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Energy and exergy analysis of drying process of banana slices

Fatemeh Karimi[1,]*, Jalal Dehghannya[1], Babak Ghanbarzadeh[1] and Shahin Rafiee[2]

[1]Department of Food Science and Technology, University of Tabriz, Tabriz, Iran.

[2]Department of Agricultural Machinery Engineering, University of Tehran, Karaj, Iran.

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ABSTRACT

In this study, estimation capabilities of response surface methodology and optimization acceptability of desirability functions methodology in an air drying process were investigated. The air temperature, air velocity, drying time and banana thickness were selected as independent factors in the process of drying banana slices. The dependent variables or responses were the moisture content, drying rate, energy efficiency and exergy efficiency. A rotatable central composite design as an adequate method was used to develop models for the responses. The regression coefficient, regression equation and analysis of variance (ANOVA) was also obtained to analysis of responses. In addition to this 3D response surface plot were helpful to predict the results by performing only limited set of experiments. Simultaneously, a minimum value for the moisture content and maximum value for the other responses was desired. Finally desirability functions found a maximum desirability equal to 0.49.

Introduction

Banana is a general term embracing a number of species or hybrids in the genus Musa of the family Musaceae. Almost all of the known edible-fruited cultivars arose from two diploid species, Musa acuminata and Musa balbisiana, which are native to Southeast Asia. There are diploid, triploid and tetraploid hybrids composing subspecies of M. acuminata, and between M. acuminata and M. Balbisiana (Robinson, 1996; Stover & Simmonds, 1987).

Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer. It is also a classical method of agricultural product preservation, which provides longer shelf-life, lighter weight for transportation and smaller space for storage (Ertekin & Yaldiz, 2004). Knowledge of heat and moisture transport is basis of process design, energy savings, and product quality. Determining moisture transport parameters for drying models are of particular interest for efficient mass transfer analysis and reproducibility of quality-controlled products. The continuously changing conditions along the period of the drying process make it difficult to determine the time duration of the process, and the most suitable values for the conditions to accomplish a successful drying process (Corzo et al., 2008). The most affecting factors related to the air drying are the air drying temperature, the air drying relative humidity and the air drying velocity in addition to the product initial moisture content (Amer, Morcos, & Sabbah, 2003).

Thermodynamics are known as an important technique to perform the energy and exergy analyses of the industrial processes. The first thermodynamic law, which is the basis of the heat-balance method of analysis, is widely used in engineering practice and used in engineering systems performance analysis commonly. However, the reversibility or irreversibility of processes is involved in the second law and play a very important role in the exergy method of energy systems analysis (Bayrak, Midilli, & Nurveren, 2003; Dincer & Cengel, 2001). Based on opinion of many researchers, energy is found as a fundamental concept of thermodynamics and one of the most significant aspects of the engineering analysis (Bayrak et al., 2003; Dincer, 2000). Exergy is consumed or destroyed due to irreversibility in any real process (Dincer, 2002). However exergy is equal to the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. In the drying industry, the goal is a maximum moisture removal using a minimum amount of energy to obtain the desired final conditions of the product. Meanwhile, the energy and exergy analyses of drying process should be performed using the first and second laws of thermodynamics in order to find out the energy interactions, and thermodynamic behavior of drying air throughout a drying chamber,.

Response Surface Methodology is a series of experimental design, analysis, and optimization techniques that originated in the work by Box and Wilson in 1951 (Castillo, 2007). The main idea of response surface methodology is to optimize an unknown and noisy function by means of simpler approximating functions that are valid over a small region using designed experiments. By moving the operating conditions of a process using a sequence of experimental designs, process improvement is achieved.

Response surface methodology has important applications in industrial to design, develop, and improve existing product. It also can be useful for formulation of new products. It defines the effect of the controlling or independent variables, alone and in combination on the response, in the processes. In addition to analyzing the effects of the controlling variables, this experimental methodology develops a mathematical model, which describes the food and industrial process (Anjum, Tasadduq, & Al-Sultan, 1997; Myers & Montgomery, 1995; Chakraborty, Kumbhar, & Sarkar, 2007; Madamba & Yabes, 2005; Mendes, de Menezes, Aparecida, & da Silva, 2001; Rodrigues & Ferna´ndez, 2007; Sharma & Prasad, 2006; Yao, Floros, & Seetharamant, 2007). It is hard to say that response

Tele:
E-mail address: mahm.karimi@gmail.com

surface methodology is applicable to optimize and fit for all studies, although it has so many advantages.

Most real life processes need to be optimized with respect to several criteria simultaneously. Frequently, operating conditions need to satisfy several conditions or constraints on responses. In the design of a process, product specifications need to be satisfied which determine the performance of the product when in use. There are different methods to optimize operating conditions such as conventional graph method (Fermin & Corzo, 2005), the improved graph method (Garrote, Coutaz, Luna, Silva, & Bertone, 1993), the desirability functions (Corzo & Go´mez, 2004) and the procedure of extended surface (Guillou & Floros, 1993).

