Studies on Conventional Vacuum Drying of Foods

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Abstract This chapter deals with the simplest way to perform the vacuum drying of foods. Such process is usually performed as a batch in a vacuum oven. The chapter presents studies carried out from year 2001 to year 2014 as surveyed in electronic databases. The vacuum dried foods used as material in these studies include herbs, fruits, vegetables and mushrooms. Most of these foods present health-promoting (functional) properties which are preserved even after drying due to the special conditions (low heating and low oxygen content) used during vacuum drying. Effective moisture diffusivity, a property related to the ability of moisture to migrate from the product to the environment, was calculated in many of these studies and the respective values are presented here. An equation for calculating this parameter in foods is also presented. Several thin-layer drying models, which are equations that fit the values of moisture content during drying, are also presented.

Keywords Vacuum drying · Effective moisture diffusivity · Drying models

In the beginning of the last decade, the vacuum drying of celery slices was optimized toward final product quality by means of the response surface methodology [17]. The effect of drying temperature (65–75 °C), slice thickness (1–3 mm) and pressure (16–20 inHg) on the rehydration capacity, bulk density, moisture content and overall acceptability of the final product was evaluated. When significant effects of the variables on the responses were observed, they were fitted by using polynomial models. All of the quality parameters studied, except from the sensory scores, were well predicted by using the proposed models. After plotting all possible combinations of variables in response surface plots, the graphs were superimposed in order to yield optimum drying conditions. The optimum drying conditions were: drying

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F. Richter Reis (ed.), *Vacuum Drying for Extending Food Shelf-Life*, SpringerBriefs
in Applied Sciences and Technology, DOI 10.1007/978-3-319-08207-3_2

temperature of 74.5 °C, vacuum pressure 17.5 inHg and slice thickness of 1 mm. When using the optimum conditions, a final product presenting high rehydration capacity, low bulk density, low moisture content and probably high overall acceptability was obtained.

The effect of different drying conditions and modified mango pulp composition on drying time, color and effective moisture diffusivity was evaluated by Jaya and Das [10]. The variables tested were initial thickness of pulp (2–4 mm) and vacuum chamber plate temperature, i.e., drying temperature (65–75 °C). Drying pressure was kept constant at 30–50 mmHg. The drying kinetics was adequately fitted by a model based on effective moisture diffusivity. The addition of tri calcium phosphate, maltodextrin and glycerol monostearate to the mango pulp led to lower values of effective moisture diffusivity. However, additives were necessary for allowing the grinding of pulp into a powder. Increase in pulp thickness and drying temperature led to increase in effective moisture diffusivity. Increased drying rates were associated with low product thickness and high temperatures. With regard to color, the reconstituted pulp powder was used as sample. The higher the product layer and the drying temperature, the higher the total color changes. In conclusion, it was recommended the use of a product layer lower than 2.6 mm and a drying temperature lower than 72.3 °C for obtaining high quality dried mango pulp.

Zhang et al. [32] optimized low-vacuum (0.67 kPa) drying conditions for obtaining dried sweet pepper with high contents of Selenium and chlorophyll. A three factor-three level response surface design with three replications at the center point was used to estimate the effects of drying temperature (60–100 °C), blanching time (3–13 min) and blanching solution pH (1–11) on the levels of Selenium and chlorophyll in the final product. Blanching solution pH was the factor that affected the most the Selenium content, while drying temperature markedly affected the chlorophyll content. By using contour plots and differentiating the second order polynomial regression equation, the authors observed that the optimum drying conditions were a dying temperature of 75 °C, a blanching solution pH of 7.0 and a blanching time of 8 min. When the optimum process conditions were used, maximum levels of Selenium (191.2 µg/g) and chlorophyll (187.8 µg/g) were observed in the dried sweet peppers.

