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Drying Kinetics and Activation Energy of Asparagus Root (*Asparagus racemosus* Wild.) for Different Methods of Drying

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Abstract

Drying reduces the water activity of food product and hence increases the shelf life of the food.In the present study, fresh asparagus roots were pretreated in hot water at 80 °C for 5 min. The methods of drying used for the study were tray drying, solar drying, vacuum drying and fluidized bed drying at four temperature levels 40, 50, 60 and 70 °C. The complete drying of asparagus follow falling rate period only. The total time for drying decreases with increase in temperature of drying air from 40 °C – 70 °C. Fluidized bed dryer hasa highest average drying rate as compare to tray dryer, solar dryer and vacuum dryer. Four empirical models, namely Page's, Exponential, Generalized exponential and Logarithmic model were fitted in the drying data to describe the phenomena of drying process using a linearized regression technique.It was found that the Page's model was bestas it describe most precisely about the drying behavior of asparagus roots. The effective moisture diffusivity of asparagus roots varies from 7.14×10^{-9} to 3.70×10^{-8} m^2/s and it was also found that diffusivityincreases with increase in temperature.The activation energy was found to be from 11.797 to 30.318 kJ/mol.

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Keywords

Asparagus roots,
Drying,
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Diffusivity,
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Introduction

Asparagus (*Asparagus racemosus*L.)growing in the Mediterranean regionis a rare wild species of *Asparagus*. It is commercially cultivated in Madhya Pradesh, Uttar Pradesh and Uttrakhand. It is a slender climber and belonging to the family *Liliaceae*. It is gaining popularity due to its texture and flavor[1].It includes about 300 species in the world andout of which the 22 species are recorded in India. It is most commonly used in traditional medicine[2].It is used for treatment and prevention of dyspepsia, gastric ulcers and as a galactogogue, nervous disorders, liver diseases, inflammation and infectious diseases. It is also used for the treatment

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of epilepsy, excessive heat, chronic fevers, kidney disorders, stomach ulcers and liver cancer, it also increases milk secretion in nursing mothers and also regulates sexual behaviors. It contains vitamins (A, B_1, B_2, C, E), minerals (Mg, P, Ca, Fe), and folic acid with few primary chemical constituents like asparagine, essential oils, arginine, tyrosine, flavonoids (kaempferol, quercetin, and rutin), resin, and tannin[3]. Crude fiber, crude protein, ash content, ether extract and nitrogen free extract analysis found that it is very rich in nitrogen freeextract and minerals like Ca, Mg, Fe, Cu, Zinc etc.[3].

Fresh *Asparagus* roots are highly perishable which leads to wastage and lossesof the fresh product. It degrades rapidly, which results in a short shelf life of roots of 3–5 days under normal postharvest handling at room temperature[4]. The short shelf life of fresh root is mainly due to its high respiration ratewhich continues even after harvesting[5]. It leads to degradation in quality, loss in quantity and reduction in economic values of the product. The reduction of these losses is important,especially to balance the supply and demand at the time of off-season. Therefore, several methodsincluding refrigeration, freezing and dryingcan be used whichincreases the shelf life of product[6].

Blanching is the pre-treatment method used to arrest few physiological processes. It helps for inactivation of the enzymes, acceleration of drying rate and for reduction of the quality loss. It expels intercellular air from the tissues and also softens the product[7]. Generally, blanching of fruits and vegetables is done by heating in steam or hot water[8].

Drying is one of the most generally used methods for preservation. It preserves food by reducing water activity which hinders the growth and reproduction of microorganisms which are responsible for deterioration and also minimizes the moisture induced problems[9]. Thin layer drying equations are used to estimate the drying time for several food products and also for the generalization of the drying curves. Drying kinetics is greatly affected by the temperature of air, velocity of air, thickness of material, and others[10]. Physical and thermal properties of food products, such as the heat and mass transfer, and moisture diffusion data are required for the ideal design of dryer[11]. The knowledge of effective moisture diffusivity is alsoimportant for designing and modeling of the mass transfer processes such as drying or moisture adsorption during storage. Drying characteristics & kinetics of fruits and vegetables have been studied by many investigators, cauliflower[12], carrot[13], yam[7], *asparagus*[14], kiwifruit and apricot[15]. However, the drying characteristic of *Asparagus* has not been investigated and a very few information are available in the literature.

