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ORIGINAL PAPER

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THE INTERACTIONS BETWEEN VARIOUS DRYING TEMPERATURES AND APPLIED DRYING MODELS OF ASPARAGUS ROOTS (*ASPARAGUS OFFICINALIS* L.)

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ABSTRACT

Background. Asparagus root (*Asparagus officinalis* L.) is one of the herbaceous by-products with potential for making value-added products because of its excellent nutritional properties and flavor/fragrance. In order to maintain its quality, drying is suggested as a suitable technique for this purpose. Several drying methods were set up to investigate and select the one which had a high reliability of drying parameters and could be widely applied in the processing of dried vegetable products.
Materials and methods. Thin-layer drying at six temperature degrees (40°C, 50°C, 60°C, 70°C, 80°C, and 90°C), solar system, and sun drying were investigated to study the kinetics of moisture ratio change in asparagus roots. Eight common drying kinetic models (Haghi and Angiz II, Henderson Pabis, Logarithmic, Newton, Page, Parobolic, Peleg, and Wang and Singh) were applied to choose the most fitting. The moisture diffusion efficiency and activation energy were determined by Fick's diffusion equation.
Results. Rising drying temperature accelerated the drying speed, and the Page model was indicated as the best fit for the experimental data among the remaining drying models. The moisture diffusivity values varied from 9.11×10^{-12} to 1.27×10^{-11} m^2/s for the thin-layer drying method and 1.2×10^{-11} and 9.55×10^{-11} m^2/s for the solar system and sun drying models, respectively. The efficiency of moisture diffusivity depended on investigating drying models, which was described using the Arrhenius's equation with an activation energy of 30.91 kJ/mol.
Conclusion. The page model is the most suitable for describing the drying process of asparagus, with high reliability between the experimental data and estimated data from this model when drying asparagus at 70°C ($R^2 = 0.9996$).

Keywords: asparagus, drying models, kinetic, moisture ratio, temperature

INTRODUCTION

Asparagus (*Asparagus officinalis* L.) is an herbaceous plant with needle-shaped leaves. It is considered a healthy food because of its excellent nutritional qualities such as necessary vitamins, amino acids, and minerals (Wenxiang and Min, 2006). Asparagus is classified as a vegetable with a high content of antioxidants

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and flavor/fragrance, which is attributed to a set of volatile components, including pyrazines and sulphur-containing compounds (Pegiou et al., 2019; Witzel and Matros, 2020). Asparagus has been ranked as having the 4th highest content of total phenols among 23 vegetables tubers that are widely consumed in the United States (Vinson et al., 2001) and in the top 20 valuable vegetable crops in the world (Pegiou et al., 2019). This well-known crop has been farmed for more than 2000 years all around the world and it requires 7–8 years to be harvested commercially. According to the present market, the worldwide asparagus market is expected to expand consistently by 3% per year and reach 10 million metric tons by 2027, with a total market value of up to 37 Bn US$ (Pegiou et al., 2019). Asparagus is seen as a perennial herb since saponins, flavonoids, vitamins, and other polysaccharides, as well as dietary fiber and oligosaccharides, have all been found in studies on the phytochemical components of asparagus (Fuentes-Alventosa et al., 2013; Zhang et al., 2019). These mixtures have benefits that increase the value of this crop, including anti-cancer, anti-tumor, antioxidant, immunomodulatory, hypoglycemic, anti-hypertensive, and anti-epileptic properties (Pegiou et al., 2019; Guo et al., 2020). However, while this crop is being harvested, its roots and rhizomes are typically dug out, clipped, and left on fields as byproducts (Viera-Alcaide et al., 2021). According to the results of some scientific publications, asparagus root is remarkably nutritious, particularly since fructans and polysaccharides are primarily accumulated (Suzuki et al., 2011; Guo et al., 2020; Witzel and Matros, 2020) and the content of aluminum and iron is higher than in the tops. Moreover, the high fiber content and loss of nutrients during storage are low (King et al., 1988). With these specific features, this raw material can be utilized by using appropriate processing technology to create products that provide fiber and biologically active ingredients for the user and at the same time create added value for existing raw materials discarded in food processing.

