https://doi.org/10.3311/PPch.24057

Periodica Polytechnica Chemical Engineering, 68(2), pp. 253–264, 2024

Effect of Hot Air Drying Temperature on Drying Kinetics, Physico-Chemical Properties, and Energy Consumption of Culture Asparagus (*Asparagus officinalis* L.)

Özlem Gökçe Kocabay[1*], Osman İsmail[2], İbrahim Doymaz[2]

[1] Istanbul Restoration and Conservation Center and Regional Laboratory Directorate T.R. Ministry of Culture and Tourism, Topkapı Palace, I. Courtyard, Bab-ı Hümayun Street, Sultanahmet, 34122 Istanbul, Turkey
[2] Department of Chemical Engineering, Faculty of Chemical and Metallurgical Engineering, Yildiz Technical University, Davutpaşa Campus, Esenler, 34210 Istanbul, Turkey
[*] Corresponding author, e-mail: ozlemmgokce@hotmail.com

Received: 13 February 2023, Accepted: 27 February 2024, Published online: 03 June 2024

Abstract

Influences of drying air temperatures on drying time, specific energy consumption as well as product quality of culture asparagus were investigated in hot-air drying. The drying properties of asparagus samples were performed in a laboratory scale convection dryer at three different temperatures. The drying times of asparagus samples were found as 1200, 630 and 510 min for 50, 60 and 70 °C, respectively. In regard to the data obtained, Midilli et al. model is superior to other models to describe drying behavior of asparagus samples. The effective moisture diffusivity values of asparagus samples were calculated between $6.32 \cdot 10^{-9}$–$1.62 \cdot 10^{-8}$ m^2/s and the activation energy was estimated as 43.59 kJ/mol. The highest rehydration content and the least total color change were found in asparagus slices dried at 50 °C. Energy consumption values for asparagus samples dried at 50, 60 and 70 °C temperatures were obtained as 10.14, 5.32 and 4.31 kWh, respectively. In terms of energy consumption values, the best efficiency among all drying temperatures was obtained at 70 °C. It has been determined that the specific energy consumption decreased with increasing temperature.

Keywords

mathematical models, moisture diffusivity, specific energy consumption, rehydration ratio

1 Introduction

There are approximately 300 species of asparagus worldwide [1], of these, solely *Asparagus officinalis* is cultivated and commercialized [2].

Asparagus officinalis L. contained steroit saponins including asparagosides A, B, D, F, G, H, I, the bitter steroid saponins, amino acids, caffeic acid, fructans (asparagose and asparagosine), lignan, polyphenol, ferulic acid, minerals, vitamines and flavonoids [3]. *Asparagus officinalis* L. is regarded as a high-valued vegetable due to its therapeutics and nutraceutical properties. Its contents saponins and fructans play an important role in antitumor activity and diminishment of the risk of diseases for instance constipation, diarrhea in addition disorders such as osteoporosis, obesity, cardiovascular disease, rheumatic and diabetes. The fruits and seeds are also used in the cure of acnes and blood purifying respectively. Pharmacologically the vegetable is invaluable because it involves anti-cancer, anti-oxidant, anti-fungal, antibacterial, antidysenteric, anti-inflammatory, antiabortifacient, anti-oxytoxic, anti-ulcer, hypertensive and anticoagulative activities [4].

China is the world's biggest grower and consumer, whereas Peru is the world's prominent exporter. China produced about 7.7 million metric tons of asparagus as of 2022. According to statistical data from the Statista, the asparagus yield all around the world is approximately 8.7 million tons; the leading producing countries are China, Peru, Mexico, Germany, Italy, Spain, France, Japan, Thailand, United States of America [5]. In 2022, production of asparagus in Turkey skyrocketed to 1.3 ktons [6].

Water is the major component of asparagus, accounting for more than 90% in green spears [7]. Green asparagus is as well a tremendously perishable vegetable. Fresh harvested asparagus degrades rapidly which causes a short shelf-life of 3–5 days under usual post-harvest processing at the room temperature. The very short shelf-life of asparagus is due to the high respiratory activity that proceeds

Cite this article as: Gökçe Kocabay, Ö., İsmail, O., Doymaz, İ. "Effect of Hot Air Drying Temperature on Drying Kinetics, Physico-Chemical Properties, and Energy Consumption of Culture Asparagus (*Asparagus officinalis* L.)", Periodica Polytechnica Chemical Engineering, 68(2), pp. 253–264, 2024. https://doi.org/10.3311/PPch.24057

after harvest. It causes deterioration in quality, loss in amount and decrease in economic values of the asparagus. Reducing of mentioned losses is crucial, particularly to equilibrate supply and demand during the off-season [8].

Drying is one of the key separation processes and is generally applied as an ultimate producing stepping prior sales or packing foodstuffs [9]. The drying processing is commonly practiced to acquire foodstuffs with low cost of transport and storing, in addition novel ways of consumption [10]. Drying is a physical unit process which contains heat and mass transfer, here the latter is generally the rate limiting parameter [11]. Dehydration, in other words drying, ensures long duration preservation and marketability of asparagus [12]. Of all the technics of food preservation, drying remains one the most efficient and largely used for extending shelf-life, conserving compounds and increasing their bioavailability, which greatly minimizes microbial spoilage and degradation reactions [13].

The majority of dryers used in the food industry are of convective type, meaning that hot air is used both to provide heat for evaporation of water and to remove the evaporated moisture from the food product [14]. Hot air drying is by far the most popular technique for drying foodstuffs and more than 85% of industrial dryers use this principle. The reason is that hot-air dryers are easily procurable, easy to operate and have a relatively low initial investment cost [15]. Conventional hot-air drying, the most popular method, is a processing in which foodstuffs are subjected to a constant flow of hot-air [16]. Utilizing hot-air drying method, a more uniform, hygienically and desirably colorful dried material may be obtained rapidly [17]. This method is free of the climatic effects and shortening the drying cycle [18]. At a conventional hot air dryer, dried air is heated electrically and afterward forced to flow through the drying product. The thermal energy provided by the hot air is transferred from the surroundings ambient to the surface of the product by convection, and from there to the interior of the product by conduction. In general, moisture content of the internal side is more than on the surface because of poor heat transfer and low moisture migration through the products, particularly for low porosity products. In consequence, sum drying period extends to provide the whole of material reaching a particular average moisture content. Increasing the hot air temperature or flow-rate can be an alternative to improve drying efficiency [19]. Hot air drying is based on conduction, convection, and diffusion of heat from hot-air for moisture elimination [20].

There are several studies in the literature that examine the drying kinetics of asparagus; for example, drying of natural asparagus by microwave drying [21], drying of wild asparagus (*Asparagus maritimus* L.) by tray drying [22], drying of wild asparagus (*Asparagus racemosus* L.) roots by tray, solar, vacuum and fluidized bed drying [8], drying of wild asparagus roots by solar and fluidized bed drying [23], drying of wild asparagus (*Asparagus maritimus* L.) by convective, natural, and freeze drying [12], drying of asparagus roots (*Asparagus racemosus* Willd.) by hybrid solar and mechanical tray drying [24], drying of shatavari roots (*Asparagus racemosus*) by osmotic dehydration, tray drying, sun drying [25], drying of shatavari roots (*Asparagus racemosus*) by osmotic dehydration and sun drying [26]. As a result of the literature review, it was determined that there are only a few methods for drying culture asparagus (*Asparagus officinalis* L.). Some of them are vacuum freeze-drying [27], a forced convection process [28], tray, spouted bed, combined microwave and spouted bed drying, refractance window and freeze-drying [29], drying using hot air oven and microwave oven [30], drying using microwave oven and hot air oven [31], drying using traditional oven and microwave oven [32], vacuum, far-infrared, hot air, and freeze drying (asparagus stems) [33].