The objective of this work was to compare the effect of different dryers (solar, tray fluidized bed and vacuum drying) and temperature of drying air (40, 50, 60 and 70 °C) on drying time and also to find a best suitable empirical mathematical model for drying, and to estimate effective moisture diffusivity for *Asparagus* roots.

Material and Method

Material

Sample

Fresh wild Asparagus (*Asparagusracemosus*L.) roots were procured from the Medicinal Plant Research and Development Centre, Pantnagar, Uttrakhand. Sample was selected carefully for uniform shape, size and samples were also checked for any defect on visual inspection. Selected roots were cleaned and washed by removing damaged fruits and all foreign matters such as dust and dirt. Theselectedsamples were cut into 2-4 mm long slices.The sliced sample was usedfor initial moisture content determination by a vacuum oven drying method[16]. Finally, pre-treatments were applied and drying experiments were performed.

Method

Experimental Procedure

For drying, pre-treatment was carried out by blanching with hot water at 80 ^{0}C for 5 min[17]. Pretreated sample was subjected to the thin layer drying in the “Tray, Solar, Fluidized bed, and Vacuum” dryers at the temperature ranges of 40 - 70 ^{o}C with an increment of 10 ^{o}C[18,19,20]. The dryer was started before 60 min for steady-state conditions to drythe samples and the drying process was started when the required drying conditions for drying were achieved.Then, the pre-treated samples of *Asparagus* root were put in a single layer in dryer for drying. The weight of the samples was continuously taken with an interval of 1 hour to check the change of sample moisture or to determine the moisture content at different drying time.The drying was carried until two to three consecutive weights which didn't vary more than 3 – 5 mg and that final weight was recorded.The dried samples were packed in polyethylene bags of 200 gauge in air tight condition and stored at room temperature in desiccators.The initial moisture content of the sample was calculated on dry basis by using formula $Mc = (W_1-W_2)/W_0$, Where,W_0 is dry weight of the sample (g), W_1 is sample weight before drying (g) and W_2 is sample weight after drying (g).

Moisture Ratio

The moisture content of *Asparagus* roots is expressed in moisture ratios (MR) with the following equation[21,22]:

$$MR = (M-M_e)/(M_0-M_e) \quad ...(1)$$

The M_e values were neglected because as compared to M_o and M the values of equilibrium moisture content were very small for long drying time and therefore the moisture ratio was calculated as the following relationship[23,24]:

$$MR = M/M_o \quad ...(2)$$

Where, M is the mean moisture content; M_o is the initial moisture content; and M_e is the equilibrium moisture content (EMC).

Determination of Effective Moisture Diffusivity

For slab geometry food particles the fick's diffusion equation was used for effective moisture diffusivity calculation of biological products[25]. The fresh cut *Asparagus* roots were assumed to besimilar as slab geometry and for calculation of moisture ratio the following equation was used[26]:

$$MR = 8/\pi^2 \exp(-\pi^2 D_{eff}\, t)/4L^2) \quad ...(3)$$

The above equation can also be written as:

$$\ln MR = t\, k_o + \ln 8/\pi^2 \quad ...(4)$$

Where, D_{eff} is the effective moisture diffusivity (m^2/s); L is the half of thickness of slab (m).According to Equation (4) by plotting graph of ln (Moisture Ratio) versus time, the slope (k_o) was calculated. On comparing the above equation with linear equation Y= mX+C, where m is the slope of the straight line and the slope was calculated as

$$k_o = (-\pi^2 D_{eff})/4L^2 \quad ...(5)$$

$$D_{eff}= (-4L^2 k_o)/\pi^2 \quad ...(6)$$

Determination of Activation Energy

The effective moisture diffusivity is related with temperature by Arrhenius equation[27]:

$$D_{eff} = D_0 \exp[-E_a/(R(T+273.15)] \quad ...(7)$$

where, D_0 is the constant of Arrhenius equation in m^2s^{-1}, Ea is the activation energy in $kJ.mol^{-1}$, T is the temperature in °C and R is universal gas constant in $kJ.mol^{-1}.K^{-1}$.

