total color difference of dried kernels.

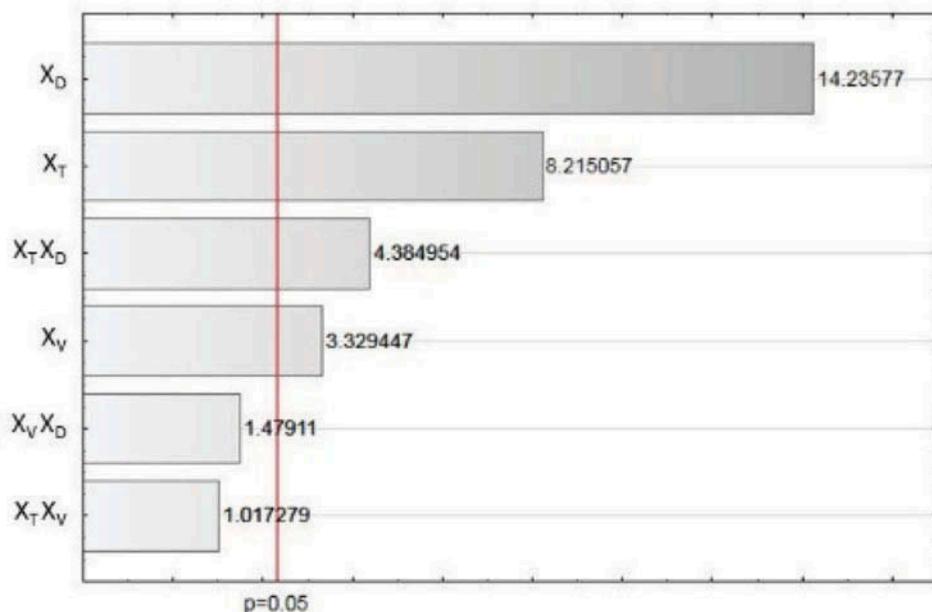
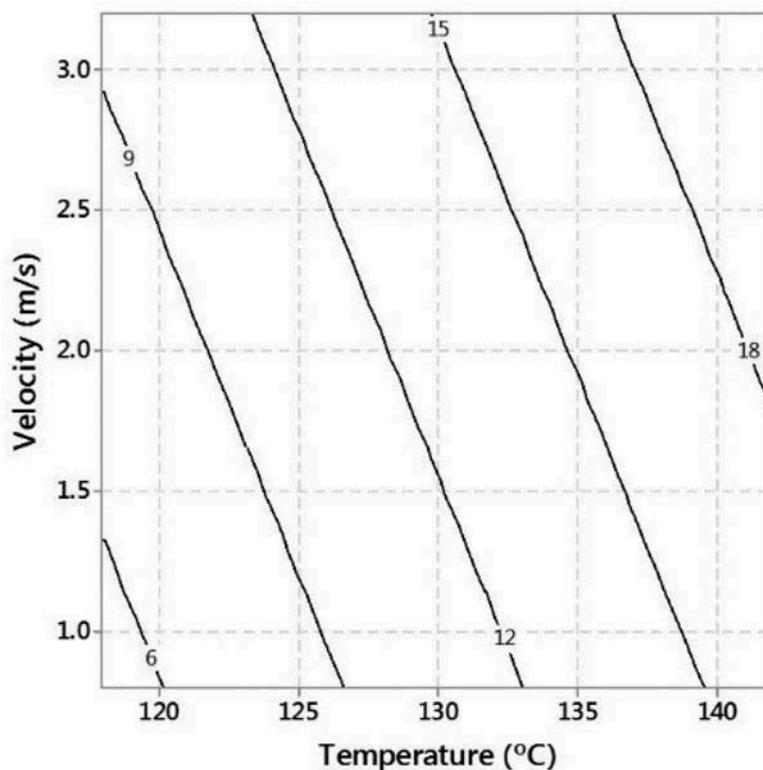


Figure 3. Contour plot for total color difference of dried kernels as a function of steam temperature and velocity at 17.5 min drying duration.