Rehydration is a significant quality indication since it is a measuring of the damage to the material led to drying [34]. Rehydration is the processing of regaining water in dried products. With rehydration, water is absorbed into the tissue in the dried product and, accordingly, the mass of the product increases. In other words, there is mass transfer. While water gain in the dried product occurs rapidly in the beginning of the rehydration process, the rehydration rate diminishes as the product moisture content approaches the equilibrium moisture content value [35]. Over the course of rehydration processing, below steps occur concurrently: absorption of liquid on the part of the dried foodstuff, swelling of the rehydrated product and filtering of the solutes (vitamin, mineral, sugar, acid) from the foodstuff to the rehydrating environment [36].

As far as we know this is the first study on the calculation of activation energy, color measurement, energy and specific energy consumption, rehydration capacity by hot air drying of culture asparagus (*Asparagus officinalis* L.). Within this framework, the goals of this work are:

1. determination of the effect of drying temperature on the drying characteristics of asparagus dried in a cabinet dryer;
2. fitting experimental data to commonly used semi-theoretical mathematical models to describe the thin-layer drying behavior of asparagus (*Asparagus officinalis* L.);

3. determination of the best model to determine drying kinetics;
4. identification of effective moisture diffusivities as a function of moisture content and determination of the activation energy based on Arrhenius Law;
5. calculation of the amount of energy used and specific energy consumption;
6. analyzing the effect of drying on quality attributes such as color, rehydration capacity.

2 Materials and methods

2.1 Sample procurement and preparation

Fresh asparagus samples were obtained at the local market (Istanbul, Turkey) in May 2022. The asparagus specimens procured were of the same size, appearance and maturity at the time of purchase. To preserve the original fresh quality, the samples were kept in the refrigerator (Arcelik, Eskisehir, Turkey) at about 4 °C until the drying experiments started. The initial moisture content of asparagus samples was determined by AOAC method at 105 °C for 24 h [37]. The initial moisture content of asparagus was 9.6145 (kg water/kg dry matter) (kg water/kg d.m.). Before drying processing, the asparagus was thoroughly cleaned and sliced into 5 ± 0.1 cm thickness with a sharp knife.

2.2 Drying equipment

The drying of asparagus slices was performed in an experimental drying cabinet, designed and manufactured at the APV & PASILAC Ltd. of Carlisle, Cumbria, UK. The equipment fundamentally comprises of a centrifuge fan to provide air flow, an electrical heater, an air filter and an electronics proportional controller.

2.3 Experimental

The cabinet dryer was operated empty for approximately 30 min to reach steady-state conditions before each drying test. Then, asparagus samples weighing approximately 100 ± 2 g were spread uniformly on the tray in a single layer. Drying experiments were carried out at air temperatures of 50, 60 and 70 °C and constant air velocity of 2 m/s. Air flow rate during drying experiments was measured with a Testo 440 Vane Anemometer (AM-4201, Lutron, Taipei, Taiwan). During the drying process, the weight changes of the products were recorded every 30 min with a digital balance (BB3000, Mettler-Toledo AG, Grefensee, Switzerland). The drying process was continued until the moisture content of the samples was reduced to approximately 10%. The samples, whose drying process was completed, were left to cool at room temperature. The dried products were then placed in low density polyethylene (LDPE) bags and the bags were thermally sealed. The prepared samples were kept in incubators at ambient conditions for rehydration tests and color measurements. All experiments were repeated three times and drying curves were plotted using average moisture content values.

2.4 Calculating moisture ratio and drying rate

The moisture ratio (*MR*) of asparagus slices was defined using Eq. (1) [20]:

$$MR = \frac{M_t - M_e}{M_0 - M_e}, \tag{1}$$

where M_0, M_t, and M_e are the initial moisture content, moisture content at any given time, and the equilibrium moisture content (kg water/kg d.m.), respectively, and t is drying time (min).

Since M_e values are relatively small compared to M_t or M_0, the moisture ratio is simplified to Eq. (2) [38]:

$$MR = \frac{M_t}{M_0}. \tag{2}$$

The drying rate (*DR*) of asparagus slices was calculated using Eq. (3) [38]:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t}, \tag{3}$$

where $M_{t+\Delta t}$ is the moisture content at time $t + \Delta t$ (kg water/kg d.m.), and t is time (min).

2.5 Statistical analysis

Statistical analyses were carried out by use of Statistica 6.0 (StatSoft Inc., USA) software package [39]. Nonlinear regression analysis was carried out based on the Levenberg-Marquardt algorithm to estimate related parameters of each drying model (given in Table 1). One-way analysis of variance (ANOVA) and multiple comparisons (post-hoc; least significant-difference (LSD) test) were used to evaluate significant differences of data at $p < 0.05$. Data are reported as mean value ± standard deviation (SD).

2.6 Mathematical formulations

The goodness of fit of the models was evaluated on the basis of the coefficient of determination (R^2), the reduced chi-square (χ^2) and the root mean square error (*RMSE*) defined according to Eqs. (4)–(6) [40]:

$$R^2 = 1 - \frac{\sum_{i=0}^{n}\left(MR_{\exp,i} - MR_{\text{pre},i}\right)^2}{\sum_{1=0}^{n}\left(MR_{\exp,i} - \overline{MR}\right)^2}, \tag{4}$$

$$x^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\text{pre},i}\right)^2}{N-n}, \tag{5}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\text{pre},i} - MR_{\exp,i}\right)^2\right]^{1/2}, \tag{6}$$

where $MR_{\exp,i}$ and $MR_{\text{pre},i}$ are the i^{th} experimental and predicted moisture ratios, respectively; N is the number of observations; and n is the number of drying constants. The goodness of fit is expressed by high R^2 values and low *RMSE* and χ^2 values [41].

2.7 Determination of the effective moisture diffusivity

Effective moisture diffusivity (D_{eff}) is an important transport property in modelling drying processes of foodstuffs and other materials, and is a function of temperature and moisture content in the material. Fick's second law of diffusion has been commonly made use to predict drying processing (controlled by internal diffusion) over the course of the falling-rate period for many agricultural products and given in Eq. (7) [42]:

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M. \tag{7}$$

The diffusion equation (Eq. (7)) was computed for slab geometry with the assumptions of constant diffusivity, unidimensional moisture movement, volume change, constant temperature and negligible external resistance [43]. The formula was presented in Eq. (8):

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right), \tag{8}$$

where L is the half-thickness of the asparagus slab (m). For long drying times, Eq. (8) can be further simplified to Eq. (9) [44]:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right). \tag{9}$$

Equation (10) is the logarithmic form of Eq. (9) and is used for long drying periods [45]:

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4L^2}\right). \tag{10}$$

When ln*MR* is plotted versus drying time (t), it produces a slope (K) that can be used to describe the effective diffusivity in Eq. (11) [45]:

$$K = \frac{\pi^2 D_{eff}}{4L^2}. \tag{11}$$

2.8 Activation energy

The effective moisture diffusivity can be related with temperature by Arrhenius-type expression [8], thus Eq. (12) is obtained:

$$D_{eff} = D_0\exp\left(-\frac{E_a}{R(T+273.15)}\right), \tag{12}$$

where D_0 is the constant of Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), T is the temperature (°C) and R is the universal gas constant (kJ/(molk)).

When Eq. (12) is rearranged, Eq. (13) is obtained:

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R(T+273.15)}. \tag{13}$$

2.9 Quality parameters

2.9.1 Color difference

The color of each sample was determined using a CR-200 model chromameter (Minolta Co., Osaka, Japan), which was calibrated before reading. One of the widely used methods for analyzing color is the Hunter color analysis, which involves measuring the lightness-darkness value L, redness-greenness value a, and yellowness-blueness value b [46]. The color parameters of the samples were measured at five points of each sample pile immediately after drying. The total color change (ΔE) of dried samples can be calculated according to Eq. (14) using fresh samples as reference standard [47]:

$$\Delta E = \sqrt{\left((L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2\right)}. \tag{14}$$

where L_0, a_0, and b_0 are the color values of fresh asparagus samples before drying. L, a and b are the color values of fresh asparagus samples after drying.