The present study focused on modeling the influence of the air temperature, air velocity and drying time (as independent variables) on changes in moisture content, drying rate, energy efficiency and exergy efficiency (as dependent variables) of a air drying process for banana slices, by using response surface methodology. Different factorial designs are available in response surface methodology techniques (Khuri and Cornell, 1987; Mason et al., 1989). Here a model four factors with four responses as full factorial central composite design was used. The study, also, presented a specific point for the four independent variables in maximum desirability to obtain minimum moisture content and maximum drying rate, energy efficiency and exergy efficiency.

Materials and methods

Fresh bananas were daily purchased from a local market. The dryer was adjusted to a preset temperature for about half an hour prior to achieve the steady state. Then, sample was uniformly spread in a square basket in a single layer. The sample weight was kept constant at 65 g (±0.5 g) for all runs. During the course of the drying process, banana slices were weighed using a digital balance connected to a computer. The relative humidity and temperature in the dryer were measured and recorded every 5 seconds. The drying process was continued until the drying rate reached zero. The samples were then placed in an oven of 85ºC for 24 h in order to find the moisture content.

Drying experiments were performed in a cabinet laboratory type dryer installed in the Agricultural Machinery Engineering Department of Tehran University, Karaj, Iran (Yadollahinia, 2006). The dryer used for the experimental work consists of a fan, heaters, a drying chamber and instruments for various measurements (Table 1).

Moisture content

Moisture content (dry basis) of banana slices for the experimented samples were calculated using the following equation:

$$MC = \frac{W_i M_{Ci} - (W_t - W_{t+\Delta t})}{W_i(1 - M_{Ci})} \quad (1)$$

where W_i is the weight initial, W_t and $W_{t+\Delta t}$ are the weight at drying time t and t + Δt, respectively, and M_{Ci} is the moisture content initial.

Drying rate

Within a period of time Δt, the mean drying rate (DR) (dry basis) could be calculated by dividing the difference in product weight (ΔW) within this period of time by Δt and dry solid weight (W_d) as following (Corzo et al., 2008):

$$DR = \frac{\Delta W}{W_d \Delta t} = \frac{W_t - W_{t+\Delta t}}{W_i(1 - M_{Ci})(t_{t+\Delta t} - t_t)} \quad (2)$$

Energy efficiency

Instantaneous energy efficiency is most quoted in technical specifications to determine the energy performance of a drying process. It could be determined by dividing the energy required for moisture evaporation at the solids feed temperature by the total energy supplied to the dryer (Menshutina, Gordienko, Voynovskiv, & Kudra, 2004; Corzo et al., 2008):

$$\eta_{energy} = \frac{Energy\ required\ for\ evaporation\ at\ time\ t}{Input\ energy\ at\ inflow\ at\ time\ t} = \frac{(W_i - W_t) h_{fg}}{m_{da}(h_{dai} - h_{dat})} \quad (3)$$

where h_{fg} is the latent heat of vaporization of water at the average temperature of the moist food, m_{da} is the mass flow rate of dry air, h_{dai} and h_{dat} are the specific enthalpy of dry air at initial and time t, respectively.

The mass flow rate of the air (m_{da}) was calculated using the following equation (Ceylan et al., 2007):

$$m_{da} = \rho_a U_a A_{dc} \quad (4)$$

where ρ_a is air density, U_a is air velocity and A_{dc} is surface area of cross section. Meanwhile, it was considered that the mass flow rate of drying air was equally passed throughout the whole cross section of the drying chamber.

The enthalpy of the air used in the drying process was obtained as following equation (Akpinar et al., 2006):

$$h_{da} = c_{pda}(T - T_{ref}) + h_{fg} w \quad (5)$$

where c_{pda} is the specific heat, T is the air temperature, T_{ref} is the reference temperature, h_{fg} is the latent heat of vaporization of water at the reference temperature, and w is the humidity ratio of air.

The specific heat of inlet and outlet air (c_{pda}) could be calculated by following equation (Corzo et al., 2008):

$$c_{pda} = 1.004 + 1.88w \quad (6)$$

The following equation was generally used to transform the relative humidity-to-humidity ratio of the air (Akpinar et al., 2005).

$$w = 0.622 \frac{\varphi P_{vs}}{P - \varphi P_{vs}} \quad (7)$$

where φ is relative humidity of air, P is atmospheric pressure and P_{vs} is saturated pressure.