each independent variable are illustrated in Figure 4. The quadratic effect was found to be negligible while linear and interaction effects were significant and positive, indicating that they had much influence over the response function. The null hypothesis that both steam temperature and drying duration had insignificant effect to the total energy consumption was rejected, as the p -value was found to be less than 0.05. It could be inferred that the response surface of total energy consumption was influenced mainly by steam temperature and length of drying time. The obtained results was consistent with Somjai, Achariyaviriya, Achariyaviriya, and Namsanguan (2009) and Tirawanichakul et al. (2011) who reported that high temperature led to a short drying duration and low total energy consumption, as a result of the high heat transfer rate to the sample. It may be concluded that the total energy consumption was increased as either higher steam temperature or longer drying time was applied. Surprisingly, no significant effect was found in the response function of total energy consumption and steam velocity. The null hypothesis was true for this case. It was found that steam velocity was not considered to be a significant factor for total energy consumption. This was in exceptionally good agreement due to the fact that steam velocity only accelerates the moisture evaporation rate, particularly at the start of the drying period corresponded to the drying duration and total energy consumption as mentioned above (Pronyk, Cenkowski, & Muir, 2004). However, the analysis of variance showed that there was an interaction effect between steam temperature and velocity to the response function. The inspection of Figure 5 indicates this relationship. It was found to have a negative effect on its quadratic term, indicating that both steam temperature and velocity had significant effect to the response function. Therefore, it could be concluded the total energy consumption was not influenced by steam velocity individually, but both steam temperature and velocity negatively affected the total energy consumption. This could be seen that total energy consumption was almost unchanged with increasing velocity but decreased when both steam temperature and velocity were increased.

Figure 4. Pareto chart of standardized effects for total energy consumption of dried kernels.

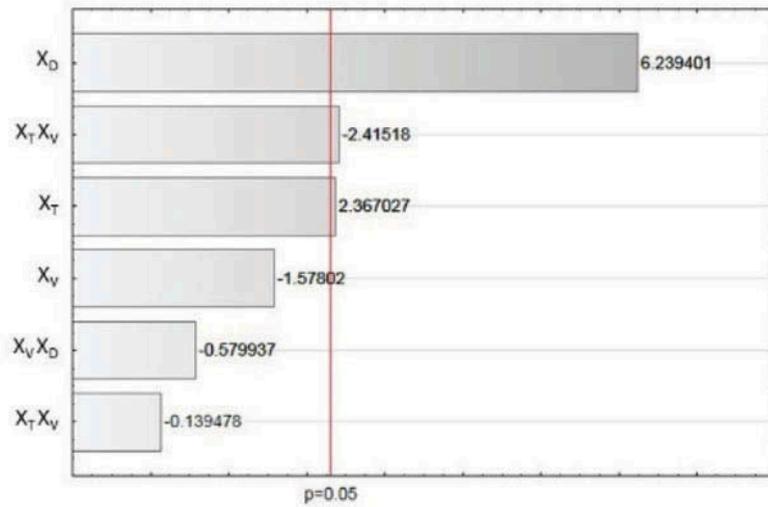
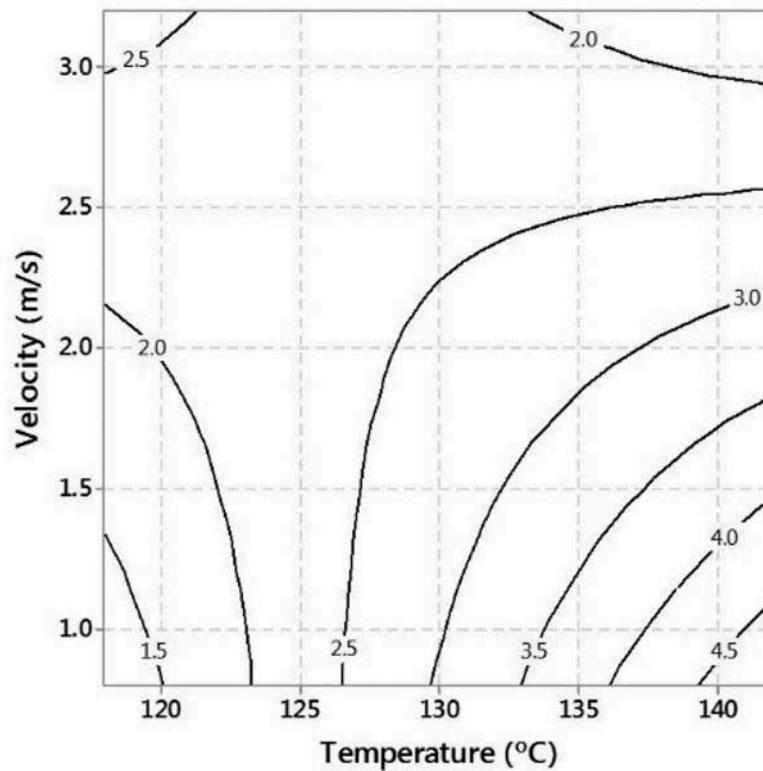