The rearranged form of the equation (7):

$$\ln (D_{eff}) = \ln(D_0) - E_a/R(T+273.15) \quad ...(8)$$

The activation energy was calculated using the curve between $\ln(D_{eff})$ versus 1/(T+273.15).

Modeling of the Thin-Layer Drying Curves

The curve of moisture ratio and time explainsbetter about the drying behavior as compare to the moisture content and time curve because the initial valueof moisture ratio was one for each of the experiments. These moisture ratio values of drying data were also used for predictionof the best drying model for pre-treated samples of *Asparagus* roots. MR data were fitted into four models listed in Table 1 to select the best model for drying of *Asparagus*.The thin-layer equations were used to fit the drying experimental data of *Asparagus* roots in their linearised form using regression technique in a spread sheet (EXCEL) and CURVE EXPERT 1.3 software package on personal computer.The comparison of the all models was done by comparing coefficient of determination (R^2) and standard error of estimation (SEE).

Table 1: Empirical Models

S. No.	Model expression	Name of model	References
1	$MR = e^{-kt}$	Exponential model[28]	Henderson, 1974
2	$MR = Ae^{-kt}$	Generalized exponential model[29]	Zhang and Litchfield,1991
3	$MR = e^{-kt^n}$	Page's model[30]	Guarte, 1996
4	$MR = a e^{-kt} + c$	Logarithmic model[31]	Karathanos, 1999

Where, MR is moisture ratio, t is time in h, k is drying constant in h^{-1} and A, n, a, c are the drying parameters.

Result and Discussion

Characteristics of the *Asparagus* roots

The value of moisture content of the root samples was found to be 86.44% (w.b.) and 637.46% (d.b.) which shows that the Asparagus roots can be grouped under a highly perishable medicinal plant. It was also be foundthat the final moisturecontent of sample decreases with the increasein drying temperature.

Moisture Ratio

The variation of moisture ratio verses time for an experimental range of temperature (40-70 °C) is shown in Figures 1 to 4.The relationship of moisture ratio and time shows that there was a rapid decrease in moisture ratio with a faster rate at initial stage of 60 to 120 min of drying and in later stagesthe moisture ratio decrease in slower rate as moisture content approached to equilibrium moisture content.Moisture ratio curves for all the four levels of temperatures showed that the drying of 70 °C was faster than other drying temperatures. It was also found that the drying rate was higher for higher air temperature and the drying was fast in case of fluidized bed dryer as compare to other dryers.The constant drying rate period was not observed and the complete drying process took place in the falling drying rate period which shows that diffusion is a dominant physical mechanism which governs moisture movement in the samples. Similar results were also obtained by other authors working with other foods[13,32].