Exergy efficiency

The exergy efficiency (η_{exergy}) was determined by dividing the exergy use (investment) in the drying of the product to exergy of the drying air supplied to the system (Akpinar, 2004; Akpinar, Midilli, & Bicer, 2006; Midilli & Kucuk, 2003):

$$\eta_{exergy} = \frac{Exergy\ inflow - Exergy\ loss}{Exergy\ inflow} = 1 - \frac{Exergy\ loss}{Exergy\ inflow} \quad (8)$$

The exergy values could be obtained using the characteristics of the working medium from the first law energy balance. For this purpose, the general form of applicable exergy equation, as following, was used for steady flow systems (Midilli & Kucuk, 2003):

$$Exergy = m_{da} c_{pda}\left[(T - T_{ref}) - \frac{T_{ref} \ln T}{T_{ref}}\right] \quad (9)$$

where m_{da} is the mass flow rate, T is the inlet or outlet, and Tref is the reference temperature. The inflow and outflow of exergy, depended on the inlet or outlet temperatures of the drying chamber was calculated using equation (9).

The exergy loss can be determined as follow (Akpinar, 2004; Akpinar et al., 2006):

$$Exergy\ loss = Exergy\ inflow - Exergy\ outflow \quad (10)$$

In this study the reference temperature was taken as the environment: T_{ref} = 28°C

Experimental design

Experimental design and process optimization are two intertwined tasks. Using response surface methodology, the relationship among the independent variables, air temperature, air velocity and drying time were expressed mathematically in the form of a polynomial model, which gave the responses as a function of relevant variables. A central composite design was employed for the present study to obtain the experimental data, which would fit full second-order polynomial models representing the response surfaces over a relatively broad range of parameters.

The principle of response surface methodology was described by Castillo (Castillo, 2007). An empirical second-order polynomial model for four factors is presented in the following form:

$$y_k = a_0 + \sum_{i=1}^{4} a_i x_i + \sum_{i=1}^{4}\sum_{j=i}^{4} a_{ij} x_i x_j \qquad (11)$$

where y_k (k = 1,2,3 and 4) are the predicted responses (moisture content, drying rate, energy efficiency and exergy efficiency) used as dependent variables; x_i (i = 1, 2, 3 and 4) are the input predictors or controlling variables or independent variables; and a_0, a_i (i = 1, 2, 3, 4) and aij (i = 1, 2, 3, 4; $j = i, \ldots, 4$) were the model coefficient parameters. The coefficient parameters were estimated by multiple linear regression analysis using the least-squares method.

Each factor in the central composite design was studied at three different levels (−1, 0, +1), two star points and three repetitions at the center point (Myers & Montgomery, 2002).

All the independent variables were taken at a central coded value considered as zero. The minimum and maximum ranges of independent variables were considered and the full experimental plan with respect to their values in actual and coded form was listed in Table 2. Upon completion of experiments, the values of moisture content, drying rate, energy efficiency and exergy efficiency were taken as the dependent variables or responses (yi). Four second-order polynomial equations were then fitted to the data based on least-squares optimization technique.

Optimization

While there has been continuous interest in academic circles to apply different multi-objective optimization techniques to solve process optimization problems as they apply in response surface methodology, few of these have attracted the attention of Applied or Industrial Statisticians (Castillo, 2007). In the present work, desirability method was used as one of the most popular methods to optimization. This approach was originally proposed by Harrington (Harrington, 1965) and later refined by Derringer and Suich (Derringer and Suich, 1980) to its most common use in practice today.

The desirability function approach is one of the most widely used methods in industry for dealing with the optimization of multiple response processes. It is based on the idea that the “quality” of a product or process that has multiple quality characteristics, with one of them out of some “desired” limits, is completely unacceptable. The method finds operating conditions x_i that provides the “most desirable” response values.

For each response y_k, a desirability function $d_k(y_k)$ assigned numbers between 0 and 1 to the possible values of y_k; with $d_k(y_k) = 0$ representing a completely undesirable value of y_k and $d_k(y_k) = 1$ representing a completely desirable or ideal response value. The individual desirabilities were then combined using the geometric mean, which gives the overall desirability (D):

$$D = (d_1(y_1) \times d_2(y_2) \times \cdots \times d_m(y_m))^{1/m} \qquad (12)$$

where m denotes the number of responses. It is noticeable that if any response k is completely undesirable $d_k(y_k) = 0$ then the overall desirability will be zero. In practice, fitted response models yi were used in the method.

Depending on whether a particular response y_k is to be maximized, minimized, or assigned to a target value, different desirability functions $d_k(y_k)$ can be used. A useful class of desirability functions was proposed by Derringer and Suich (Derringer and Suich, 1980). L_k, U_k and T_k were the lower, upper, and target values desired for response k, where $L_k \le T_k \le U_k$. If a maximum value results a complete desirability, the individual desirability is defined as:

(13)

where in this case T_k is interpreted as a large enough value for the response and the exponent s determine how strictly the target value is desired. For s = 1, the desirability function increases linearly towards T_k, for s < 1, the function is convex, and for s > 1, the function is concave. In the present study s was taken equal 1.