Several technical treatments are employed to make efficient use of by-products. One potential method is drying, which plays a pivotal role in reducing handling and distribution costs while simultaneously prolonging the shelf life of raw materials with a high moisture content (Chen and Mujumdar, 2009). In the drying process, the principles of simultaneous heat and mass transfer come into the operation. Heat penetrates the food product, prompting the migration of moisture from the interior to the surface, which is subsequently evaporated into the air as vapor. The utilization of oven drying, particularly when employing a thin-layer configuration, is widespread due to its cost-effectiveness and suitability for plant materials (Chen and Mujumdar, 2009, Tai et al., 2021). Ensuring the quality of the dried product hinges on the control of operational parameters during the process and the ability to forecast the effectiveness of drying through mathematical modeling (Ertekin and Firat, 2017). This paper focused on determining the impact of different temperatures (40–90°C) applied using the thin-layer drying method, compared to dried samples dried using a solar system and exposed to the sun on the physicochemical characteristics of dried asparagus root as a potential raw material for creating added-value products.

MATERIALS AND METHODS

Materials and equipment

Asparagus officinalis L. roots which were in good condition and fresh without physical damage or infestation were purchased at My Thoi Ward, Long Xuyen city, An Giang province, Vietnam.

The drying experiments were conducted in different types of drying methods: using a Forced Convection Drying Oven (ESCO, OFA-110-8, Indonesia), a solar system drying (SETECH, Vietnam), and sun drying. In this paper, samples dried using solar system and exposure to the sun were used as comparative factors.

Experimental design. The collected green asparagus roots, after sorting and washing, were pre-treated before drying by blanching at 85°C for 2 minutes. Each sample used 2 kg of green asparagus root; the samples were cut into 0.5–1 cm. After blanching, the samples were spread evenly on stainless steel trays (40 × 60 cm^2) and dried in a Forced Convection Drying oven (ESCO, OFA-110-8, Indonesia) with an airflow velocity of 1 m/s. The temperature was arranged from 40°C to 90°C, and two more samples were conducted using sun drying and solar system drying. A digital balance (Ohaus, SR series, America, d = 0.001) recorded weight change at hourly intervals throughout drying. The drying process finished when the moisture content of samples was less than 10%.

Before the drying process, a slightly modified version of AOAC method 925.45 (2005) was applied to determine the initial moisture content. During the drying process, each investigated temperature and drying method was performed in triplicate, and the averages were recorded.

Mathematical modelling of asparagus roots' moisture ratio change

Eight common drying kinetic models including Haghi and Angiz II, Henderson Pabis, Logarithmic, Newton, Page, Parobolic, Peleg, and Wang and Singh were applied in order to figure out the most suitable model for describing the drying process (Ertekin and Firat, 2017). The kinetics were fitted into the investigated models (Table 1). Eight common drying models were statistically analyzed using Statgraphics Centurion XVI (U.S.A.) software. Nonlinear regression analysis was applied in evaluating the parameters to choose the best model describing the efficient drying process of asparagus roots.

Moisture ratio (MR) of asparagus roots during drying is calculated according to Equation 1 (Akpinar, 2010).

$$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

where:

M_o, M_e, and M_t are the moisture content at the initial, equilibrious, and the t stages (kg water / kg dry matter content)

t is the drying time (hour).