Arévalo-Pinedo and Murr [2] modeled the vacuum drying kinetics of pumpkin slabs under various drying conditions, studied the impact of blanching and freezing on the drying rates and evaluated the impact of shrinkage on the effective moisture diffusivity of the slabs. The drying temperature varied from 50 to 70 °C and the absolute pressure in the drying chamber varied from 5 to 25 kPa. The authors found that higher temperatures and lower pressures led to higher drying rates. In addition, both blanching and freezing reduced the drying time, being freezing more effective than blanching in this sense. The experimental data were well modeled by two fashions of the Fick's second law of diffusion, viz. considering the occurrence of shrinkage or not. The latter is presented below for unidirectional moisture diffusion through one side of a slab [7]:

$$M_R = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-[2n+1]^2 \pi^2 \frac{D_{eff} \cdot t}{L^2}\right) \tag{1}$$

where M_R is the dimensionless moisture ratio; D_{eff} is the effective moisture diffusivity ($m^2\ s^{-1}$), t is time (h), L is the thickness of the slab (m) and n is a positive integer. The dimensionless moisture ratio can be defined as

$$M_R = \frac{M - M_e}{M_0 - M_e} \tag{2}$$

where M is the moisture content of the product (kg water kg dry solid^{-1}) at any time; M_e is the moisture content of the product when equilibrium is attained; and M_0 is the initial moisture content of the product. The obtained effective moisture diffusivities ranged from 2.01×10^{-9} to $5.70 \times 10^{-9}\ m^2\ s^{-1}$ when shrinkage was neglected and from 1.13×10^{-9} to $3.90 \times 10^{-9}\ m^2\ s^{-1}$ when shrinkage was taken into account. Summarizing, the use of freezing pretreatment followed by drying under high temperature and low pressure leads to high drying rates. In addition, when product shrinkage is taken into account, the values of effective diffusivity are lower.

Arévalo-Pinedo and Murr [3] studied the vacuum drying kinetics of pre-treated and untreated carrot and pumpkin slabs. The pre-treatments consisted in blanching in hot water at 95 °C for 5 min or freezing at –20 °C for 3 h. The drying temperature varied from 50 to 70 °C and the absolute pressure in the drying chamber varied from 5 to 25 kPa. The drying curves presented a long falling rate period. The faster drying process was the one where freezing was used as pre-treatment, followed by the one where blanching was used and then the control (no pre-treatment). This behavior was attributed to the cell disruption that takes place when the food is frozen, allowing moisture to be removed more easily during the subsequent drying. The drying kinetics was adequately modeled by the Fick's second law of diffusion for slabs (Eq. 1), with high values of R^2 and low values of error of prediction. Pumpkin effective moisture diffusivities ranged from 2.01×10^{-9} to $5.70 \times 10^{-9}\ m^2\ s^{-1}$, while carrot effective moisture diffusivities ranged from 1.273×10^{-9} to $4.844 \times 10^{-9}\ m^2\ s^{-1}$. Such variations are related to various drying temperatures and pressures. In sum, freezing proved better than blanching for enhancing the rates of carrot and pumpkin vacuum drying and the observed effective moisture diffusivities were higher for pumpkin in detriment of carrot.

Jena and Das [11] studied the vacuum drying of coconut presscake, a by-product of the coconut processing industry. The main contribution of this study was the development of a new thin-layer drying model, which adequately fitted the changes in coconut presscake moisture content during vacuum drying. The new model, called "Jena and Das", is

$$M_R = a\exp\left(-k\theta + b\sqrt{\theta}\right) + c \tag{3}$$

where M_R is the dimensionless moisture ratio presented in Eq. 2; a, b and c are model constants; and θ is time (s). Relative deviations lower than 15 % were obtained when using the new model. Experiments were carried out by using a 3^2 factorial design where sample thickness (2–4 mm) and drying temperature (65–75 °C) were varied. Pressure was fixed at 62 ± 3 mmHg. Faster drying was associated with high temperature and low thickness. In addition, values of effective moisture diffusivity were calculated by using Fick's second law for slabs (Eq. 1). Effective diffusivities ranged from 7.026×10^{-10} to 3.326×10^{-9} $m^2\ s^{-1}$ for various temperatures and thicknesses. Concluding, the Jena and Das model showed suitable for fitting the drying kinetics of coconut presscake and the use of high sample thickness and high drying temperature enhanced the effective moisture diffusivities.