If a minimum value results a complete desirability, instead, the individual desirability is instead defined as

(14)

where T_k represents a small enough value for the response.

Statistical analysis

The analysis of results was performed with statistical and graphical analysis software (SAS 9.1). This software was used for regression analysis of the data obtained and to estimate the coefficients of regression equations for moisture content, drying rate, energy efficiency and exergy efficiency in function of air temperature and velocity and drying time. ANOVA (analysis of variance) which is statistical testing of the model in the form of linear, squared and interaction terms was also used to test the significance of each term in the equation and goodness of fit of the regression model obtained (Huiping et al., 2007). These response surface models were also used to predict the result by 3D surface plots.

Results and discussion

Interpretation of regression analysis

In this study, effects of air temperature, air velocity, banana thickness and drying time on moisture content, drying rate, energy efficiency and exergy efficiency of the air drying for banana slices were investigated. The obtained results from the experimented samples are shown in Table 2. In order to fitting of the explanatory models for the variation of the noticed responses, the sum of sequential squares of the model was analyzed considering: (1) the average of the response, (2) the average plus the linear effects, (3) average plus the linear effects and the interactions, and (4) the average plus the linear effects, the interactions and the quadratic effects of the factors air temperature (T), air velocity (V), banana thickness (d) and drying time (t).

The summary of ANOVA is shown in Table 3. The ANOVA demonstrates that the regression models were highly significant, as is evident from the calculated Fisher’s ‘F’ values of 83.24, 61.15, 57.87 and 112.60 for responses of moisture content, drying rate, energy efficiency and exergy efficiency and a probability (P) value of 0.000 for all responses. The large value of F means that most of the variation in the response can be predicted by the regression equation. The P value also estimates whether F is large enough to indicate statistical significance. If P value is lower than 0.05, the model is statistically significant. These analyses characterized that a quadratic model is the more appropriate model for the four response variables. Table 3 also shows no residual error, which means the variation in the response data can be very well explained by the model.

The regression results obtained from central composite design models are given in Table 4 where P values are represented along with the coefficients. The P value is defined as the smallest level of significance leading to rejection of null hypothesis. In general, a smaller value of P will result a more significant for the corresponding coefficient term (Ravikumar et al., 2007).

The values of constants, which also do not depend on any factor and interaction of the factors, were found to be 0.288, 1.516, 0.643 and 0.895 for coded responses of moisture content, drying rate, energy efficiency and exergy efficiency, respectively.

Moisture content

The effect of the linear factors the air temperature, air velocity, drying time and thickness was found to be highly significant (P = 0.0001 for all the linear factors) on the moisture content of banana in the air drying. The square terms of the drying time and thickness were also found to be significant (P = 0.0001 and 0.0088, respectively). Since the squared terms were significant which means there was a curved line relationship between the moisture content and the square factors. The interaction terms of the air temperature*the drying time, the air temperature* the thickness, air velocity* thickness and drying time* thickness were also found to be significant in the model (P = 0.005, 0.013, 0.021 and 0.001, respectively). However, the other interaction terms didn't have a significant effect on moisture content in the model.

A positive sign of the coefficient means a synergistic effect, while a negative sign represents an antagonistic effect. In the present work, all the linear variables except of thickness had a negative relationship with the moisture content. So with the increasing these factors there will be a decreasing in the moisture content of banana samples. Whereas all the square terms in the model had a positive effect on the moisture content which indicates with an increase of these factors there will be an increase in the moisture content. Furthermore, high values of R^2 (97.88%) and R^2 (adjusted) (96.71%) indicates a high dependence and correlation between the observed and the predicted values of the moisture content. This also shows that 96.71% of result of the total variation can be explained by this model. The model as fitted in terms of the experimental factors corresponded to:

$$MC = 3.0032 - 0.0239 \times T + 0.0173 \times V - 0.0231 \times t + 0.3903 \times d + 0.0001 \times T \times t - 0.0030 \times T \times d - 0.0554 \times V \times d + 0.0001 \times t^2 - 0.0010 \times t \times d + 0.0247 \times d^2 \quad (15)$$

where MC is the moisture content, T is the air temperature, V is the air velocity, t is the drying time and d is the banana thickness. The predicted values of the moisture content of banana slices obtained using Eq. (15) are closed to the experimental values.

Drying rate

The effect of all the linear factors the air temperature, air velocity, drying time and thickness and all the square terms except of the air temperature and velocity were found to be significant on the drying rate of banana slices in the air drying. Whereas among all interaction terms, the air temperature * air velocity, air temperature* thickness and air velocity* drying time were not found to be significant.

The linear variables the drying time and thickness and the interaction term the air temperature* the drying time had a negative relationship with the drying rate. Whereas other terms had a positive effect on the drying rate which indicates that with an increase of these factors there will be an increase in the drying rate.