In the case of the moisture content on the material's surface being equivalent to the equilibrium moisture content of the whole material and the surface continuing to drain moisture throughout drying process ($M_e \approx 0$), the moisture ratio can be calculated simply using Equation 2 (Thakor et al., 1999).

$$\mathrm{MR} = \frac{M_t}{M_o} \tag{2}$$

The drying rate constant and the coefficients of the model are determined by regression analysis nonlinear (Thorat et al., 2012). Coefficient of determination (R^2) is an important criterion to choose a good model to best describe the drying curve. In addition, the value χ^2 and the root mean square error (RMSE) were also used to determine the most suitable equation accounting for variation in the drying curves of the dried samples (Ertekin and Yaldiz, 2004). The higher the R^2 value and the lower the RMSE value, the better the model will fit (Yaldýz and Ertekýn, 2001; Gunhan et al., 2005). Value R^2 and RMSE are calculated according to equations 3 and 4 (Akpinar, 2010; Zarein et al., 2015):

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{\mathrm{exp,i}} - MR_{\mathrm{pre,i}})^2}{N - z} \tag{3}$$

$$RMSE = [1/N \sum_{i=1}^{N} (MR_{\mathrm{pre,i}} - MR_{\mathrm{exp,i}})^2]^{1/2} \tag{4}$$

where:

MR_{exp} is the experimental dimensionless moisture ratio

MR_{pre} is the predicted dimensionless moisture ratio

N is the number of experimental data points

z is the number parameters in the model.

Table 1. The commonly used drying kinetic models

Models	Equations	Models	Equations
Haghi and Angiz II	$\mathrm{MR} = a + bt + ct^2 + dt^3$	Page	$\mathrm{MR} = \exp(-kt^n)$
Henderson Pabis	$\mathrm{MR} = a\exp(-kt)$	Parobolic	$\mathrm{MR} = a + bt + ct^2$
Logarithmic	$\mathrm{MR} = a\exp(-kt) + c$	Peleg	$\mathrm{MR} = 1 - (t / (a + bt))$
Newton	$\mathrm{MR} = \exp(-kt)$	Wang and Singh	$\mathrm{MR} = 1 + at + bt^2$

a, b, c, d, n are constants of models; k, k_1, k_2 are drying rate constants.

The moisture diffusion efficiency and activation energy

Similar to other vegetables, the moisture diffusion efficiency of asparagus roots was estimated using Fick's diffusion model (Equation 5), which included the shrinkage from the material during the drying (Thorat et al., 2012).

$$\frac{\partial_u}{\partial_t} = D_{eff} \frac{\partial^2 u}{\partial x^2} \quad (5)$$

where:

u is the concentration (mol/m^3)
D_{eff} is the diffusion coefficient (m^2/s)
t is the time (second)
x is the length of the diffusion (m).

Moisture diffusion is determined by plotting a graph of the experimental ln(MR) according to (t/r^2) due to a straight line graph with a slope (α) followed the equation 6 (Doymaz, 2006).

$$\alpha = \pi^2 D_{eff} \quad (6)$$

The activation energy is determined based on Arrhenius's equation (7), which shows the dependence of the moisture diffusion efficiency on the temperature (Sanjuán et al., 2003).

$$D_{eff} = D_o \exp(-E_a/RT) \quad (7)$$

where:

D_o is the Arrheenius factor (previous exponential factor, D_o is equivalent to diffusivity at infinitely high temperature (m^2/s)
E_a is the activation energy (kJ/mol)
R is the ideal gas constant (R = 8.314 J/mol·K)
T is the absolute temperature (K).

RESULTS AND DISCUSSION

Effects of temperature on the moisture changes during the drying time

The drying process changes the moisture content of the raw materials. Figure 1 illustrated the effect of thin-layer drying (40, 50, 60, 70, 80, and 90°C) and two comparative drying methods, using solar system (45–47°C) and sun drying (33–35°C) to ratio of moisture (MR). The ratio of moisture decreases continuously with drying time; in particular, the moisture loss occurs rapidly during the initial period of the drying process due to the high free moisture content in the raw materials (Thorat et al., 2012) and then the drying speed is reduced. Time required for drying asparagus roots from initial moisture content 90.45 ±0.51% (wet basis) to the moisture content less than 10% (wet basis) is