Figure 5. Contour plot for total energy consumption of dried kernels as a function of steam temperature and velocity at 17.5 min drying duration.

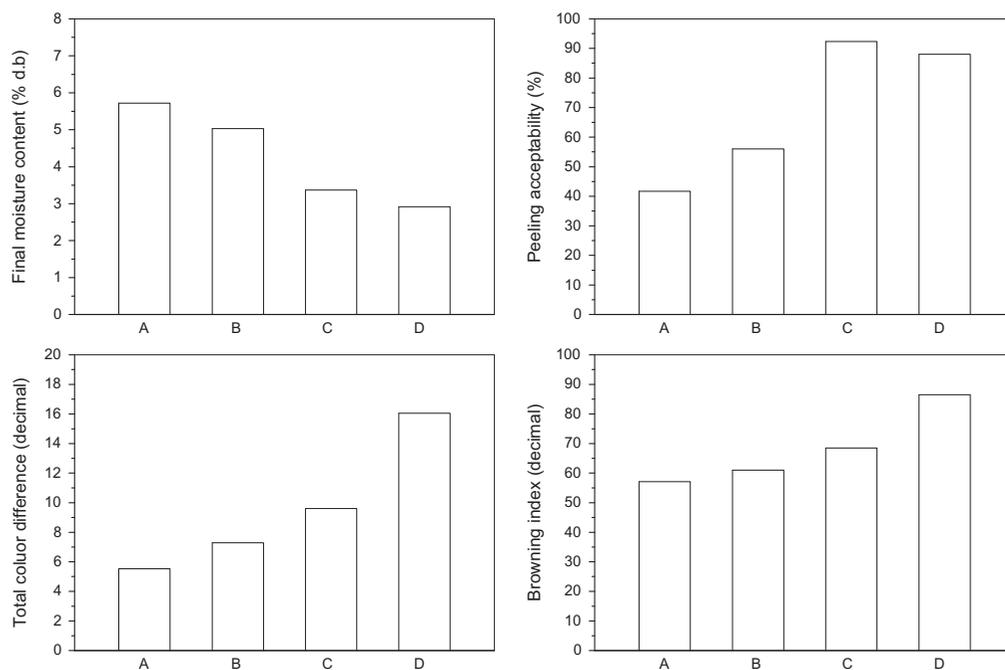


3.3. Optimization

3.3.1. Quality constraints

The test runs were carried out as part of the experimental design to examine the effect of superheated steam on the quality indexes of dried kernels. Temperature and velocity of steam were kept constant interchangeably, and the results revealed as evident in Figure 6. The investigation was conducted at a constant velocity of 3 m/s, as the temperature of steam was increased

Figure 6. Effect of steam temperature and velocity to the final moisture content, peeling acceptability, total color difference, and browning index of dried cashew nuts.