2.9.2 Rehydration ratio measurement

The rehydration ability of a dried material is measured by the amount of water gained by soaking the product in water under certain conditions. Asparagus samples dried with hot air at three different temperatures were then subjected to rehydration tests at 25 ± 2 and 50 ± 2 °C. Samples of asparagus weighing approximately 5 ± 0.5 g on a dry basis was immersed into a 500 mL glass Erlenmeyer flask including 400 mL of distilled water. Specimens were removed from the rehydration media every 30 min, the surface was gently dried with a paper towel and weighed. The weights of the specimens were measured using an electronic digital balance with an accuracy of 1 mg. Rehydration trials continued until the product reached equilibrium weight. The rehydration ratio (*RR*) of asparagus specimens during rehydration (weight gain on rehydration) can be expressed by Eq. (15) [12]:

$$RR = \frac{W_r}{W_d}, \tag{15}$$

where W_r is the drained weight (g) of the rehydrated specimen and W_d is the weight of the dry specimen used for rehydration. All rehydration tests were repeated three times.

2.10 Energy consumption

In hot-air drying, the electricity necessity for both drying of the specimens and blowing of the air were taken into consideration in the total energy consumption and was calculated by Eq. (16) [48]:

$$E_t = Av\rho_a c_a \Delta T D_t. \tag{16}$$

where E_t is the total energy consumption (kWh), ρ_a is the air density (kg/m^3), A is the cross sectional area of the container in which the sample is placed (m^2), v is the air velocity (m/s), c_a is the specific heat (kJ/(kg°C)), ΔT is the temperature difference between inlet and outlet air (°C), D_t is the total drying time of each sample (h).

Other significant point for drying favorable circumstances is the energy consumption quantity. The total energy consumption of the drying process was evaluated by specific energy consumption (SEC). Specific energy consumption, a measure of the energy required to evaporate a unit mass of water from the material, can be calculated by Eq. (17) [41]:

$$Q_s = \frac{E_t}{m_w}, \tag{17}$$

where Q_s is the specific energy consumption (kWh/kg water), E_t is the energy consumed (kWh), and m_w is the mass of water vaporized (kg).

3 Results and discussion

3.1 Determining the drying characteristics of asparagus samples

Fig. 1 shows how the moisture content of asparagus slices decreases with increasing drying time for different drying temperatures. Experimental error was calculated in the terms of standard deviation (SD). The average results were presented with ± SD value.

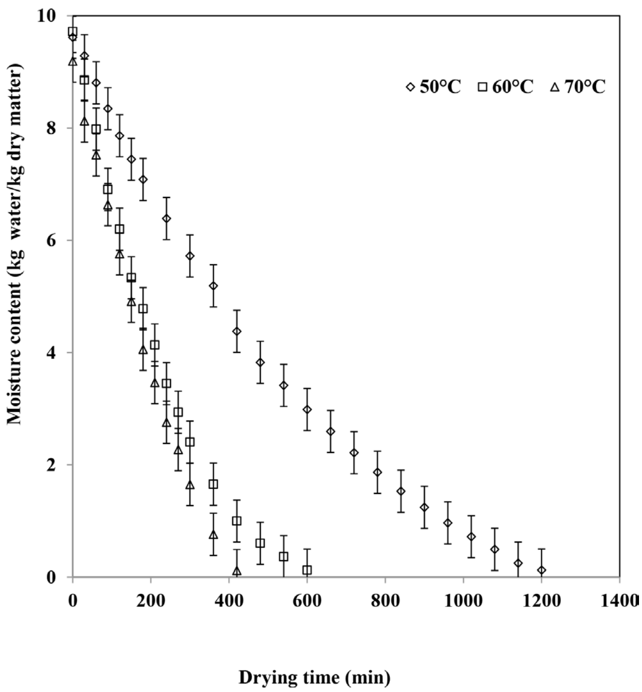

Fig. 1 Drying curves of asparagus specimens dried at 50, 60 and 70 °C

As shown in Fig. 1, the drying times of asparagus samples were found to be 1200, 630 and 510 min at 50, 60 and 70 °C, respectively. The type of graph is similar to reports presented in the literature [24]. The results obtained show that air temperature has a significant effect on drying time in hot-air drying technique. If the drying air temperature rises, the difference between the air and drying material temperatures increases. Higher temperatures therefore lead to faster evaporation of moisture and a shorter drying period. In addition, the interfacial moisture concentration for drying materials is higher when the temperature increases. This is because the interfacial concentration is a function of the wet-bulb temperature of the air. At higher temperatures the interfacial concentration and thus the driving force for mass transfer increases. Accordingly, this effect results in faster mass transfer between the materials and the drying air and therefore, shorter drying periods [49].

The drying rates of asparagus samples at 50, 60 and 70 °C were calculated using Eq. (3) and this change is shown in Fig. 2.

According to Fig. 2, as the drying air temperature increases, the drying rate also increases. Increasing the temperature increases the mass transfer coefficient, thus increasing the evaporation rate. Similar findings were also observed by Elmizadeh et al. [50]. The drying kinetics showed that the drying of asparagus slices took place

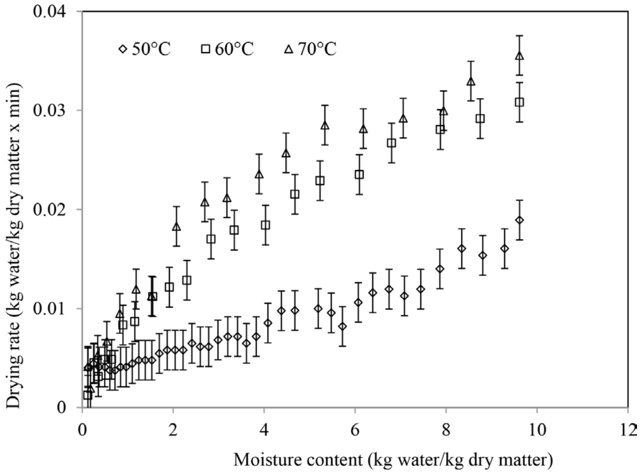

Fig. 2 Drying rates versus moisture content of asparagus samples at 50, 60 and 70 °C

predominantly during the falling rate period, which proves that the product surface is henceforth saturated with water and the drying rate is controlled by the internal diffusion phenomenon according to the mass transfer controlling processing [51]. At the falling rate period, water migration from the material inner to the surface is largely owing to molecular diffusion, in other words the water flux is proportional to the moisture content gradient. This means that water moves from sites with higher moisture content to the sites with lower values, a phenomenon expressed by the second law of thermodynamics [49]. Similar findings are also available in the literature [23].

3.2 Models of drying kinetics

Drying is a complicated thermal process in which unsteady heat and moisture transfer take place at the same time. From an engineering perspective, a better comprehension of the control factors of this complicated process is crucial. Mathematical models of drying processes are used to control the drying process. Numerous mathematical models have been suggested to determine the drying process, of which thin layer drying models are widely used [17]. To calculate the moisture rates, the data obtained from asparagus specimens dried at 50, 60 and 70 °C were entered into Eq. (2). The data obtained were then fitted to the six thin layer drying models given in Table 1 [52–57].

Nonlinear regression was used to calculate each parameter value of each model. The statistical results obtained through the models are summarized (Tables 2–4).

As seen in Tables 2–4, according to the statistical parameter calculations, R^2, χ^2, and *RMSE* values are between 0.9728 and 0.9999, 0.000006 and 0.002667 and 0.002118 and 0.058096, respectively. The Midilli et al. [57] model has a good fit with high R^2 and low χ^2 and RMSE values and was selected as the best model (as shown in Tables 2–4). The data obtained in a study showed that among the tens tested mathematical models, the Midilli et al. [57] model described more correctly experimental data for all drying temperatures and for both olive leaf varieties [58]. The R^2, χ^2, and RMSE values ranged between 0.9990 and 0.9999, 0.000006 and 0.000131, 0.002118 and 0.009864, respectively. This result is consistent with previous studies [59].