Multiregression analysis was performed to obtain a quadratic response surface model which is presented in following:

$$DR = 2.1942 + 0.0443 \times T - 0.1060 \times V - 0.0105 \times t - 0.5604 \times d - 0.0002 \times T \times t + 0.0627 \times V \times d + 0.0001 \times t^2 + 0.0012 \times t \times d + 0.0245 \times d^2 \quad (16)$$

where DR is drying rate.

Energy efficiency

For energy efficiency of the used air drying in the present work, the effect of all the linear factors and all the square terms except of the thickness were found to be significant.

Except of the interaction terms air velocity* drying time, air velocity* thickness and drying time* thickness, others the interaction terms were also found to be significant.

The factors that had a negative relationship with energy efficiency involved the linear factors air temperature, air velocity and drying time, the square term temperature and also the interaction term air temperature* thickness. However other terms had a positive effect on energy efficiency.

Quadratic response surface model found from multiregression analysis for energy efficiency is in following equation:

$$e_{energy} = 0.7223 + 0.0108 \times T - 0.4253 \times V - 0.0020 \times t + 0.0528 \times d - 0.0001 \times T^2 + 0.0026 \times T \times V + 0.0001 \times T \times t - 0.0005 \times T \times d + 0.0902 \times V^2 + 0.00001 \times t^2 \quad (17)$$

where e-energy is energy efficiency.

Exergy efficiency

The effect of all the linear factors and the square terms air temperature, drying time and thickness were found to be significant on exergy efficiency of banana slices in the air drying. Aside from the interaction term drying time* thickness other interaction terms were not significantly affected on exergy efficiency. All the linear variables had a positive effect on the exergy efficiency except of drying time. Aside from the square term air temperature, other square terms had a positive relationship with the exergy efficiency.

The model of exergy efficiency as fitted in terms of the experimental factors corresponded to:

$$e_{exergy} = 0.6689 + 0.0089 \times T + 0.0061 \times V - 0.0007 \times t - 0.0118 \times d - 0.0001 \times T^2 + 0.00001 \times t^2 - 0.00001 \times t \times d + 0.0020 \times d^2 \quad (18)$$

where e-exergy is exergy efficiency.

Interpretation of response 3D surface and contour plots

The 3D response surface is a three dimensional graphic representation, which can be employed to determine the individual and cumulative effect of the variable and the mutual interaction between the variable and the dependent variable. The response surface displays the geometric nature of the surface and analyzes the significance of the coefficients of the canonical equation (Ravikumar et al., 2007).

Whereas the air velocity had the least effect on responses in comparison of other factors, therefore, to visualize the combined effects of the two factors (T-t, T-d and t-d) on the responses, the response surface were generated for each of the fitted models in function of the air temperature, drying time and thickness factors, with the air velocity held as a constant.

The surface plots (Fig. 1), where moisture content of banana slices was represented by varying air temperature and thickness from -1 to +1 and drying time from -2 to +2 in coded units with air velocity held as a constant at a coded value equal zero. From these response surface plots this is clear that moisture content decreases when the temperature and the time increases and thickness decreases.

It is clear from Figure 1-a, that at air velocity and thickness equal zero coded, moisture content obtained a minimum value in high temperature and time and obtained a maximum value in low temperature and time simultaneously. At air velocity and drying time equal zero coded, lowest value of moisture content obtained in high temperature and low thickness simultaneously (Fig. 1-b). Also when air velocity and temperature are constant at a coded value equal zero, minimum value for moisture content occurred in high drying time and low thickness simultaneously (Fig. 1-c). The surface plots also describing individual and cumulative effect of each two test variable and test their subsequent effect on the response.

The response surfaces of drying rate with air velocity held as a constant at a coded value equal zero are shown in Figure 2. As can see in the figure, the drying rate had a maximum value in lowest drying time and thickness and highest air temperature. In the meantime, in the low drying time it was found that the drying rate increased with an increase in the air temperature, whereas in the high drying time, the air temperature don't played an effective rule on the drying rate (Fig. 2-a). In the high drying time, thickness also had no effect on the drying time while in the low drying time, drying rate increased with a decrease in thickness (Fig. 2-c). In the other word because drying time had a strong effect on drying rate, air temperature and thickness can't be clearly affected on the drying rate.

At air velocity and drying time equal zero coded, highest value of drying rate obtained in a maximum temperature and a minimum thickness simultaneously (Fig. 2-b).

The response surfaces of energy efficiency with air velocity held as a constant at a coded value equal zero are shown in Figure 3. As is found in the surface plots with increasing the temperature, the energy efficiency decreased while maximum value for energy efficiency occurred at the lowest value of the temperature. However varying drying time as well as thickness was also affected on the values of the energy efficiency, so that energy efficiency decreased with an increasing in drying time and a decreasing in thickness. In the surface plots presented in Fig. 3 that is clear that maximum value of the energy efficiency occurred in one level of the minimum temperature and time and the maximum thickness. However minimum value of this efficiency occurred in the maximum value of temperature and time and the minimum thickness simultaneously.