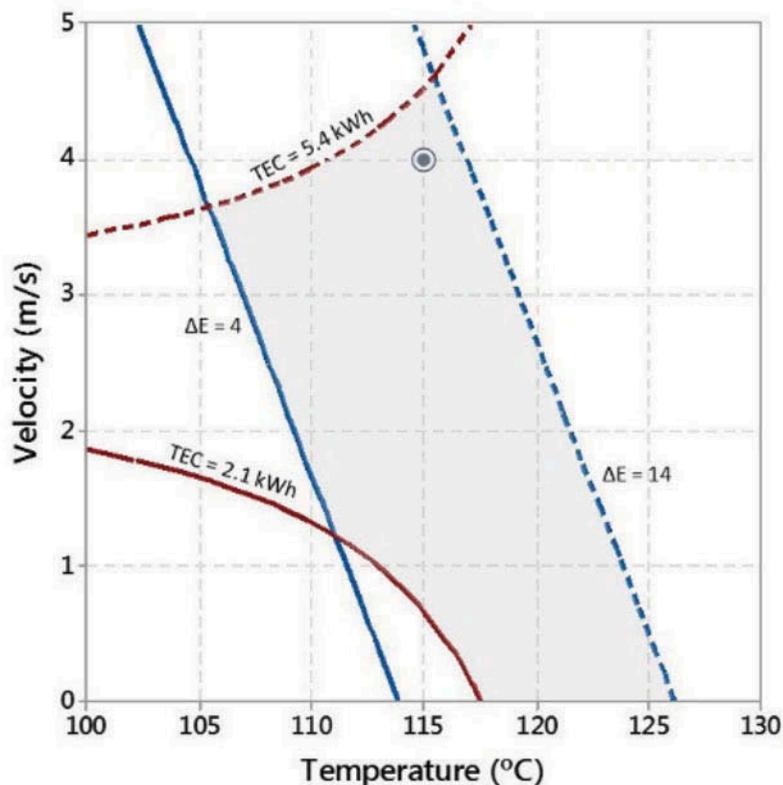


from 110°C to 120°C for cases A and C, respectively. With the exception of final moisture content, all important quality indexes were observed to improve with increasing steam temperature. In cases B and C, the analyses highlighted the effect of steam velocity at a constant temperature of 120°C when it was increased from 2 to 3 m/s, respectively. The results were found to be similar. It was therefore speculated that not only total color difference and BI were promoted which resulted in the redness, yellowness and darkness of dried nut, but high velocity of steam also enhanced the kernels with good peelability. It was apparent that both steam velocity and temperature had similar effects on all important quality indexes at varying degree of significance. Regardless of being greatly influenced by temperature, dried kernels with low final moisture content were shown to have broken and split kernels when high steam temperature was applied. In cases C and D, a remarkable trend was found when the drying temperature was increased from 120°C to 130°C, on the contrary to the decrease of steam velocity from 3 to 2 m/s. There appeared to be a drop in both peeling acceptability and final moisture content of dried kernels if steam velocity was decreased even though steam temperature was increased. The peeling acceptability was found to be greatly influenced by steam velocity, unlike other quality indexes. This was in contrast to steam temperature which strongly affected all quality indexes. High velocity and low temperature of steam helped prevent high color change and promoted the easiness of peeling ability but slightly decreased the final moisture content of dried kernels. Therefore, it is likely that a superposition of optimum thermal processing condition can be obtained at a sufficient drying duration, coupled with low temperature and high steam velocity.

3.3.2. Optimum conditions

The area of overlap represented by the shaded region in both total color difference and total energy consumption indicated the zone that any points of combination for the two response functions would result in optimum thermal processing. Figure 7 shows the effect of two independent variables on the responses plotted while one independent variable was held constant. Superposition of the plots was performed to obtain optimum conditions giving minimum value of the responses. The optimum region in the superimposed plots was generated at 30 min drying duration, as the total color difference and total energy consumption were set between 4 and 14 color unit and 2.1 and 5.4 kWh, respectively. This setting was made due to the fact that low

Figure 7. Optimum zones for conditions of superheated steam thermal processing for cashew kernels with testa.



temperature and long drying duration were more advantageous than high temperature for short drying duration in order to obtain a good color and desired mouthfeel of dried kernels (Hebbar & Ramesh, 2005). Optimum region for the respective response was found at 0–4.5 m/s steam velocity and temperature of 110–125°C. It should, however, be noted that a superposition of optimum thermal processing condition can be obtained only at a sufficient drying duration coupled with low temperature and high velocity of steam. Other possible optimum conditions were rejected, and a superposition of optimum thermal processing conditions of superheated steam drying was found at 30 min of drying duration along with 4 m/s velocity and 115°C temperature of steam.