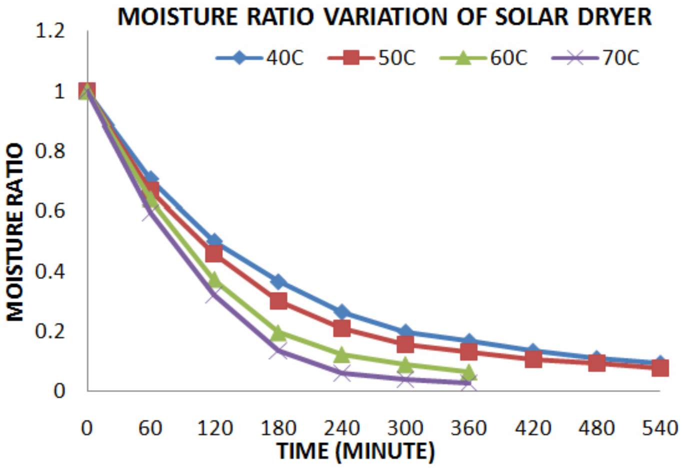

Fig. 1: Variation in moisture ratio with drying time in solar dryer

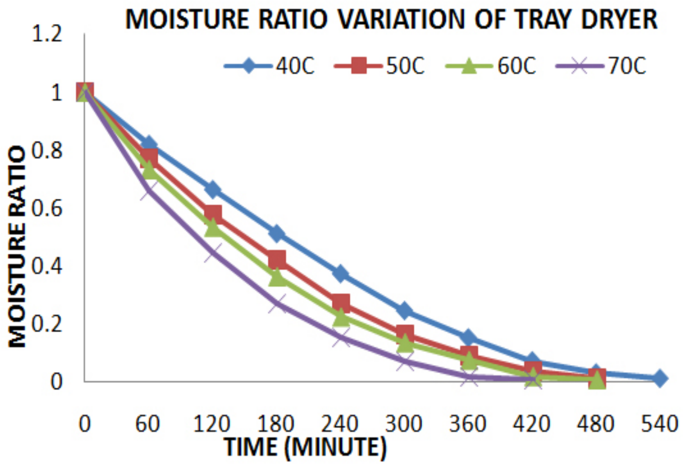

Fig. 2: Variation in moisture ratio with drying time in tray dryer

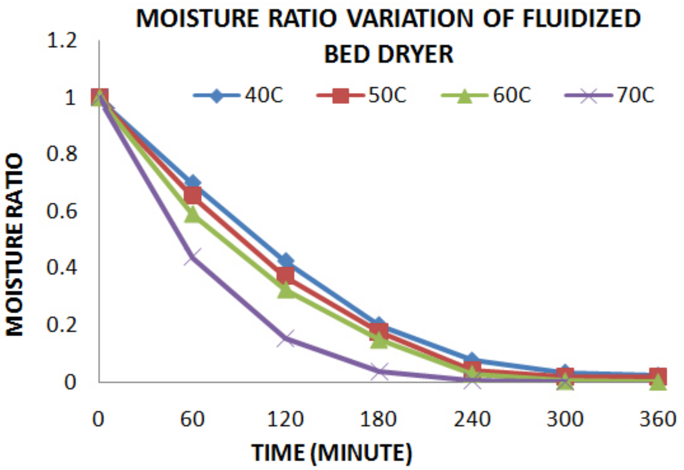

Fig. 3: Variation in moisture ratio with drying time in fluidized bed dryer

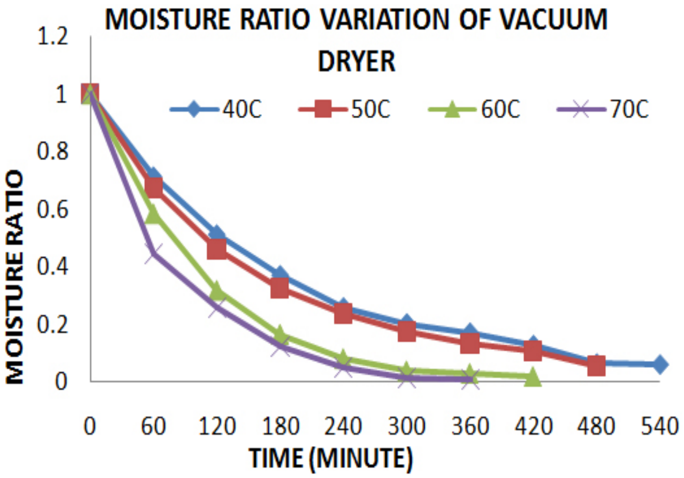

Fig. 4: Variation in moisture ratio with drying time in vacuum dryer.

Effective Moisture Diffusivity

The result indicate that internal mass transfer resistance controls the drying time thereforethe falling rate period dominated the drying process.For estimation of diffusion coefficients (D_{eff}), the slope of ln(MR) versus time(Figures 5 to 8) was used. The value of effective moisture diffusivity is shown in Table 2. The effective diffusivity was determined to be 7.14×10^{-9} to 1.75×10^{-8} m^2/s for the solar drying, 8.44×10^{-9} to 2.19×10^{-8} m^2/s for vacuum drying, 1.31×10^{-8} to 1.95×10^{-8} m^2/s for tray drying and 1.85×10^{-8} to 3.70×10^{-8} m^2/s for fluidized bed drying in the temperature range of 40–70 ^{0}C.It was found that the effective diffusivity of samples increased with increase in drying air temperature, which may be because of the increase in diffusion with the increase of temperature of samples[33]. The values of effective moisture diffusivity obtained from this study are in the range of 10^{-12} to 10^{-8} for biological materials[34].