Wu et al. [30] studied the vacuum drying characteristics of eggplant slices (*Solanum melongena*), an important food in several countries. Such as other vegetables, eggplants present short shelf life due to their high water activity. In that study, the effect of variable drying temperatures (30–50 °C) and pressures (2.5–10 kPa) on the drying kinetics was evaluated. The drying kinetics was tentatively fitted by three well-known mathematical models and by a new model that was proposed. The proposed model is shown below:

$$M_R = at^2 + bt + 1 \tag{4}$$

where M_R is the dimensionless moisture ratio defined as in Eq. 2; a and b are model constants and t is time (h). The effect of moisture on shrinkage was modeled too. Effective moisture diffusivity was evaluated by using Eq. 1, and their dependence on temperature was estimated on the basis of the following Arrhenius-type equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{5}$$

where D_{eff} is the effective moisture diffusivity ($m^2\ s^{-1}$); D_0 is the pre-exponential factor ($m^2\ s^{-1}$); E_a is referred to as activation energy for moisture diffusion (kJ mol^{-1}); R is the universal gas constant (8.315×10^{-3} kJ mol^{-1} K^{-1}); and T is the absolute temperature (K). The obtained data showed that an increase in drying temperature resulted in a lower drying time. On the other hand, drying chamber pressure did not affect the drying time. Among the drying models used for fitting the drying curve, the proposed polynomial model provided the best result. The effect of moisture content on the shrinkage was well described ($R^2 > 0.98$) by linear models. It was observed that the lower the moisture content, the higher the shrinkage. Effective diffusivities of eggplant slices ranged between 1.6×10^{-9} and 3.4×10^{-9} $m^2\ s^{-1}$ as function of variable temperature and pressure. The activation energy for moisture diffusion was presented per unity of mass, i.e., 1,640 kJ/kg. Considering the molecular weight of water as 18 g mol^{-1}, the activation energy was 29.52 kJ mol^{-1}.

Sahari et al. [27] optimized the vacuum drying of dates in order to obtain high quality date powder. Dates are important to the economy of Middle East countries and this was claimed to be the first time that the vacuum drying of dates was studied. The drying temperature varied from 85 to 100 °C and the vacuum pressure varied from 15.3 to 60.1 cmHg. In addition, five different thicknesses of product were tested: 0.2, 1.0, 2.0, 2.5 and 3.0 cm. As a result, a temperature of 85 °C, a pressure of 54.6 cmHg and a product thickness of 1 cm were selected as the optimum conditions. When using the optimum drying conditions, a final product with good smell and color was obtained and the process proved to be cost-effective.

Amellal and Benamara [1] studied the vacuum drying of date pulp cubes from three different varieties, emphasizing the effect of different drying temperatures (60–100 °C) on the drying kinetics of the product. Pressure was fixed at 200 mbar. The Newton [16] and the Henderson-Pabis [8] drying models were used to fit the data. They are respectively presented below:

$$M_R = \exp(-kt) \tag{6}$$

$$M_R = a\exp(-kt) \tag{7}$$

where M_R is the dimensionless moisture ratio presented in Eq. 2; k is the drying rate constant (min^{-1}); a is a model constant and t is time (min). In addition, effective diffusion coefficients were obtained by using Eq. 1 and their temperature dependency was estimated by means of Eq. 5. As expected, an increase in temperature from caused an increase in drying rates. The Henderson-Pabis model was superior to the Newton model as for fitting the kinetics, which was denoted by higher R^2 value and lower mean relative error. The effective diffusion coefficients varied between 2.72×10^{-11} and 1.0×10^{-10} m^2 s^{-1}, being this variation with respect to different date varieties and drying temperatures. The activation energies varied between 13.29 and 24.70 kJ mol^{-1} for different varieties of date. In conclusion, vacuum drying proved a suitable process for increasing dates shelf life and the drying kinetics was well described by the Henderson-Pabis model.