Table 1 Drying models

Model names	Model equation*	References
Lewis	$MR = \exp(-kt)$	[52]
Page	$MR = \exp(-kt^n)$	[53]
Wang and Singh	$MR = 1 + at + bt^2$	[54]
Logarithmic	$MR = a\exp(-kt) + c$	[55]
Aghbashlo	$MR = \exp((-k_1 t) / (1 + k_2 t))$	[56]
Midilli	$MR = a\exp(-kt^n) + bt$	[57]

* a, b: coefficients; k, k_1, k_2; n: drying constants; MR: moisture ratio; t: drying time

Table 2 Statistical parameters of thin layer drying models used for drying kinetics of asparagus specimens at 50 °C

Model name	R^2	χ^2	RMSE
Lewis	0.9930	0.000381	0.016573
Page	0.9961	0.000543	0.021739
Wang and Singh	0.9982	0.000215	0.014598
Logarithmic	0.9991	0.000103	0.009972
Aghbashlo	0.9994	0.000078	0.008361
Midilli	0.9997	0.000029	0.005043

Table 3 Statistical parameters of thin layer drying models used for drying kinetics of asparagus specimens at 60 °C

Model name	R^2	χ^2	RMSE
Lewis	0.9783	0.002067	0.055192
Page	0.9974	0.000214	0.015608
Wang and Singh	0.9969	0.000446	0.019978
Logarithmic	0.9979	0.000453	0.019314
Aghbashlo	0.9995	0.000064	0.007428
Midilli	0.9990	0.000131	0.009864

Table 4 Statistical parameters of thin layer drying models used for drying kinetics of asparagus specimens at 70 °C

Model name	R^2	χ^2	RMSE
Lewis	0.9728	0.002667	0.058096
Page	0.9955	0.000311	0.018093
Wang and Singh	0.9974	0.000456	0.019897
Logarithmic	0.9971	0.000432	0.019304
Aghbashlo	0.9997	0.000012	0.005589
Midilli	0.9999	0.000006	0.002118

3.3 Determination of effective moisture diffusivity

The calculated D_{eff} values are shown in Fig. 3.

D_{eff} values ranged between $6.32 \cdot 10^{-9}$ and $1.62 \cdot 10^{-8}$ m²/s. The range obtained is in good agreement with other hot air dried materials, in particular $1.809 \cdot 10^{-9}$ to $4.649 \cdot 10^{-9}$ m²/s for peppermint leaves [49] and $9.20 \cdot 10^{-8}$ m²/s for Shatavari roots (*Asparagus racemosus*) [25]. The calculated effective moisture diffusivity values were in agreement with the general range reported to be between 10^{-8} and 10^{-12} m²/s for foodstuffs [60]. If the drying temperature increases, the D_{eff} values also increase. This is probably due to the fact that the increase in drying temperature leads to more absorption of moisture, increasing the moisture gradient between the sample and the medium, which results in an increase in D_{eff} [61]. The result is consistent with the report by Patil et al. [25] for shatavari roots (*Asparagus racemosus*) dried by osmotic dehydration, tray and sun drying.

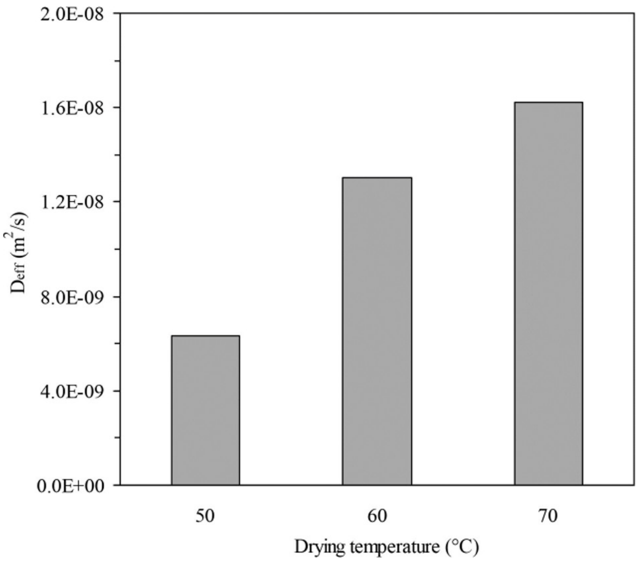

Fig. 3 Effective moisture diffusivity values versus different drying air temperatures

3.4 Calculation of activation energy

E_a is the energy required for moisture diffusion in materials. The (E_a) was calculated from the slope of the plot of ln(D_{eff}) versus the reciprocal of temperature (1)/(T+273.15) in Fig. 4.

Eq. (18) shows the effect of temperature on the D_{eff} of the samples with the following coefficients:

$$D_{eff} = 7.6115 \times 10^{-2} \exp\left(-\frac{5243.5}{(T + 273.15)}\right) \quad (18)$$

$$\left(R^2 = 0.9222\right).$$

The E_a value was calculated as 43.59 kJ/mol. The activation energy values calculated in this study are in the range of 12.7–110 kJ/mol indicated for various food materials [60].

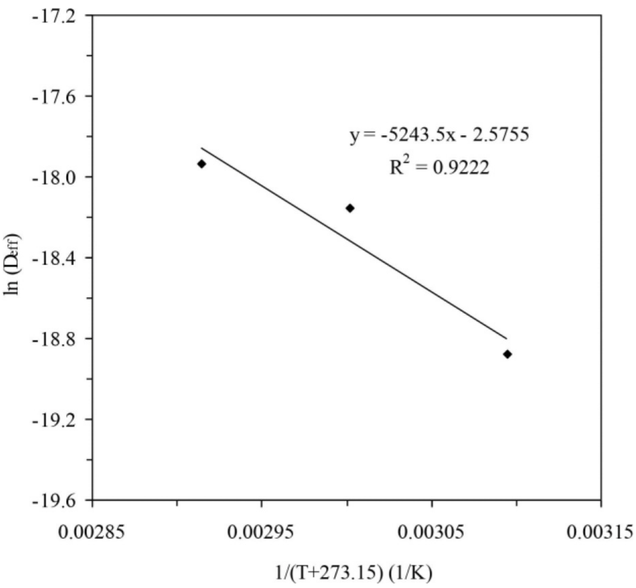

Fig. 4 Arrhenius-type relationship between the logarithm of effective moisture diffusivity (D_{eff}) and the inverse of absolute temperature for asparagus slices

3.5 Color measurement

Color changes of fruits and vegetables can be considered as a criterion of their chemical changes [62]. One of the main criteria used in the evaluation of the color quality of dried asparagus specimens is to obtain products with higher brightness, slight redness and slightly yellowness, which are more preferred in terms of color quality. Changes in the color of the asparagus samples are illustrated by the data (Table 5).

The color values of asparagus samples before drying were as follows: $L_0 = 42.03 \pm 0.47$; $a_0 = 0.61 \pm 0.18$; $b_0 = 10.35 \pm 0.53$. L, a and b values of dried asparagus specimens were ranged between 42.14 ± 0.93–45.69 ± 0.58, 0.97 ± 0.19–2.71 ± 0.31 and 10.38 ± 0.28–11.13 ± 0.32, respectively (Table 5). L values of fresh asparagus samples increased slightly after hot air drying ($p < 0.05$). In other words, the calculated results show that there is no statistically significant differences in lightness values between 50 and 70 °C as a result of hot air drying. Furthermore, the a and b values of dried asparagus samples were higher than fresh asparagus ($p < 0.05$). Compared to the color parameters of fresh asparagus samples, the a values of dried asparagus samples increased significantly, while the increase in b values was very limited. A higher

Table 5 Color parameters of the samples and statistical analysis with one-way ANOVA with variances

Temperature (°C)	*L*	*a*	*b*	Δ*E*
Fresh	42.03 ± 0.47^{c}	0.61 ± 0.18^{c}	10.35 ± 0.53^{c}	–
50	43.82 ± 0.95^{d}	0.97 ± 0.19^{d}	11.13 ± 0.32^{d}	1.985 ± 0.26^{d}
60	45.69 ± 0.58^{e}	1.53 ± 0.25^{e}	10.97 ± 0.64^{e}	3.824 ± 0.29^{e}
70	42.14 ± 0.93^{f}	2.71 ± 0.31^{f}	10.38 ± 0.28^{f}	2.103 ± 0.46^{c}

Values are shown as means ± standard deviation (SD); c, d, e, f- groups that are statistically significantly ($p < 0.05$) different from each other according to drying temperature.