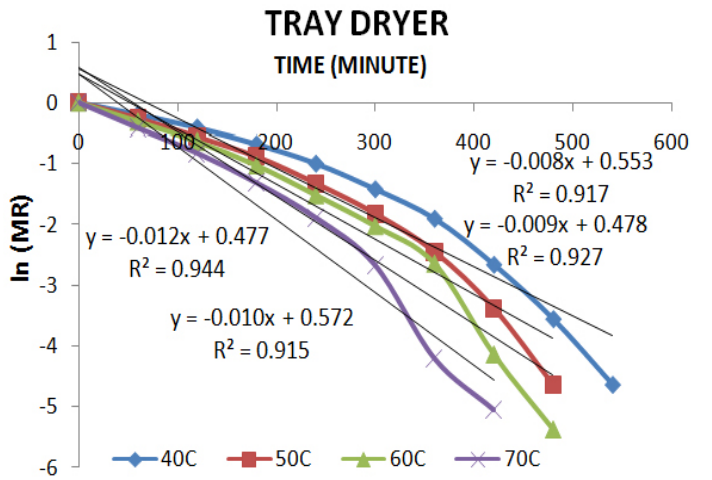

Fig. 5: Experimental and predicted ln(MR) vs time for tray dryer

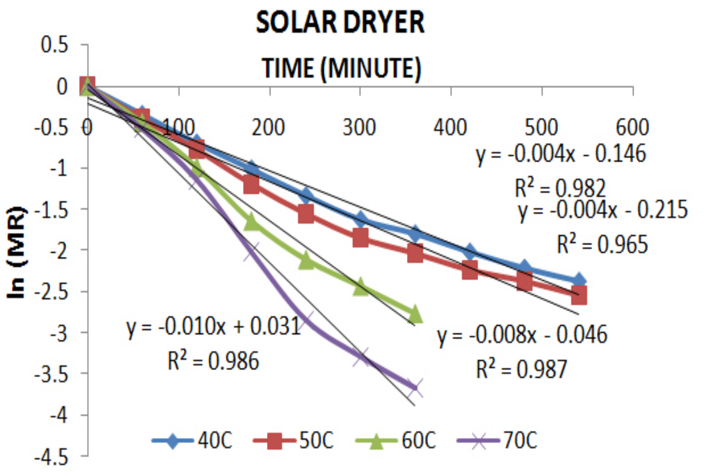

Fig.6: Experimental and predicted ln(MR) vs time for solar dryer

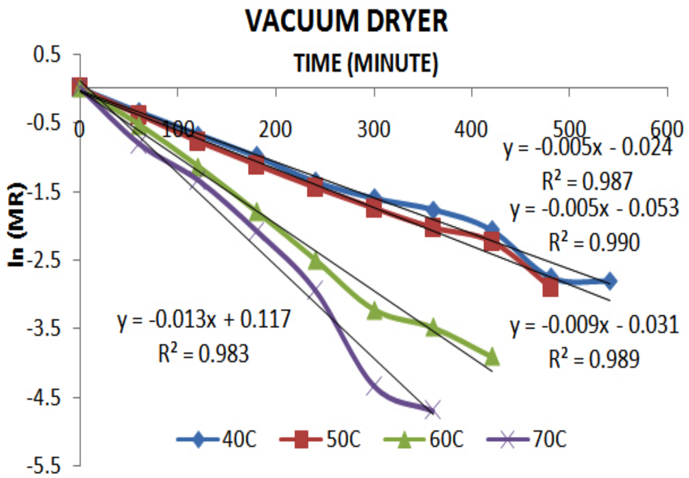

Fig. 7: Experimental and predicted ln(MR) vs time for vacuum dryer

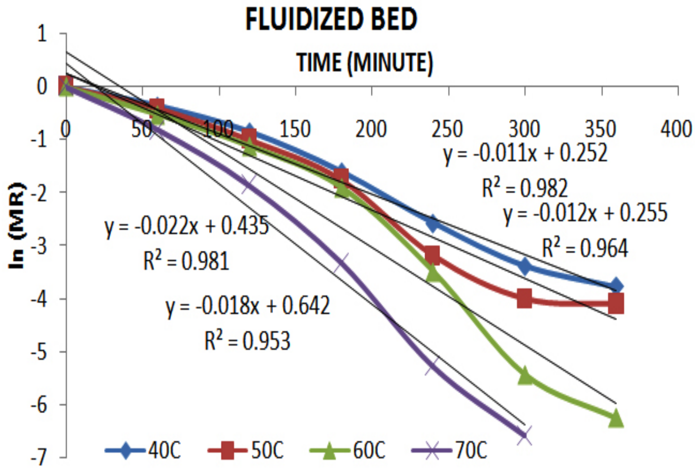

Fig. 8: Experimental and predicted ln(MR) vs time for fluidized bed dryer

Table 2: Effective moisture diffusivity at different conditions

Temp. (°C)	Dryers	Equation	k_o	D_{eff}(m²/s)
40	Vacuum	y = -0.0052x - 0.0242	-0.0052	8.44×10^{-9}
	Tray	y = -0.0081x + 0.5532	-0.0081	1.31×10^{-8}
	Solar	y = -0.0044x - 0.1463	-0.0044	7.14×10^{-9}
	Fluid	y = -0.0114x + 0.2527	-0.0114	1.85×10^{-8}
50	Vacuum	y = -0.0056x - 0.0534	-0.0056	9.09×10^{-9}
	Tray	y = -0.0091x + 0.478	-0.0091	1.48×10^{-8}
	Solar	y = -0.0047x - 0.2156	-0.0047	7.63×10^{-9}