Lee and Kim [13] carried out a comprehensive study on the vacuum drying of Asian radish slices, a popular vegetable in South Korea. The effect of different drying temperatures (40–60 °C) and sample thicknesses (4–6 mm) on drying kinetics/drying rate was compared. Pressure was fixed at 0.1 mPa. Nine thin-layer drying models were tentatively used to fit the changes in radish moisture during drying. The effective diffusivities for various drying conditions were estimated by using Fick's second law for slabs (Eq. 1) and their dependence on temperature was estimated by using an Arrhenius-type relationship (Eq. 5). Those authors observed that working with high temperature and low slice thickness yielded high drying rates. The logarithmic model [31] was found to best represent the drying kinetics, yielding high values of coefficient of determination and low values of root mean square error, mean relative percent deviation and reduced chi-square. Such model is presented below:

$$M_R = a\exp(-kt) + c \tag{8}$$

where M_R is the dimensionless moisture ratio presented in Eq. 2; k is the drying rate constant (min^{-1}); a and c are model constants and t is time (min). The values of effective diffusivity ranged from 6.92×10^{-9} to 14.59×10^{-9} m^2 s^{-1}, being this variation with regard to various product thicknesses and drying temperatures. Increase in temperature promoted an augment in the values of effective diffusivity, while increase in thickness promoted a decrease in these values. A linear regression was successfully applied to relate effective diffusivity and temperature for the two thicknesses tested. In this way, it became possible to estimate the effective diffusivity of Asian radish slices on the basis of drying temperature for process designing purposes. The values of activation energy ranged from 16.49 to 20.26 kJ mol^{-1}, for different thicknesses. Summarizing, the logarithmic model provided the best fit for the vacuum drying kinetics of Asian radish slices and the effective diffusivities and activation energies were within the range usually observed for foods.

Arévalo-Pinedo et al. [4] compared the effect of variable vacuum drying conditions on the values of effective diffusivity of carrot as obtained by using Fick's diffusional model with and without shrinkage. In the lab, the carrots were sliced and then, pretreated by either blanching or freezing, in an attempt to improve the drying rate. The vacuum drying process was carried out at a temperature of 50, 60 or 70 °C and a pressure of 5, 15 or 25 kPa. For modeling the drying kinetics without considering product shrinkage, unidirectional moisture diffusion in a flat plate (slab) was considered (Eq. 1), as based on Fick's second law of diffusion. For considering shrinkage, the above mentioned diffusional model was changed by adding the density of the dry solid to it (see [23] for more details). Results showed that both pretreatments increased the drying rate, even though frozen/thawed carrots were dried faster than blanched/cooled carrots. Such behavior was attributed to easier moisture removal due to cell disruption caused by freezing. Higher temperatures and lower pressures led to higher drying rates, which were associated with higher values of effective moisture diffusivity. This behavior was attributed to the puffed structure formed in the food during low pressure drying. Considering the different temperatures, pressures and pretreatments, the values of effective diffusivity ranged from 1.27×10^{-9} to 4.84×10^{-9} m^2 s^{-1} when shrinkage was neglected and from 1.11×10^{-9} to 3.40×10^{-9} m^2 s^{-1} when shrinkage was considered. To sum up, it can be affirmed that combining freezing pretreatment, high drying temperatures and low drying pressures leads to high values of effective moisture diffusivity and high drying rates during the vacuum drying of carrots.

Artnaseaw et al. [5] studied the heat pump vacuum drying of mushrooms and chilies from Thailand. As mentioned by the authors, in a vacuum drying process heat can be obtained by several ways, such as electric sources, microwaves and heat pumps. The latter was chosen for that study. For this purpose, an experimental apparatus was constructed. Different temperatures (55–65 °C) and pressures (0.1–0.4 bar) were used. In most of the cases, the use of higher temperatures and lower pressures yielded increased drying rates. Among eleven thin layer drying models used to fit the drying kinetics, the Midilli model [18] presented the best results, i.e., high values of R^2, low values of reduced chi-square and low values of root mean square error. The Midilli model is presented below:

$$M_R = a\exp\left[-k\left(t^n\right)\right] + bt \tag{9}$$

where M_R is the dimensionless moisture ratio presented in Eq. 2; a, k, n and b are model constants and t is time (h). The four constants of the Midilli model were obtained by using regression analysis and expressed as a function of drying temperature or drying pressure. For this purpose, polynomial models provided a good fit ($R^2 > 0.98$). Some quality parameters, viz. color and rehydration capacity were measured in the dried product. In this sense, higher drying temperatures led to lower color degradation, which was attributed to shorter drying times. In addition, lower drying pressures led to lower color degradation too, which was attributed to low oxygen concentration in the drying chamber. In time: oxygen participates in the enzymatic browning reaction. The rehydration capacity decreased with an augment in drying pressure, but no effect of temperature was observed. In sum, this study established process conditions suitable for producing dried mushrooms and chilies by vacuum drying with a proper quality.