ΔE means a larger color change then the reference product. In this study, ΔE values of the samples convectively dried at different temperatures varied between 1.985 ± 0.26 and 3.824 ± 0.29. Drying at 60 °C caused the highest total color difference value (ΔE). The minimum ΔE value was obtained in asparagus samples dried at 50 °C. The findings are comparable to those of Jokič et al. [12] for wild asparagus and Kipcak and İsmail [21] for culture and natural asparagus.

The analysis showed that drying temperature had a statistically significant effect on asparagus color. ANOVA analysis of the total color change of dried asparagus samples showed the existence of four groups significantly different from each other ($p < 0.05$; post-hoc LSD) due to different drying temperatures. Increasing the drying temperature generally led to a greater color change and resulted in a darker color. This indicates that the intensity of greenness decreases and yellowness increases due to the decrease in total chlorophyll content [12]. High temperature can cause the magnesium in chlorophyll to be replaced by hydrogen, thereby transforming chlorophylls into pheophytins [63]. Color changes caused by drying temperatures in asparagus samples may be closely related to pigment degradation, formation of brown pigments with nonenzymatic (Maillard reaction) and enzymatic reaction.

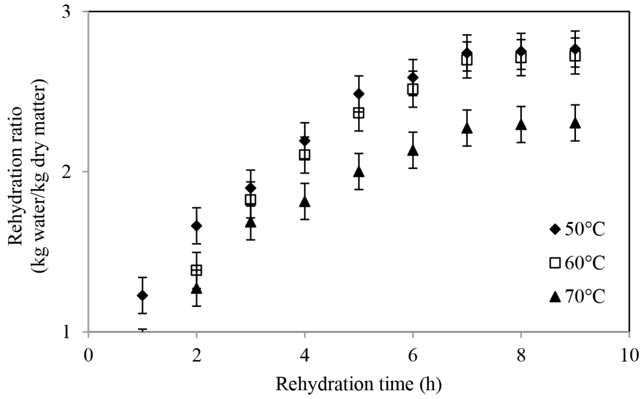

Fig. 5 Rehydration curves of asparagus samples dried at three different temperatures at 25 °C

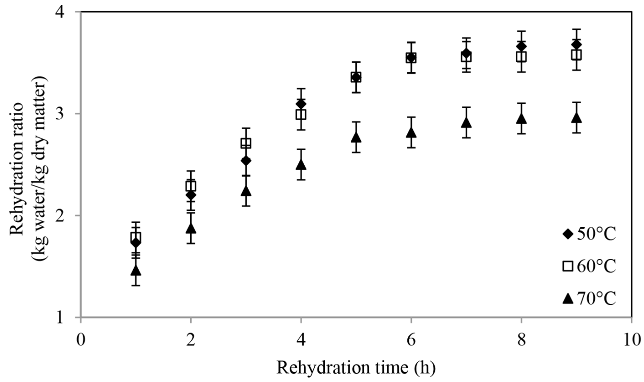

Fig. 6 Rehydration curves of asparagus samples dried at three different temperatures at 50 °C

3.6 Rehydration ratio (*RR*)

Rehydration is a complex process influenced by different parameters (e.g., drying method and conditions, pretreatments, physical structure and chemical composition). To obtain dried material with good rehydration properties, it is very important to optimize the drying conditions, because rehydration governs the subsequent processes [64].

The plots of rehydration ratio versus rehydration time of asparagus samples dried at different temperatures and subjected to rehydration tests at 25 and 50 °C are shown in Figs. 5 and 6. Experimental error was calculated in the terms of standard deviation (SD). The average results were presented with ± SD value.

Hyperbolic curves were obtained as shown in Figs. 5 and 6. As can be seen from the figures, the dried asparagus samples absorbed a high amount of water for 3–4 hours, but the change in water content became negligible after 6 hours. This finding is consistent with the work of other researchers who have previously studied rehydration [65]. According to Fig. 5, the rehydration ratios of asparagus samples dried at 50, 60 and 70 °C for 25 °C rehydration temperature were calculated as 2.76, 2.72 and 2.30 (kg water/kg d.m.), respectively. For rehydration temperature of 50 °C, rehydration ratios of asparagus samples dried at 50, 60 and 70 °C were calculated as 3.68, 3.57 and 2.96 (kg water/kg d.m.), respectively (Fig. 6). Moisture content at 50 °C changed more rapidly than at 25 °C in all cases. In other words, increasing the temperature from 25 to 50 °C increased the amount of water absorbed. This result can be expressed by the fact that the higher the wetting water temperature, the faster the water spreads through the material.

In rehydration trials at 25 and 50 °C, the highest rehydration value was obtained in asparagus dried with hot air at 50 °C. Low rehydration values are evidence of higher temperature (70 °C), which has the capacity to break cellular structure [66].

3.7 Calculation of energy and specific energy consumption

The energy consumption values obtained by drying asparagus samples with hot air at different temperatures are given in Fig. 7.

Energy consumption values for asparagus samples dried at 50, 60 and 70 °C temperatures were found to be 10.14, 5.32 and 4.31 kWh, respectively. Considering the energy consumption values, the best efficiency was obtained at 70 °C among all drying temperatures. According to Fig. 7, energy consumption in the hot air method is significantly affected by the air temperature. Increasing the temperature increases the evaporation rate and, consequently energy consumption decreases [50]. From this study, it can be concluded that drying processes carried out at low temperature lead to a longer drying time and higher energy consumption. Similar results were reported for convective drying of nettle leaves (*Urtica dioica* L.) [67].

The specific energy consumption was determined by considering the total energy provided to dry the asparagus samples from an initial moisture content of about 9.6145 kg water/kg d.m. to a final moisture contents of about 0.1270, 0.1255 and 0.1193 kg water/kg d.m. for 50, 60 and 70 °C, respectively. The specific energy consumption of the drying process at different drying temperatures was calculated using Eq. (17) and presented in Fig. 8.

According to Fig. 8, the minimum energy required for drying 1 kg asparagus at 70 °C drying temperature is 34.75 kWh/kg. The maximum energy requirement (81.77 kWh/kg) was observed at a drying temperature of 50 °C. Expectedly, with increasing the temperature, the drying period and specific energy consumption decreased since the thermal gradient and accelerating moisture extraction increased. In other words, drying at higher temperatures led to greater mass transfer and thereby shorter drying period which decreased SEC [68]. Therefore, 70 °C is the optimum drying temperature for drying fresh asparagus samples due to minimum energy consumption (34.75 kWh/kg) and drying time (510 min). Similar findings were also found by İsmail and Kocabay [41].