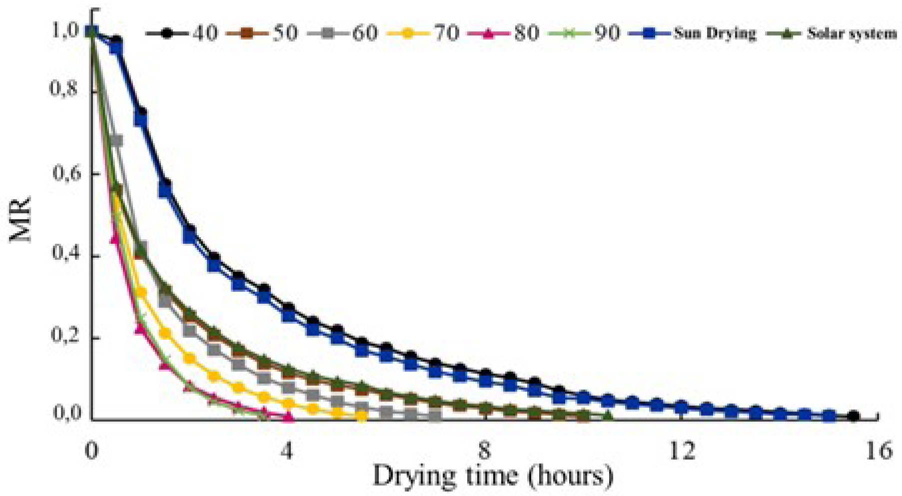

Fig. 1. Ratio of moisture (MR) through drying time at different temperatures

a. b. c.

Fig. 2. Asparagus roots samples at different drying methods: a – thin-layer drying at 50°C; b – solar system; c – sun drying

shortened with the increase in drying temperature, due to high heat and mass transfer (Thorat et al., 2012). With a temperature of 40°C, the time of the material drying time lasted up to 15 hours to reach the required moisture degree; meanwhile, the drying time was shortened to 10.0 hours, 7.0 hours, 5.5 hours, 4.0 hours, and 3.5 hours in the drying process performed at a higher temperature (corresponding to 50, 60, 70, 80, and 90°C). The increased drying temperature accelerated the transition from the liquid phase to the gas phase, so the evaporation rate was faster (Babalis and Belessiotis, 2004). According to Giri and Prasad (2007), when drying at a temperature of 30°C to 90°C, the higher the temperature, the faster the heat transfer ability to the material, making the moisture on the surface of the material evaporate faster and thus, the moisture removal capacity at 90°C is higher than 40°C. The drying time was inversely proportional to the drying temperature, that is, the higher the drying temperature, the faster the moisture removal time and vice versa (Chong et al., 2008). This trend was similar to previous studies on dried butterfly pea flowers (Mahmud et al., 2021) and purple sweet potato flour (Thuy et al., 2022) using the thin-layer drying method. Along with the study on the sun drying of asam gelugor (*Garcinia cambogia*) (Lim et al., 2019), there was a similarity with the samples dried by solar system and sun drying, which had the unstable temperature and fluctuated around 45–47°C for solar system and 33-35°C for sun drying method. Both methods took a long time to finish the whole drying process: around 10.5 hours and 15 hours, respectively. Furthermore, the quality of the products dried by solar system and sun drying, including the color criteria, was not good and had a yellow-brown color (Fig. 2) and a stale odor. Therefore, they were less recommended compared to dried samples using thin-layer drying method.

Modeling the drying curve

Data on moisture content subsequent to drying time were tested for suitability with eight commonly used drying models (Table 1). Statistical analysis results are illustrated in Table 2. The fit of the models was also evaluated based on χ^2 and RMSE values. In general, R^2, χ^2, and RMSE fluctuated in the range of 0.6632–0.9996, 0.0031–0.0445, and 0.0002–0.0358, respectively. It could be seen that R^2 values were mostly greater than 0.86, which showed good agreement of most models (Doymaz and Ismail, 2011), except for the Peleg model when drying at 50°C and solar system (0.7235 and 0.6632, respectively).