The surface plots shown in Figure 4 represent the exergy efficiency depended on the air temperature, drying time and thickness with air velocity held as a constant at a coded value equal zero. With increasing the time, the exergy efficiency was faced with a strong decreasing process. Although, with increasing air temperature and thickness, the exergy efficiency experimented an increasing process; in the plots it is found that the drying time factor had a more effect on the exergy efficiency in comparison with the temperature and thickness factor.

Optimization by desirability functions methodology

Optimization is one of the most important steps in the design and analysis of experiment. Often the object of experimentation is to find the levels of factors which optimize the response. Because of working with more than one response in the present work such as moisture content, drying rate, energy efficiency and exergy efficiency, it was performed a simultaneous multiple response optimization.

The prediction profiler for the used design in the present work shows the predicted responses for each combination of the factor settings. The plotted line (that is visitable in each cell in Fig.5) for a factor from a specific surface is the prediction line (or prediction trace) when the factor is changed and the other factors are held constant. The vertical dotted line for each factor is the current factor setting. When the vertical dotted line for a factor changed, the horizontal dotted line is updated by recomputing the predicted response at the new mixture blend setting. The horizontal dotted line and the number on the Y axis between the axis minimum and maximum is the predicted response at the current factor setting.

In the present experiment that involved multiple responses, the acceptability of the process was depended on more than one response. In order to optimizing the process, moisture content must be as low as possible and drying rate, energy efficiency and exergy efficiency must be as high as possible. In such situations the desirability of the process depends on the simultaneous optimization of all responses. Optimization was implemented by using the desirability profile and its function.

As can be seen in Fig. 5, the highest desirability point was found at temperature equal to 0.5 (75°C), air velocity equal -0.9 (0.55 m/s), drying time equal -1 (100 min) and thickness equal -1 (2 mm) in order to obtain moisture content equal 0.37 g/g, drying rate equal 0.027 g water/g min, energy efficiency equal 0.66 and exergy efficiency equal 0.91.

Overlay contour plot for multiple responses the moisture content, drying rate, energy efficiency and exergy efficiency at the constant point of air velocity equal to 0.55 m/s and thickness equal to 2 mm is shown in Figure 6. With the air temperature held as a constant at the desirability point (air temperature at coded value equal to 0.5) and increasing the drying time from -2 to 2 as coded values it is clear from this overlay contour that all the responses were faced to a decreasing process. However the moisture content and energy efficiency decreased when the temperature changed from -1 to 1 and other factors were constant at the desirability point. While in this condition the exergy efficiency had no noticeable process as decreasing or increasing.

Conclusion

The moisture content, drying rate, energy efficiency and exergy efficiency during drying of banana slices were investigated as functions of the air temperature, air velocity, drying rate and thickness. The surfaces were determined at 29 experimental points. The aim of the study was to fit models for predicting surfaces using response surface methodology and to optimize for obtaining the maximum acceptability using desirability functions methodology. The response 3D surface and contour plots related to fitted functions using response surface methodology describes effects of the factors on values of each response individually and cumulatively. Finally the maximum desirability point to minimize the moisture content and to maximize the drying rate, energy and exergy efficiency was found as 0.5 (75°C), -0.9 (0.55 m/s), -1 (100 min) and -1 (2 mm) for the air temperature, air velocity, drying rate and thickness, respectively, to obtain moisture content equal 0.37 g/g, drying rate equal 0.027 g water/g min, energy efficiency equal 0.66 and exergy efficiency equal 0.91.

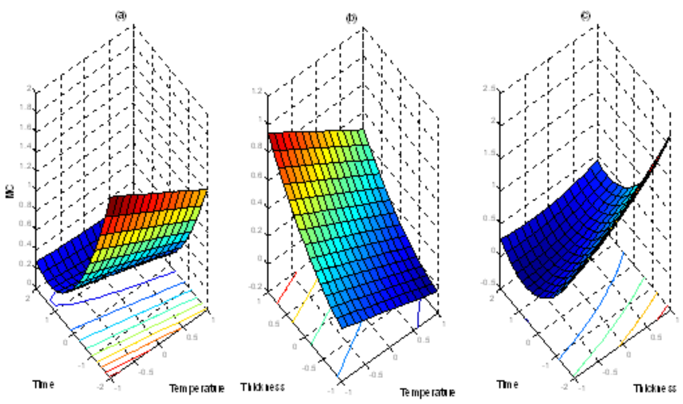

Fig. 1. Response surfaces for moisture content (MC) at air velocity equal zero and a) thickness equal zero, b) drying time equal zero and c) air temperature equal zero.