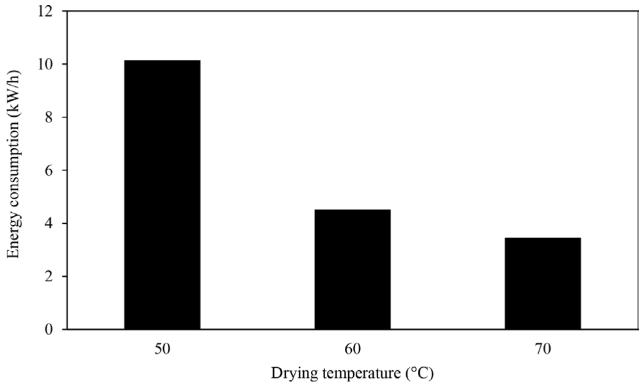

Fig. 7 Energy consumption at various temperatures for asparagus samples

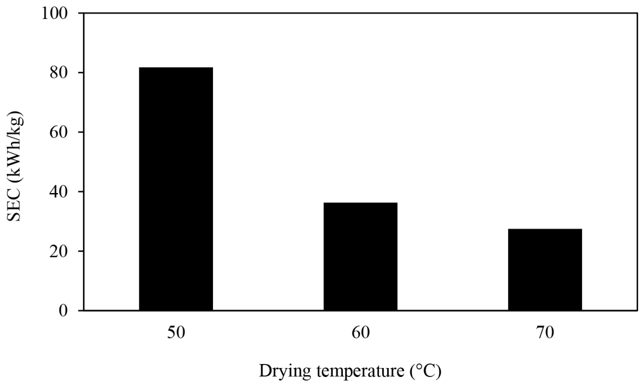

Fig. 8 Specific energy consumption for asparagus samples at 50, 60 and 70 °C

4 Conclusion

The drying characteristics of culture asparagus (*Asparagus officinalis* L.) were investigated during thin-layer drying with convective hot air. The effect of 50, 60 and 70 °C temperatures on the drying of asparagus samples was investigated. The drying process took place in the falling rate period. Six drying kinetics models were used to describe the drying behavior of asparagus and fitted to experimental data. According to the statistical analyses applied to all models, Midilli et al. [57] model gave the best results. Effective moisture diffusivity values were calculated between $6.32 \cdot 10^{-9}$ and $1.62 \cdot 10^{-8}$ m²/s. E_a was determined as 43.59 kJ/mol. Drying processes performed at high temperature lead to a shorter drying time and lower energy consumption. On the other hand, the minimum ΔE value was obtained in asparagus samples dried at 50 °C. In rehydration experiments, the highest rehydration value was obtained in asparagus samples dried with hot air at 50 °C. The total energy consumption of the drying process decreased with increasing air temperature. Specific energy consumption was found between 34.75 and 81.77 kWh/kg.

References

[1] Zhang, H., Birch, J., Xie, C., Yang, H., Bekhit, A. E.-D. "Optimization of ultrasound assisted extraction method for phytochemical compounds and in-vitro antioxidant activity of New Zealand and China Asparagus cultivars (officinalis L.) roots extracts", Food Chemistry, 294, pp. 276–284, 2019. https://doi.org/10.1016/j.foodchem.2019.03.012

[2] Chitrakar, B., Zhang, M., Adhikari, B. "Asparagus (Asparagus officinalis): Processing effect on nutritional and phytochemical composition of spear and hard-stem byproducts", Trends in Food Science & Technology, 93, pp. 1–11, 2019. https://doi.org/10.1016/j.tifs.2019.08.020

[3] Minh, N. P., Them, L. T., Dang, N. C., Ho, T. P., Hieu, N. T., Luan, L. Q. "Investigation of Asparagus officinalis shoot size and drying affecting to herbal tea production", Journal of Pharmaceutical Sciences and Research, 11(2), pp. 267–272, 2019. Available at: https://www.jpsr.pharmainfo.in/Documents/Volumes/vol11issue02/jpsr11021901.pdf [Accessed: 13 January 2023]

[4] Iqbal, M., Bibi, Y., Raja, N. I., Ejaz, M., Hussain, M., Yasmeen, F., Saira, H., Imran, M. "Review on therapeutic and pharmaceutically important medicinal plant Asparagus officinalis L", Journal of Plant Biochemistry & Physiology, 5(1), 1000180, 2017. https://doi.org/10.4172/2329-9029.1000180

[5] Statista "Global leading asparagus producing countries in 2022", Statista Inc., New York, USA, 2022. [online] Available at: https://www.statista.com/statistics/279556/global-top-asparagus-producing-countries/ [Accessed:13 January 2023]

[6] INDEXBOX "Production Asparagus Turkey", Turkey-Asparagus-Market Analysis, Forecast, Size, Trends and Insights, 2022. [online] Available at: https://www.indexbox.io/search/production-asparagus-turkey/ [Accessed: 15 August 2023]

[7] Hamdi, A., Jaramillo-Carmona, S., Rodríguez-Arcos, R., Jiménez-Araujo, A., Guillén-Bejarano, R. "Asparagus", In: Jaiswal, A. K., (ed.) Nutritional Composition and Antioxidant Properties of Fruits and Vegetables, Academic Press, 2020, pp. 121–140. ISBN 978-0-12-812780-3 https://doi.org/10.1016/B978-0-12-812780-3.00008-8

[8] Kohli, D., Shahi, N. C., Kumar, A. "Drying kinetics and activation energy of Asparagus root (Asparagus racemosus Wild.) for different methods of drying", Current Research in Nutrition and Food Science, 6(1), pp. 191–202, 2018. https://doi.org/10.12944/CRNFSJ.6.1.22

[9] Aral, S., Beşe, A. V. "Convective drying of hawthorn fruit (Crataegus spp.): Effect of experimental parameters on drying kinetics, color, shrinkage, and rehydration capacity", Food Chemistry, 210, pp. 577–584, 2016. https://doi.org/10.1016/j.foodchem.2016.04.128

[10] Ricce, C., Rojas, M. L., Miano, A. C., Siche, R., Augusto, P. E. D. "Ultrasound pre-treatment enhances the carrot drying and rehydration", Food Research International, 89, pp. 701–708, 2016. https://doi.org/10.1016/j.foodres.2016.09.030

[11] Rojas, M. L., Silveira, I., Augusto, P. E. D. "Improving the infrared drying and rehydration of potato slices using simple approaches: Perforations and ethanol", Journal of Food Process Engineering, 42(5), e13089, 2019. https://doi.org/10.1111/jfpe.13089

[12] Jokič, S., Mujič, I., Martinov, M., Velič, D., Bilič, M., Lukinac, J. "Influence of drying procedure on colour and rehydration characteristic of wild asparagus", Czech Journal of Food Sciences, 27(3), pp. 171–177, 2009. https://doi.org/10.17221/149/2008-CJFS

[13] Yao, L., Fan, L., Duan, Z. "Effect of different pretreatments followed by hot-air and far-infrared drying on the bioactive compounds, physicochemical property and microstructure of mango slices", Food Chemistry, 305, 125477, 2020. https://doi.org/10.1016/j.foodchem.2019.125477

[14] Sabarez, H. "3.04 - Advanced Drying Technologies of Relevance in the Food Industry", In: Knoerzer, K., Muthukumarappan, K. (eds.) Reference Module in Food Science, Elsevier Inc, 2020, pp. 64–81. ISBN 978-0-12-815782-4 https://doi.org/10.1016/B978-0-08-100596-5.23042-4

[15] Ndisya, J., Mbuge, D., Kulig, B., Gitau, A., Hensel, O., Sturm, B. "Hot air drying of purple-speckled Cocoyam (Colocasia esculenta (L.) Schott) slices: Optimisation of drying conditions for improved product quality and energy savings", Thermal Science and Engineering Progress, 18, 100557, 2020. https://doi.org/10.1016/j.tsep.2020.100557

[16] Wang, Q., Li, S., Han, X., Ni, Y., Zhao, D., Hao, J. "Quality evaluation and drying kinetics of shitake mushrooms dried by hot air, infrared and intermittent microwave-assisted drying methods", LWT - Food Science and Technology, 107, pp. 236–242, 2019. https://doi.org/10.1016/j.lwt.2019.03.020

[17] Wankhade, P. K., Sapkal, R. S., Sapkal, V. S. "Drying characteristics of okra slices on drying in hot air dryer", Procedia Engineering, 51, pp. 371–374, 2013. https://doi.org/10.1016/j.proeng.2013.01.051