The reliability of the Page model was also evaluated by comparing the moisture rates at different drying temperatures to the moisture ratios obtained from experimental data. Regression analysis results show that the data value fluctuated nearly to a linear line with a 45° degree slope, which demonstrated the suitability of the Page model in describing the drying process of asparagus roots. The data obtained at a temperature of 70°C with the highest value of R^2 was 0.9996 (Fig. 3). Similarly, at the remaining temperatures (40, 50, 60, 80, and 90°C), solar system and sun drying methods, R^2 values were 0.9858, 0.9953, 0.9954, 0.9993, 0.9902, 0.9990, and 0.9889, respectively (Yaldiz et al., 2001).

Table 2. Statistical analysis results on different types of commonly used drying models

Drying methods/Models	Model constants	R^2	RMSE	χ^2
1	2	3	4	5
40°C				
Haghi and Angiz II	a = 1.0095, b = –0.2663, c = 0.0236, d = –0.0007	0.9846	0.0069	0.0079
Henderson Pabis	a = 1.0686, k = 0.3507	0.9846	0.0066	0.0071
Logarithmic	a = 1.0765, c = –0.0186, k = 0.3309	0.9856	0.0065	0.0072
Newton	k = 0.3295	0.9808	0.0073	0.0075
Page	k = 0.2689, n = 1.1526	0.9858	0.0064	0.0068
Parobolic	a = 0.9041, b = –0.1744, c = 0.0080	0.9563	0.0113	0.0126
Peleg	a = 2.4662, b = 0.7843	0.9423	0.0128	0.0142
Wang and Singh	a = –0.1995, b = 0.0094	0.9702	0.0092	0.0102
50°C				
Haghi and Angiz II	a = 0.8519, b = –0.3902, c = 0.0626, d = –0.0033	0.9508	0.0135	0.0169
Henderson Pabis	a = 0.9112, k = 0.6036	0.9727	0.0095	0.0106
Logarithmic	a = 0.9049, c = 0.0283, k = 0.6880	0.9772	0.0089	0.0105
Newton	k = 0.6718	0.9643	0.0106	0.0111
Page	k = 0.8217, n = 0.7093	0.9953	0.0039	0.0044
Parobolic	a = 0.7313, b = 0.2150, c = 0.0153	0.8870	0.0199	0.0234
Peleg	a = 0.8770, b = 0.9075	0.7235	0.0302	0.0356
Wang and Singh	a = –0.3251, b = 0.0248	0.9963	0.0002	0.0035
60°C				
Haghi and Angiz II	a = 0.9764, b = –0.6044, c = 0.1358, d = –0.0102	0.9920	0.0080	0.0112
Henderson Pabis	a = 0.9911, k = 0.7082	0.9937	0.0065	0.0076
Logarithmic	a = 0.9781, c = 0.0250, k = 0.7730	0.9957	0.0056	0.0071
Newton	k = 0.7147	0.9936	0.0063	0.0068
Page	k = 0.7489, n = 0.9141	0.9954	0.0055	0.0065
Parobolic	a = 0.8667, b = –0.3546, c = 0.0361	0.9410	0.0207	0.0264
Peleg	a = 0.9953, b = 0.8434	0.9086	0.0247	0.0314
Wang and Singh	a = –0.4334, b = 0.0458	0.9934	0.0066	0.0084
70°C				
Haghi and Angiz II	a = 0.9551, b = –0.7986, c = 0.2385, d = –0.0235	0.9871	0.0123	0.0193
Henderson Pabis	a = 0.9733, k = 0.9799	0.9937	0.0065	0.0076
Logarithmic	a = 0.9512, c = 0.0376, k = 1.1250	0.9967	0.0056	0.0077
Newton	k = 1.0077	0.9908	0.0087	0.0096
Page	k = 1.0581, n = 0.8047	0.9993	0.0025	0.0031
Parobolic	a = 0.8494, b = –0.4628, c = 0.0624	0.9280	0.0271	0.0373
Peleg	a = 0.6366, b = 0.8818	0.8846	0.0324	0.0445
Wang and Singh	a = –0.5771, b = 0.0805	0.9989	0.0031	0.0043

Table 2 – cont.