Lee and Kim [14] performed the dehydration under controlled conditions of water dropwort (*Oenanthe javanica* DC.), an herb that is used in Korean soups and stews. The work aimed at evaluating the effect of various drying temperatures and pretreatments on drying kinetics and product color parameters. The drying temperature varied between 50 and 70 °C. The pretreatments consisted in blanching at 80 °C during 2 min or dipping in a 1 % potassium meta bisulphate (KMS) aqueous solution for 3 min. Pressure was fixed at 0.1 mPa. Results showed that the use of higher temperatures led to higher drying rates, as expected. Blanched samples were dried faster than control while 1 % KMS treated samples were dried slower than control. The drying kinetics was tentatively fitted by nine thin layer drying models. The goodness of the fit was evaluated by taking into account the values of coefficient of determination, reduced chi-square and root mean square error. The Page model [22] proved to be the most appropriate for explaining the moisture loss of water dropwort during vacuum drying. The Page model can be expressed as:

$$M_R = \exp\left(-kt^n\right) \tag{10}$$

where M_R is the dimensionless moisture ratio presented in Eq. 2; k and n are model constants and t is time (min). The drying process was shown to occur in the falling rate period, i.e., no constant-rate drying period was observed. Regarding color, the herbs turned darker and lost some of their green-yellow color, i.e., decrease in L* and b* values and increase in a* value. The total color change was more pronounced for 1 % KMS treated samples. Summarizing, the authors recommended that the vacuum dried water dropwort be obtained by blanching followed by drying at 60 °C, which yields a final product with the lowest color degradation.

Mitra et al. [19] optimized the vacuum drying of onion slices by using the response surface methodology. This was a significant study given the wide culinary use of the selected raw material. A factorial design was used to investigate the effect of drying temperature (50–70 °C), slice thickness (1–3 mm) and presence/absence of pretreatment (5 % NaCl plus 0.2 % $K_2S_2O_5$ for 15 min) on quality features of the final product, namely moisture content, color, flavor and rehydration capacity. Second and first order polynomial models successfully explained the effect of the factors on the responses, as denoted by high values of coefficient of determination and low values of coefficient of variation. Optimum quality, expressed as low moisture content, low color change, high flavor retention and high rehydration capacity, was obtained by using the following process conditions: pretreatment followed by slicing the onions to 4.95 mm thickness and drying them at 58.66 °C and 50 mmHg of absolute pressure.

Mitra et al. [20] studied the vacuum drying of onion emphasizing the effect of different process temperatures, slice thicknesses and the use of a pretreatment on the drying kinetics. Thin layer drying models were tentatively used to fit the drying data. Furthermore, the effective diffusivity under different conditions was calculated (Eq. 1) and its dependence on temperature and thickness was investigated. Those authors observed that, at a fixed pressure (50 mmHg), a rise in drying temperature from 50 to 70 °C caused an increase in drying rate. On the other hand, the pretreatment tested (5 % NaCl and 0.2 % $K_2S_2O_5$) did not affect the drying kinetics of thin slices (1 and 3 mm), only of thick slices (5 mm). Comparing four drying models, the Page model (Eq. 10) was found to be the most proper to fit the drying kinetics, yielding high values of R^2 and low values of root mean square error and reduced chi-square. The effective diffusivity as calculated by Fick's second law (Eq. 1) ranged from 1.32×10^{-10} to 1.09×10^{-9} m^2 s^{-1}, values that are related to different thicknesses and temperatures. The dependence of effective diffusivity on temperature and thickness was more properly described by an Arrhenius type equation when compared to a regression model. To sum up, the Page model showed to be proper for describing the moisture variation of onion slices during vacuum drying and the effective diffusivities obtained were within the general range for foods.