[18] Chen, Q., Bi, J., Wu, X., Yi, J., Zhou, L., Zhou, Y. "Drying kinetics and quality attributes of jujube (Zizyphus jujuba Miller) slices dried by hot-air and short-and medium-wave infrared radiation", LWT - Food Science and Technology, 64(2), pp. 759–766, 2015. https://doi.org/10.1016/j.lwt.2015.06.071

[19] Pu, Y.-Y., Sun, D.-W. "Combined hot-air and microwave-vacuum drying for improving drying uniformity of mango slices based on hyperspectral imaging visualisation of moisture content distribution", Biosystems Engineering, 156, pp. 108–119, 2017. https://doi.org/10.1016/j.biosystemseng.2017.01.006

[20] Ali, A., Oon, C. C., Chua, B. L., Figiel, A., Chong, C. H., Wojdylo, A., Turkiewicz, I. P., Szumny, A., Łyczko, J. "Volatile and polyphenol composition, anti-oxidant, anti-diabetic and anti-aging properties, and drying kinetics as affected by convective and hybrid vacuum microwave drying of Rosmarinus officinalis L", Industrial Crops and Products, 151, 112463, 2020. https://doi.org/10.1016/j.indcrop.2020.112463

[21] Kipcak, A. S., İsmail, O. "Comparison of the microwave drying kinetics of culture and natural asparagus", Acta Scientiarum - Technology, 40(1), e39922, 2018. https://doi.org/10.4025/actascitechnol.v40i1.39922

[22] Lukinac, J., Jokić, S., Planinić, M., Magdić, D., Bilić, M., Tomas, S., Velić, D., Bucić-Kojić, A. "An application of image analysis and colorimetric methods on color change of dehydrated asparagus (Asparagus Maritimus L.)", Agriculturae Conspectus Scientificus, 74(3), pp. 233–237, 2009. Available at: file:///C:/Users/user/Downloads/acs74_40.pdf [13 January 2023]

[23] Kohli, D., Shahi, N. C., Pandey, J. P., Singh, A. "Drying of asparagus roots in solar and fluidised bed dryer!, International Journal of Agriculture Sciences, 9(13), pp. 4072–4076, 2017. Available at: file:///C:/Users/user/Downloads/9_13_5_IJAS.pdf [13 January 2023]

[24] Bala, B. K., Hoque, M. A., Hossain, M. A., Uddin, M. B. "Drying Characteristics of Asparagus Roots (Asparagus racemosus Wild.)", Drying Technology, 28(4), pp. 533–541, 2010. https://doi.org/10.1080/07373931003618899

[25] Patil, B. N., Tipre, P. G., Kakade, S. R., Gupta, S.V. "Selection of a suitable drying model for drying Shatavari Roots (Asparagus Racemosus)", International Journal of Chemical Studies, 7(6), pp. 1782–1790, 2019.

[26] Patil, B., Tipre, P. "Effect of syrup concentration on shatavari roots", Journal of Pure and Applied Research in Engineering and Technology, 6(2), pp. 1782–1790, 2017. Available at: https://www.chemijournal.com/archives/2019/vol7issue6/PartAD/7-6-387-240.pdf [13 January 2023]

[27] Ullah, F. "Experimental studies on re-hydration of vacuum freeze-dried Asparagus (Asparagus officinalis L.) with a hydrophilic substance", Pure and Applied Biology, 10(2), pp. 445–457, 2021. https://doi.org/10.19045/bspab.2021.100048

[28] Strahm, B. S., Flores, R. A. "Dehydration of low-grade asparagus", Drying Technology, 12(4), pp. 903–921, 1994. https://doi.org/10.1080/07373939408960001

[29] Nindo, C. I., Sun, T., Wang, S. W., Tang, J., Powers, J. R. "Evaluation of drying technologies for retention of physical quality and antioxidants in asparagus (Asparagus officinalis, L.)", LWT - Food Science and Technology, 36(5), pp. 507–516, 2003. https://doi.org/10.1016/S0023-6438(03)00046-X

[30] Baltacioğlu, C. "Optimization of drying and osmotic dehydration of asparagus officinalis in microwave and conventional hot air oven using response surface methodology", Carpathian Journal of Food Science and Technology, 9(3), pp. 5–16, 2017. [online] Available at: file:///C:/Users/user/Downloads/CARPATHIAN_JOURNAL_OF_FOOD_SCIENCE_AND_T.pdf [13 January 2023]

[31] Okur, İ., Baltacıoğlu, C. "Kinetic and mathematical modeling of drying of Asparagus officinalis in different drying methods", Turkish Journal of Agriculture - Food Science and Technology, 6(10), pp. 1431–1436, 2018. https://doi.org/10.24925/turjaf.v6i10.1431-1436.2060

[32] Baltacıoğlu, C., Okur, İ., Buzrul, S. "Model based comparison of drying of asparagus (Asparagus officinalis L.) with traditional method and microwave", The Journal of Food, 45(3), pp. 572–580, 2020. https://doi.org/10.15237/gida.GD20040

[33] Yu, Q., Li, J., Fan, L. "Effect of Drying Methods on the Microstructure, Bioactivity Substances, and Antityrosinase Activity of Asparagus Stems", Journal of Agricultural and Food Chemistry, 67(5), pp. 1537–1545, 2019. https://doi.org/10.1021/acs.jafc.8b05993

[34] Aravindakshan, S., Nguyen, T. H. A., Kyomugasho, C., Buvé, C., Dewettinck, K., Loey, A. V., Hendrickx, M. E. "The Impact of Drying and Rehydration on the Structural Properties and Quality Attributes of Pre-Cooked Dried Beans", Foods, 10(7), 1665, 2021. https://doi.org/10.3390/foods10071665

[35] Deng, Y., Luo, Y., Wang, Y., Yue, J., Liu, Z., Zhong, Y., Zhao, Y., Yang, H. "Drying-induced protein and microstructure damages of squid fillets affected moisture distribution and rehydration ability during rehydration", Journal of Food Engineering, 123, pp. 23–31, 2014. https://doi.org/10.1016/j.jfoodeng.2013.09.006

[36] Górnicki, K., Choińska, A., Kaleta, A. "The Impact of Drying and Rehydration on the Structural Properties and Quality Attributes of Pre-Cooked Dried Beans", Processes, 8(11), 1454, 2020. https://doi.org/10.3390/pr8111454

[37] Helrich, K. "Official methods of analysis of the Association of Official Analytical Chemists", AOAC, 1990. ISBN 0-935584-42-0

[38] Doymaz, I., Kipcak, A. S., Piskin, S. "Microwave drying of green bean slices: drying kinetics and physical quality", Czech Journal of Food Sciences, 33(4), pp. 367–376, 2015. https://doi.org/10.17221/566/2014-CJFS

[39] STATISTICA "STATISTICA, 6.0", [online] Available at: https://statistica.software.informer.com/6.0/ [Accessed: 17 July 2021]

[40] Zhang, B., Li, M., Qiao, Y., Gao, P., Li, L., Zheng, Z. "Potential use of low-field nuclear magnetic resonance to determine the drying characteristics and quality of *Arctium lappa* L. in hot-blast air", LWT-Food Science and Technology, 132, 109829, 2020. https://doi.org/10.1016/j.lwt.2020.109829

[41] İsmail, O., Kocabay, Ö. G. "Evaluation of the drying methods and conditions with respect to drying kinetics, colour quality and specific energy consumption of thin layer pumpkins", Bulgarian Chemical Communications, 48(3), pp. 480–491, 2016. [online] Available at: http://bcc.bas.bg/BCC_Volumes/Volume_48_Number_3_2016/3991-Gokce-BCC-48-3-2016-480-491.pdf [13 January 2023]