3.3.3. Confirmatory studies

The experimental trials were carried out at the optimum condition obtained from the above study. The quality parameters of dried product were examined and reported in Table 4. The experimental color difference and energy consumption at the optimum level was 5.85 ± 1.12 color unit and 4.1 kWh, respectively. These values were found to be within the optimum range between 4 and 14 color unit and

Table 4. Characteristics of dried cashew kernels with testa under optimum superheated steam thermal processing condition

Symbol	Product characteristics	
	Quality parameters	Index
TEC	Total energy consumption	2.1 < 4.1 kWh < 5.4
ΔE	Total color difference	4 < 5.85 < 14
BI	Browning index	56.33 \pm 3.58
PA	Peeling acceptability	74.45%
MC	Final moisture content	4.0% d.b.

2.1 and 5.4 kWh as calculated with the processing parameters using regression model. It was observed that the final moisture content of 4% dry basis, BI of 56.33 ± 3.58 , and peeling acceptability of 74.45% with small amount of split/or broken dried kernel were also found at the experimental optimum condition. The pattern of these results indicated us that there is an agreement between regression model and experimental data, and therefore it is confirmed that at 4 m/s velocity and 115°C temperature of steam for 30 min of drying duration was the optimum condition for the superheated steam drying of cashew nuts.

4. Conclusion

In this work, the thermal processing of superheated steam for cashew nuts drying has been investigated. The influence of process temperature (120–140°C), velocity (1–3 m/s) and drying time (5–30 min) were studied using the RSM to derive the optimum process variables for the product quality and energy consumption. Measurements of moisture content, peeling ability, color and energy used were performed in a laboratory drying system. This approach proved to have potential features to understand the complexity of superheated steam thermal processing condition and the product quality criteria. It was shown that second-order polynomials had the goodness of the fit and confirmed the adequacy of the regression model with R^2 of 96.40% and 86.35% for total color difference and total energy consumption. Both were found to be linearly related to steam temperature, velocity, and duration. The drying duration was found to be dominant among the three independent variables. Even though, steam velocity was found to have little effect to the response function individually, but combined temperature and velocity of steam together had negative effect to total energy consumption. The optimum set of operation variables can be obtained graphically at 30 min drying time and optimum region for the respective response was found at 0–4.5 m/s steam velocity and temperature of 110–125°C. However, the maximum yield of kernel was not only based on its white whole kernels but also the other quality parameters. High velocity and low temperature of steam were set to prevent high color change and promote the easiness of peeling ability while slightly decreased the final moisture content of dried kernels. Therefore, superposition of optimum thermal processing condition of superheated steam drying was found at 30 min of drying duration along with 4 m/s velocity and 115°C temperature of steam.

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References

- Bart-Plange, A., Addo, A., Kumi, F., & Piegue, A. K. (2012). Some moisture dependent thermal properties of Cashew kernel (*Anacardium occidentale* L.). *Australian Journal of Agricultural Engineering*, 3, 65–69.
- Cunniff, P. A., & AOAC International. (1995). *Official methods of analysis of AOAC International* (16th ed.). Washington, DC: Author.