Ashraf et al. [6] modeled the vacuum drying of date paste and investigated the effect of variable drying conditions on drying rates. The variables tested were drying temperature (60–80 °C) and sample thickness (1–2 cm). The absolute pressure was kept at 20 kPa. In addition, effective diffusivities were calculated (Eq. 1) and their dependence on temperature was estimated (Eq. 5). Results showed that the Jena and Das, the Verma and the modified Henderson-Pabis models were the most suitable for estimating the changes in moisture content of date paste, yielding high values of coefficient of determination and low values of reduced chi-square and root mean square error. Since the Jena and Das model has been presented before (Eq. 3), only the Verma [29] and the modified Henderson-Pabis [11] models will be shown below, respectively:

$$M_R = a\exp(-kt) + (1 - a)\exp(-gt) \tag{11}$$

$$M_R = a\exp(-kt) + b\exp(-gt) + c\exp(-ht) \tag{12}$$

where M_R is the dimensionless moisture ratio presented in Eq. 2; a, b, c, g, h and k are model constants and t is time (min). It was observed that the use of low product thickness and high drying temperatures resulted in high drying rates. The effective diffusivities as calculated by the Fick's second law of diffusion for a slab (Eq. 1) presented values between 6.085×10^{-8} and 4.868×10^{-7} m^2 s^{-1}. When high temperatures and high sample thickness were used, high values of effective diffusivities were obtained. In time: thin slabs are more subjected to surface hardening, which impairs the moisture diffusion. Finally, the temperature dependence of the effective diffusion coefficient was well described by an Arrhenius type equation (Eq. 5). The activation energy ranged from 33.71 to 54.96 kJ mol^{-1} for variable product thickness. In conclusion, three models presented a proper fit for the kinetic data and the values of effective diffusivity and activation energy were slightly above the usual values for foods.

Lee et al. [15] studied the vacuum drying of *Salicornia herbacea* L., a salt-tolerant herb which presents functional properties. The drying kinetics was obtained for 50, 60, 70 and 80 °C. Absolute pressure was kept at 0.1 mPa. The drying rates were calculated. Thin layer drying models were used to fit the data. The dependence of the drying constant of the best model on temperature was estimated by an Arrhenius type equation. With regard to quality evaluation, the color of the dried/powdered herbs and the image of the dried herbs were analyzed. It was observed that the higher the drying temperatures, the higher the drying rates. Drying rates decreased with the advance of the drying process. In time: the residual water present in the food at the end of drying is strongly bounded to the other food components, taking longer to be removed. Among seven mathematical models used, the logarithmic model (Eq. 8) was found to be the most suitable for fitting the drying kinetics. This finding was supported by the values of coefficient of determination, root mean square error, mean relative percent deviation and reduced chi-square. The drying constant "k" in the logarithmic model was shown to be temperature dependent, with an activation energy of 15.02 kJ mol^{-1}. The dried product, which was originally dark green, became light green after drying, as expressed by increase in lightness (L*), yellowness (b*) and saturation (C*) and decrease in redness (a*) and hue angle (h*). The total color difference (ΔE) between the fresh and the dried sample varied between 26.40 and 27.03 for the various temperatures tested. The images obtained with a scanning electron microscope presented a high amount of wrinkles, especially for higher drying temperatures. On the other hand, pores were not found. Taking into consideration proper color preservation and short drying time, the process conducted at 80 °C was found to be the most suitable.

Reis et al. [24] elucidated and modeled the vacuum drying kinetics of yacon (*Smallanthus sonchifolius*) and studied the effect of variable drying conditions on the final product fractal dimension and rehydration ratio. The tubers were sliced at thicknesses ranging from 0.2 to 0.6 cm and pretreated by immersion in citric acid solutions (0.2–1.0 % w/w). Drying temperature varied from 45 to 65 °C. Pressure was fixed at 7.6 kPa. Among the models tested, the modified Page model [21] was found to provide the best fit to the experimental data. The modified Page model can be represented as

$$M_R = \exp\left[(-kt)^n\right] \tag{13}$$

where M_R is the dimensionless moisture ratio presented in Eq. 2; k and n are model constants and t is time (h). Among the variable drying conditions, it was observed that the higher the drying temperature, the lower the product fractal dimension. The use of the fractal dimension to express the quality of foods is recent. This novel quality parameter presents the advantages of being easily measured by an image analysis and providing a comprehensive profile of one food appearance, which is not achievable with a colorimeter. Increase in slice thickness was found to negatively affect the rehydration capacity of the yacon slices, which was justified by the difficulty of the rehydration water to reach the inner portions of the thicker slices. In addition, significant correlations were obtained between fractal dimension and color, moisture content and rehydration capacity, suggesting that these typical quality features could be substituted by an image analysis.