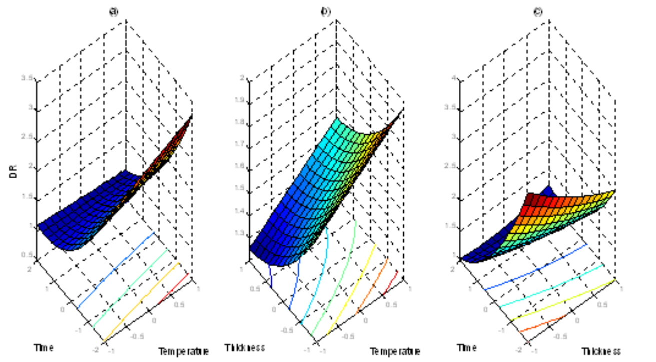

Fig. 2. Response surfaces for drying rate (DR) at air velocity equal zero and a) thickness equal zero, b) drying time equal zero and c) air temperature equal zero.

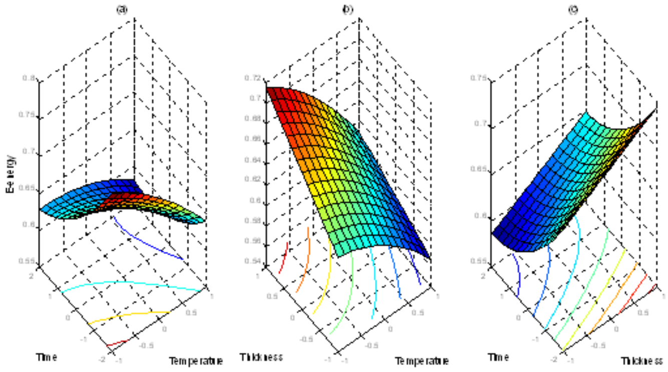

Fig. 3. Response surfaces for energy efficiency (η_{energy}) at air velocity equal zero and a) thickness equal zero, b) drying time equal zero and c) air temperature equal zero.

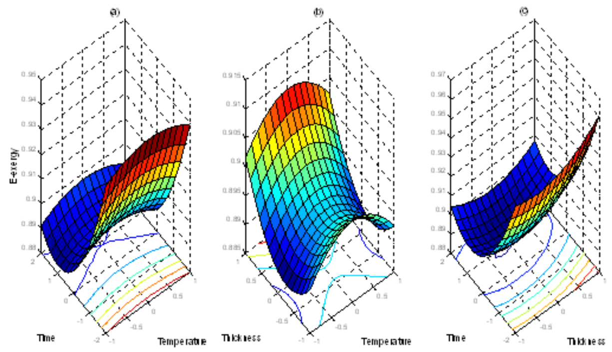

Fig. 4. Response surfaces for exergy efficiency (η_{exergy}) at air velocity equal zero and a) thickness equal zero, b) drying time equal zero and c) air temperature equal zero.

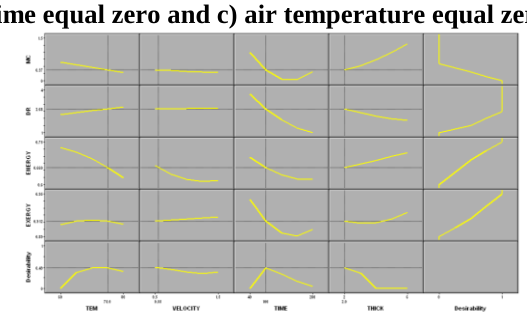

Fig. 5. Prediction profile of trends of moisture content, drying rate, energy efficiency and exergy efficiency at the maximum desirability.

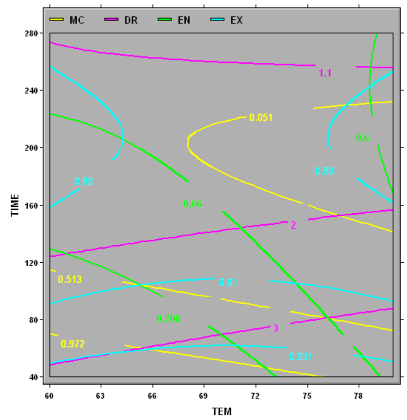

Fig. 6. Overlay contour plots at the point of air velocity equal 0.55 m/s and thickness equal 2 mm

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Table 1. Specifications of measurement instruments including their rated accuracy

Instrument	Model	Accuracy	Make
Digital balance	GF3000	±0.02gg	A&D, Japan
T-sensor	LM35	±1°C	NSC, USA
RH-sensor	Capacitive	±3%	PHILIPS, UK
V-sensor	405-V1	±3%	TESTO, UK