- Das, I., Shah, N. G., & Kumar, G. (2014). Cashew nut quality as influenced by microwave heating used for stored grain insect control. *International Journal of Food Sciences*, 2014, 1–7. doi:10.1155/2014/516702
- Eang, R., & Tippayawong, N. (2017). Superheated steam drying of cashew kernels with testa. *Energy Procedia*, 138, 674–679. doi:10.1016/J.EGYPRO.2017.10.199
- Ezhil, C. (2010). Superheated steam drying of foods—A review. *World Journal of Dairy & Food Sciences*, 5, 214–217.
- Hebbar, H., & Rastogi, N. (2001). Mass transfer during infrared drying of cashew kernel. *Journal of Food Engineering*, 47, 1–5. doi:10.1016/S0260-8774(00)00088-1
- Hebbar, U. H., & Ramesh, M. (2005). Optimisation of processing conditions for infrared drying of cashew kernels with testa. *Journal of the Science of Food and Agriculture*, 85, 865–871. doi:10.1002/jsfa.2045
- Hossain, S. M. Z., Mansour, N., & Sultana, N. (2017). Design of a laboratory experiment for the performance analysis of a retrofitted tray dryer unit. *Education in Chemical Engineering*, 18, 35–44. doi:10.1016/J.ECE.2016.10.001
- Jacob, R. A., & Burri, B. J. (1996). Oxidative damage and defense. *The American Journal of Clinical Nutrition*, 63, 985–990. doi:10.1093/ajcn/63.6.985
- Jamradloedluk, J., Nathakaranakule, A., Soponronnarit, S., & Prachayawarakorn, S. (2007). Influences of drying medium and temperature on drying kinetics and quality attributes of durian chip. *Journal of Food Engineering*, 78, 198–205. doi:10.1016/j.jfoodeng.2005.09.017

- Jekayinfa, S. O., & Bamgboye, A. I. (2006). Estimating energy requirement in cashew (*Anacardium occidentale* L.) nut processing operations. *Energy*, 31, 1305–1320. doi:10.1016/j.energy.2005.07.001
- Khan, J., Beasley, D., & Alatas, B. (1991). Evaporation from a packed bed of porous particles into superheated vapor. *International Journal of Heat and Mass Transfer*, 34, 267–280. doi:10.1016/0017-9310(91)90193-I
- Muhammad, N., & Feng, C. J. (2014, January). Methodology to optimize value in discrete event simulation for production planning and control studies. *Proceedings International Conference on Industrial Engineering & Operations Management*, Bali, Indonesia, (pp.676–684).
- Pronyk, C., Cenkowski, S., & Muir, W. (2004). Drying food-stuffs with superheated steam. *Drying Technology*, 22, 899–916. doi:10.1081/DRT-120038571
- Sehrawat, R., Nema, P. K., & Kaur, B. P. (2016). Effect of superheated steam drying on properties of food-stuffs and kinetic modeling. *Innovative Food Sciences Emerging Technology*, 34, 285–301. doi:10.1016/j.ifset.2016.02.003
- Somjai, T., Acharyaviriya, S., Acharyaviriya, A., & Namsanguan, K. (2009). Strategy for longan drying in two-stage superheated steam and hot air. *Journal of Food Engineering*, 95, 313–321. doi:10.1016/j.jfoodeng.2009.05.005
- Strumillo, C. (2009). A review of advanced drying technologies, 2nd ed., by T. Kudra and A.S. Mujumdar. *Drying Technology*, 27, 1164–1165. doi:10.1080/07373930903221846
- Tang, Z., & Cenkowski, S. (2000). Dehydration dynamics of potatoes in superheated steam and hot air. *Canadian Agricultural Engineering*, 42, 43–49.
- Tippayawong, N., Chaichana, C., Promwangkwa, A., & Rerkkriangkrai, P. (2011). Gasification of cashew nut shells for thermal application in local food processing factory. *Energy for Sustainable Developments*, 15, 69–72. doi:10.1016/j.esd.2010.10.001
- Tippayawong, N., Tantakitti, C., & Thavornun, S. (2008). Energy efficiency improvements in longan drying practice. *Energy*, 33, 1137–1143. doi:10.1016/j.energy.2008.02.007
- Tippayawong, N., Tantakitti, C., Thavornun, S., & Peerawanitkul, V. (2009). Energy conservation in drying of peeled longan by forced convection and hot air recirculation. *Biosystems Engineering*, 104, 199–204. doi:10.1016/j.biosystemseng.2009.06.018
- Tirawanichakul, S., Saenaratana, N., Boonyakiat, P., & Tirawanichakul, Y. (2011, December). Microwave and hot air drying of cashew nut: Drying kinetics and quality aspects. In *2011 IEEE Colloquium on Humanities, Science and Engineering, Penang, Malaysia*, (pp. 825–830).
- Van Deventer, H., & Heijmans, R. (2001). Drying with superheated steam. *Drying Technology*, 19, 2033–2045. doi:10.1081/DRT-100107287



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