Reis et al. [25] studied the changes in color and texture of yacon slices during vacuum drying and the effect of different drying conditions on such quality features. In addition, the vacuum drying conditions were optimized toward color quality by means of the response surface methodology. The tubers were sliced to 0.2, 0.4 and 0.6 cm and pretreated by immersion in citric acid solutions (0.2–1.0 % w/w). Drying temperature was set at 45, 55 or 65 °C. Pressure was fixed at 7.6 kPa. Yacon color was expressed by using CIE L*a*b* and CIE L*C*h* color spaces. The authors observed that the product color changed during drying as per a decrease in lightness (L*) and an increase in redness (a*) and yellowness (b*). The product hardness did not present significant changes during initial stages of drying, followed by softening and hardening. Such results are attributed a loss of the original vegetable cells turgor followed by formation of external crust at the end of drying. Results showed that the use of high drying temperatures (58–65 °C), high citric acid concentrations (0.8–1.0 g/100 g) in the pretreatment solution and low thicknesses ($\leq$0.4 cm) yielded a product of ideal color, which was represented by high lightness (L*), high yellowness (b*) and high colorfulness (C*).

Thorat et al. [28] studied the vacuum drying of ginger (*Zingiber officinale* R.). The influence of different vacuum drying temperatures (40–65 °C) on the drying kinetics of ginger slices was elucidated. The absolute drying pressure was 8 kPa. The drying curve was modeled by using five thin layer drying models. The effective diffusion coefficient was estimated by using Eq. 1 and the effect of temperature on it was tentatively described by an Arrhenius-type relationship (Eq. 5). It was observed that the use of higher temperatures (65 °C) led to higher drying rates compared to the use of lower temperatures (40 °C). The two-term mathematical model provided the best fit to the drying curve, as confirmed by high values of R^2 and low values of reduced chi-square and root mean square error. The two-term model (Henderson 10) is represented as follows:

$$M_R = a\exp(-kt) + b\exp(-k_0 t) \tag{14}$$

where M_R is the dimensionless moisture ratio presented in Eq. 2; a, b, k and k_0 are model constants and t is time (min). The drying curve could be divided in two falling rate periods, while no constant rate period was observed. The effective diffusion coefficient varied roughly from 1.9 to 4.8×10^{-8} m^2 s^{-1} and proved to be temperature-dependent. The calculated activation energy for water diffusion was 35.7 kJ mol^{-1}. Concluding, the vacuum drying curve of ginger slices was adequately fitted by the two-term model and the values of effective moisture diffusivity and activation energy obtained for the process were within the typical range for food products.

The vacuum drying of loquat fruit (*Eriobotrya japonica* Lindl.) was studied by Saberian et al. [26]. More specifically, the influence of different drying temperatures on the drying time, drying rate and effective moisture diffusivity was evaluated and the drying was tentatively modeled by nine thin layer drying models. Vacuum drying was performed at 60, 70 and 80 °C and a vacuum of 52 cmHg (absolute pressure of ~32 kPa). Results showed that the higher the temperature, the higher the drying rates and the shorter the drying time, as expected. Effective moisture diffusivity as calculated by using Eq. 1 ranged from 6.87×10^{-10} to 1.29×10^{-9} m^2 s^{-1}, increasing with an increase in temperature. With regard to the loquat fruit drying curves modelling, the Page model (Eq. 10) was the most suitable model, with the highest value of coefficient of determination and the lowest values of root mean square error. In addition, the approximation of diffusion model presented a good fit as well. In conclusion, the vacuum drying of loquat fruit was accelerated by an increase in temperature and could be well described by the Page model.

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