[42] Sarpong, F., Zhou, C., Bai, J., Amenorfe, L. P., Golly, M. K., Ma, H. "Modeling of drying and ameliorative effects of relative humidity (RH) against β-carotene degradation and color of carrot (Daucus carota var.) slices", Food Science and Biotechnology, 28(1), pp. 75–85, 2019. https://doi.org/10.1007/s10068-018-0457-3

[43] Crank, J. "The Mathematics of Diffusion", Clarendon Press, Oxford, 1975. ISBN 0 19 853344 6

[44] Salehi, F., Kashaninejad, M., Jafarianlari, A. "Drying kinetics and characteristics of combined infrared-vacuum drying of button mushroom slices", Heat Mass Transfer, 53(5), pp. 1751–1759, 2017. https://doi.org/10.1007/s00231-016-1931-1

[45] Ojediran, J. O., Okonkwo, C. E., Adeyi, A. J., Adeyi, O., Olaniran, A. F., George, N. E., Olayanju, A. T. "Drying characteristics of yam slices (Dioscorea rotundata) in a convective hot air dryer: Application of ANFIS in the prediction of drying kinetics", Heliyon, 6(3), e03555, 2020. https://doi.org/10.1016/j.heliyon.2020.e03555

[46] Özyalcin, Z. Ö., Kipcak, A. S. "Ultrasonic Pre-Treatment and Vacuum Effect on the Drying of Cancer Pagurus Meat", Aquatic Sciences and Engineering, 38(3), pp. 137–144, 2023. https://doi.org/10.26650/ASE20231270399

[47] Yu, F., Li, Y., Wu, Z., Wang, X., Wan, N., Yang, M. "Dehydration of wolfberry fruit using pulsed vacuum drying combined with carboxymethyl cellulose coating pretreatment", LWT-Food Science and Technology, 134, 110159, 2020. https://doi.org/10.1016/j.lwt.2020.110159

[48] Aghbashlo, M., Kianmehr, M. H., Samimi-Akhijahani, H. "Influence of drying conditions on the effective moisture diffusivity, energy of activation and energy consumption during the thin-layer drying of berberis fruit (Berberidaceae)", Energy Conversion and Management, 49(10), pp. 2865–2871, 2008. https://doi.org/10.1016/j.enconman.2008.03.009

[49] Torki-Harchegani, M., Ghanbarian, D., Pirbalouti, A. G., Sadeghi, M. "Dehydration behaviour, mathematical modelling, energy efficiency and essential oil yield of peppermint leaves undergoing microwave and hot air treatments", Renewable and Sustainable Energy Reviews, 58, pp. 407–418, 2016. https://doi.org/10.1016/j.rser.2015.12.078

[50] Elmizadeh, A., Shahedi, M., Hamdami, N. "Comparison of electrohydrodynamic and hot-air drying of the quince slices", Innovative Food Science and Emerging Technologies, 43, pp. 130–135, 2017. https://doi.org/10.1016/j.ifset.2017.07.030

[51] Kaveh, M., Sharabiani, V. R., Chayjan, R. A., Taghinezhad, E., Abbaspour-Gilandeh, Y., Golpour, I. "ANFIS and ANNs model for prediction of moisture diffusivity and specific energy consumption potato, garlic and cantaloupe drying under convective hot air dryer", Information Processing in Agriculture, 5(3), pp. 372–387, 2018. https://doi.org/10.1016/j.inpa.2018.05.003

[52] Bruce, D. M. "Exposed-layer barley drying: Three models fitted to new data up to 150°C", Journal of Agricultural Engineering Research, 32(4), pp. 337–348, 1985. https://doi.org/10.1016/0021-8634(85)90098-8

[53] Page, G. E. "Factors influencing the maximum rates of air-drying shelled corn in thin layers", Master's thesis, Purdue University, Purdue, 1949.

[54] Wang, C., Singh, R. P. "Use of variable equilibrium moisture content in modeling rice drying", Transactions of the ASAE, 11, pp. 668–672, 1978.

[55] Jain, D., Pathare, P. B. "Study the drying kinetics of open sun drying of fish", Journal of Food Engineering, 78(4), pp. 1315–1319, 2007. https://doi.org/https://doi.org/10.1016/j.jfoodeng.2005.12.044

[56] Aghbashlo, M., Kianmehr, M. H., Khani, S., Ghasemi, M. "Mathematical modelling of thin-layer drying of carrot", International Agrophysics, 23(4), pp. 313–317, 2009.

[57] Midilli, A., Kucuk, H., Yapar, Z. "A new model for single-layer drying", Drying Technology: An International Journal, 20(7), pp. 1503–1513, 2002. https://doi.org/10.1081/DRT-120005864

[58] Boukhiar, A., Benamara, S., Bouchal, Y., Touderte, K., Messouidi, S. "High-temperature thin-layer drying kinetic of cultivated and wild Algerian olive leaves", Periodica Polytechnica Chemical Engineering, 66(4), pp. 660–674, 2022. https://doi.org/10.3311/PPch.20264

[59] Qiu, G., Jiang, Y.-L., Deng, Y. "Drying characteristics, functional properties and in vitro digestion of purple potato slices dried by different methods", Journal of Integrative Agriculture, 18(9), pp. 2162–2172, 2019. https://doi.org/10.1016/S2095-3119(19)62654-7

[60] Zogzas, N. P., Maroulis, Z. B., Marinos-Kouris, D. "Moisture diffusitivy data compilation in foodstuffs", Drying Technology, 14(10), pp. 2225–2253, 1996. https://doi.org/10.1080/07373939608917205

[61] Olanipekun, B. F., Tunde-Akintunde, T. Y., Oyelade, O. J., Adebisi, M. G., Adenaya, T. A. "Mathematical modeling of thin-layer pineapple drying", Journal of Food Processing and Preservation, 39(6), pp. 1431–1441, 2015. https://doi.org/10.1111/jfpp.12362

[62] Seyedabadi, E., Khojastehpour, M., Abbaspour-Fard, M. H. "Online measuring of quality changes of banana slabs during convective drying", Engineering in Agriculture, Environment and Food, 12(1), pp. 111–117, 2019. https://doi.org/10.1016/j.eaef.2018.10.004

[63] Therdthai, N., Zhou, W. "Characterization of microwave vacuum drying and hot air drying of mint leaves (Mentha cordifolia Opiz ex Fresen)", Journal of Food Engineering, 91(3), pp. 482–489, 2009. https://doi.org/10.1016/j.jfoodeng.2008.09.031

[64] Aghbashlo, M., Kianmehr, M. H., Hassan-Beygi, S. R. "Drying and rehydration characteristics of sour cherry (*Prunus cerasus* L.)", Journal of Food Processing and Preservation, 34(3), pp. 351–365, 2010. https://doi.org/10.1111/j.1745-4549.2008.00310.x

[65] Maldonado, S., Arnau, E., Bertuzzi, M. A. "Effect of temperature and pretreatment on water diffusion during rehydration of dehydrated mangoes", Journal of Food Engineering, 96(3), pp. 333–341, 2010. https://doi.org/10.1016/j.jfoodeng.2009.08.017

[66] Seremet Ceclu, L., Botez, E., Nistor, O.-V., Andronoiu, D. G., Mocanu, G.-D. "Effect of different drying methods on moisture ratio and rehydration of pumpkin slices", Food Chemistry, 195, pp. 104–109, 2016. https://doi.org/10.1016/j.foodchem.2015.03.125

[67] Alibas, I. "Energy consumption and colour characteristics of nettle leaves during microwave, vacuum and convective drying", Biosystems Engineering, 96(4), pp. 495–502, 2007. https://doi.org/10.1016/j.biosystemseng.2006.12.011

[68] Kaveh, M., Chayjan, R. A., Taghinezhad, E., Sharabiani, V. R., Motevali, A. "Evaluation of specific energy consumption and GHG emissions for different drying methods (Case study: Pistacia Atlantica)", Journal of Cleaner Production, 259, 120963, 2020. https://doi.org/10.1016/j.jclepro.2020.120963