Table 2. Observed values of moisture content (MC), drying rate (DR), energy efficient (ηenergy) and exergy efficiency (ηexergy) for drying banana based on central rotatable composite design

Air temperature (°C)		Air velocity (ms^{-1})		Drying time (minute)		Thickness (mm)		MC ($g_{water}\ g_{dsw}^{-1}$)	DR *10-^{2}($g_{water}\ g_{dsw}^{-1}.min^{-1}$)	η_{energy}	η_{exergy}
Coded	Uncoded	Coded	Uncoded	Coded	Uncoded	Coded	Uncoded				
-1	60	-1	0.5	-1	100	-1	2	0.692	2.081	0.747	0.907
-1	60	-1	0.5	-1	100	1	6	1.737	1.447	0.839	0.918
-1	60	-1	0.5	1	220	-1	2	0.128	1.202	0.668	0.887
-1	60	-1	0.5	1	220	1	6	0.831	1.069	0.757	0.892
-1	60	1	1.5	-1	100	-1	2	0.467	2.380	0.652	0.913
-1	60	1	1.5	-1	100	1	6	1.377	1.721	0.735	0.925
-1	60	1	1.5	1	220	-1	2	0.052	1.270	0.589	0.891
-1	60	1	1.5	1	220	1	6	0.441	1.208	0.662	0.896
1	80	-1	0.5	-1	100	-1	2	0.215	2.969	0.629	0.907
1	80	-1	0.5	-1	100	1	6	1.138	1.878	0.680	0.918
1	80	-1	0.5	1	220	-1	2	0.018	1.439	0.592	0.889
1	80	-1	0.5	1	220	1	6	0.355	1.210	0.636	0.893
1	80	1	1.5	-1	100	-1	2	0.139	2.707	0.588	0.913
1	80	1	1.5	-1	100	1	6	0.791	2.307	0.627	0.924
1	80	1	1.5	1	220	-1	2	0.020	1.285	0.561	0.892
1	80	1	1.5	1	220	1	6	0.189	1.323	0.594	0.897
-1	60	0	1	0	160	0	4	0.454	1.459	0.640	0.888
1	80	0	1	0	160	0	4	0.196	1.517	0.605	0.889
0	70	-1	0.5	0	160	0	4	0.369	1.337	0.679	0.886
0	70	1	1.5	0	160	0	4	0.171	1.739	0.637	0.901
0	70	0	1	-1	100	0	4	0.770	2.137	0.676	0.916
0	70	0	1	1	220	0	4	0.131	1.262	0.628	0.892
0	70	0	1	-2	40	0	4	1.727	2.949	0.700	0.946
0	70	0	1	2	280	0	4	0.065	1.015	0.627	0.896
0	70	0	1	0	160	-1	2	0.083	1.949	0.619	0.894
0	70	0	1	0	160	1	6	0.718	1.446	0.678	0.912
0	70	0	1	0	160	0	4	0.317	1.618	0.647	0.898
0	70	0	1	0	160	0	4	0.251	1.424	0.643	0.895
0	70	0	1	0	160	0	4	0.235	1.351	0.646	0.896

Table 3. Analysis of variance for Master and Predictive models of moisture content, drying rate, energy efficiency and exergy efficiency using air temperature (°C), air velocity (ms^{-1}), drying time (min) and thickness (mm) data in coded units

Source	Moisture content			Drying rate			Energy efficiency			Exergy efficiency		
	DF	SS	p-value	DF	SS	p-value	DF	SS	p-value	DF	SS	p-value
Master Model												
Model	14	6.463	0.0001	14	8.122	0.0001	14	0.095	0.0001	14	0.0057	0.0001
(Linear)	4	5.341	0.0001	4	7.031	0.0001	4	0.085	0.0001	4	0.0043	0.0001
(Quadratic)	4	0.680	0.0001	4	0.434	0.0024	4	0.003	0.0181	4	0.0014	0.0001
(Cross Product)	6	0.441	0.0004	6	0.658	0.0012	6	0.006	0.0023	6	0.0001	0.4363
Error	14	0.114		14	0.213		14	0.002		14	0.0001	
(Lack of fit)	12	0.110	0.182	12	0.179	0.6442	12	0.002	0. 220	12	0.0001	0.2208
(Pure Error)	2	0.004		2	0.034		2	0.000		2	0.0000	
Total	28	0.577		28	8.336		28	0.097		28	0.0058	
Predictive Model												
Model	10	6.437	0.0001	9	8.057	0.0001	10	0.094	0.0001	8	0.0057	0.0001
Error	18	0.139		19	0.278		18	0.003		20	0.0001	
(Lack of fit)	16	0.135	0.196	17	0.244	0.6674	16	0.003	0.234	18	0.0001	0.287
(Pure Error)	2	0.003		2	0.034		2	0.000		2	0.0000	
Total	28	6.577		28	8.336		28	0.097		28	0.0058	

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