1	2	3	4	5
80°C				
Haghi and Angiz II	a = 0.9775, b = –1.1449, c = 0.4762, d = –0.0653	0.9931	0.0130	0.0259
Henderson Pabis	a = 0.9883, k = 1.3694	0.9961	0.0080	0.0107
Logarithmic	a = 0.9654, c = 0.0308, k = 1.52	0.9990	0.0045	0.0072
Newton	k = 1.3845	0.9959	0.0076	0.0087
Page	k = 1.3755, n = 0.8402	0.9993	0.0026	0.0035
Parobolic	a = 0.8918, b = –0.6957, c = 0.1332	0.9426	0.0335	0.0537
Peleg	a = 0.4718, b = 0.8722	0.9215	0.0358	0.0572
Wang and Singh	a = –0.8103, b = 0.1587	0.9984	0.0051	0.0082
90°C				
Haghi and Angiz II	a = 0.9808, b = –1.0276, c = 0.3679, d = –0.0422	0.9929	0.0132	0.0264
Henderson Pabis	a = 0.9942, k = 1.2669	0.9888	0.0135	0.0180
Logarithmic	a = 0.9618, c = 0.0425, k = 1.4524	0.9942	0.0107	0.0171
Newton	k = 1.2738	0.9889	0.0125	0.0143
Page	k = 1.2730, n = 0.8969	0.9902	0.0126	0.0168
Parobolic	a = 0.9254, b = –0.7374, c = 0.1462	0.9717	0.0235	0.0376
Peleg	a = 0.5154, b = 0.8742	0.9616	0.0250	0.0400
Wang and Singh	a = –0.8164, b = 0.1638	0.9849	0.0157	0.0251
Solar system (45–47°C)				
Haghi and Angiz II	a = 0.8433, b = –0.3629, c = 0.0546, d = –0.0027	0.9508	0.0122	0.0149
Henderson Pabis	a = 0.8982, k = 0.5555	0.9669	0.0095	0.0104
Logarithmic	a = 0.8917, c = 0.0459, k = 0.6963	0.9814	0.0073	0.0084
Newton	k = 0.6321	0.9558	0.0107	0.0112
Page	k = 0.8066, n = 0.6672	0.9990	0.0027	0.0032
Parobolic	a = 0.7099, b = –0.1901, c = 0.0125	0.8695	0.0193	0.0223
Peleg	a = 0.8702, b = 0.9325	0.6632	0.0302	0.0349
Wang and Singh	a = –0.2979, b = 0.0209	0.9992	0.0015	0.0017
Sun drying (33–35°C)				
Haghi and Angiz II	a = 0.9872, b = –0.2692, c = 0.0262, d = –0.0009	0.9832	0.0067	0.0077
Henderson Pabis	a = 1.0223, k = 0.3274	0.9891	0.0052	0.0056
Logarithmic	a = 1.0160, c = 0.0233, k = 0.3565	0.9912	0.0048	0.0053
Newton	k = 0.32	0.9886	0.0052	0.0054
Page	k = 0.3344, n = 0.9665	0.9889	0.0052	0.0056
Parobolic	a = 0.8575, b = –0.1560, c = 0.0070	0.9338	0.0130	0.0144
Peleg	a = 2.2827, b = 0.8339	0.8981	0.0159	0.0176
Wang and Singh	a = –0.1934, b = 0.0091	0.9842	0.0062	0.0069

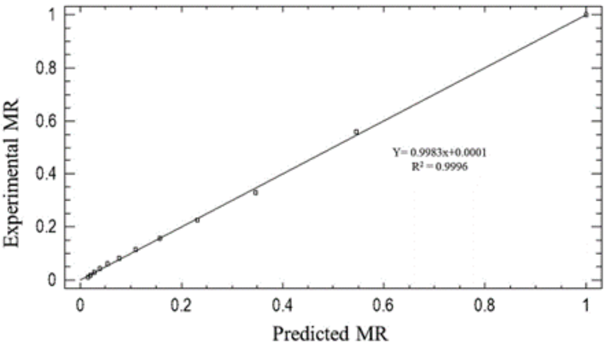

Fig. 3. The compatibility between the experimental data and the predicted data according to the Page model (based on the moisture content of asparagus roots dried at 70°C)

The moisture diffusion efficiency and activation energy

The moisture diffusion efficiency (D_{eff}) value of asparagus roots at the temperature range of 40–90°C fluctuated at about 9.1×10^{-12} – 4.5×10^{-11} m²/s (Table 3), and the D_{eff} value increased gradually as the temperature increased. There was a similar trend observed from dried samples using solar system and exposure to the sun: the D_{eff} values were 1.2×10^{-11} and 9.5×10^{-12}, respectively. These results are lower than previous studies when drying red pepper (D_{eff} = 5.0–8.3 × 10^{-10} m²/s) at 50–70°C (Karina and Guillermo, 2007) and banana peel (D_{eff} = 2.3–3.3 × 10^{-8} m²/s) at 60–80°C (Tai et al., 2021). Because asparagus is an herbaceous, perennial plant with much-branched stout stems and with cladodes (modified stems) in the axils of scale leaves clustered as a layer structure, this causes the slow speed of water diffusion during the drying process. Observations show that the process of drying exhibits inherent instability, resulting in variations in the moisture content of the material over both spatial and temporal dimensions. Consequently, sun drying exhibits a superior moisture removal rate when compared to thin-layer drying, owing to its larger drying space (Man, 2011).

Table 3. The moisture diffusion efficiency and activation energy values of asparagus roots dried at different temperatures in the solar system and sun drying methods

Drying methods		The moisture diffusion efficiency (m²/s)
Thin-layer drying	40°C	9.11×10^{-12}
	50°C	1.27×10^{-11}
	60°C	2.03×10^{-11}
	70°C	2.63×10^{-11}
	80°C	3.71×10^{-11}
	90°C	4.26×10^{-11}
Solar system (45–47°C)		1.20×10^{-11}
Sun drying (33–35°C)		9.55×10^{-12}

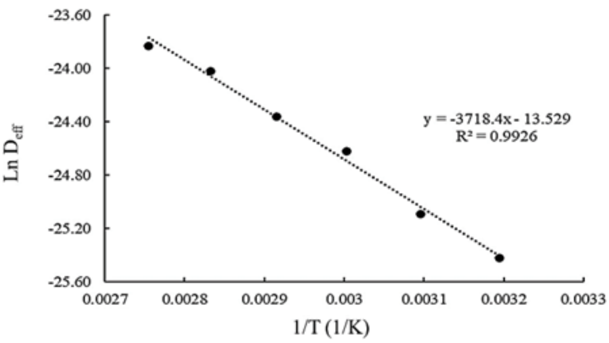

Fig. 4. Relationships according to Arrhenius model between moisture diffusion efficiency and temperature

The Arrhenius equation is used to calculate the activation energy, which is the minimal amount of energy needed to start moisture diffusion from the material (Fig. 4). In this study, the recorded activation energy for the thin-layer drying method was 30.91 kJ/mol. This value was higher than the activation energy recorded by thin-layer drying banana peel as another by-product at 60–80°C (16.98 kJ/mol), which also has higher moisture diffusion efficiency, as mentioned above (Tai et al., 2021). This difference could be explained by the higher range of temperature used in this study (40–90°C).

CONCLUSION

Among eight applied mathematical models, the Page model was chosen to describe the kinematics of the drying process of asparagus roots under thin-layer drying at different temperatures, solar system, and sun drying. The results with higher compatibility compared with other models ($R^2 > 0.9993$, $\chi^2 < 0.0031$ and RMSE < 0.0025) came from thin-layer drying at 70°C. This method was considered an effective temperature for drying asparagus roots with a reasonable drying time (5.5 hours) to achieve the desired product moisture (<10%) and could ensure the sensory quality of the final product, compared with other shorter drying time methods.

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