	Fluid	y = -0.0129x + 0.2558	-0.0129	2.09×10^{-8}
60	Vacuum	y = -0.0097x - 0.0313	-0.0097	1.57×10^{-8}
	Tray	y = -0.0105x + 0.5725	-0.0105	1.70×10^{-8}
	Solar	y = -0.008x - 0.0466	-0.0080	1.30×10^{-8}
	Fluid	y = -0.0184x + 0.6426	-0.0184	2.99×10^{-8}
70	Vacuum	y = -0.0135x + 0.1174	-0.0135	2.19×10^{-8}
	Tray	y = -0.012x + 0.4771	-0.0120	1.95×10^{-8}
	Solar	y = -0.0108x + 0.0312	-0.0108	1.75×10^{-8}
	Fluid	y = -0.0228x + 0.4351	-0.0228	3.70×10^{-8}

Activation Energy

The activation energy for the drying methods was calculated by using the curves between ln(D_{eff}) and 1/(T+273.15) (Figures 9 to 12). By using slope of the straight lines, the activation energy was found to 11.797 kJ/mol for tray dryer, 21.687 kJ/mol for fluidized bed dryer, 28.667 kJ/mol for solar dryer 30.318 kJ/mol.

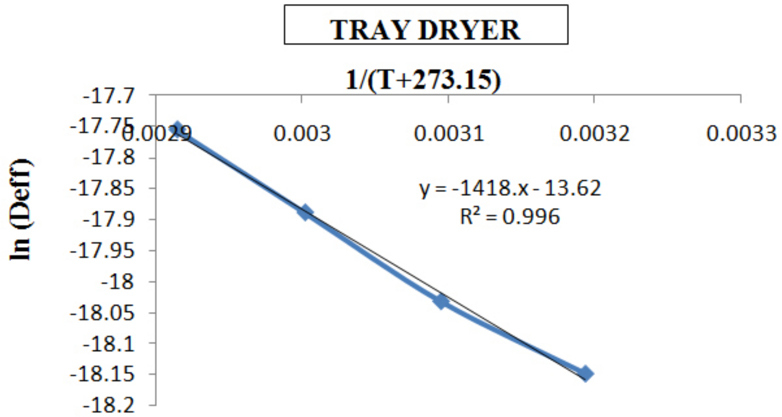

Fig. 9: Effective diffusivity vs reciprocal of absolute temperature for tray dryer

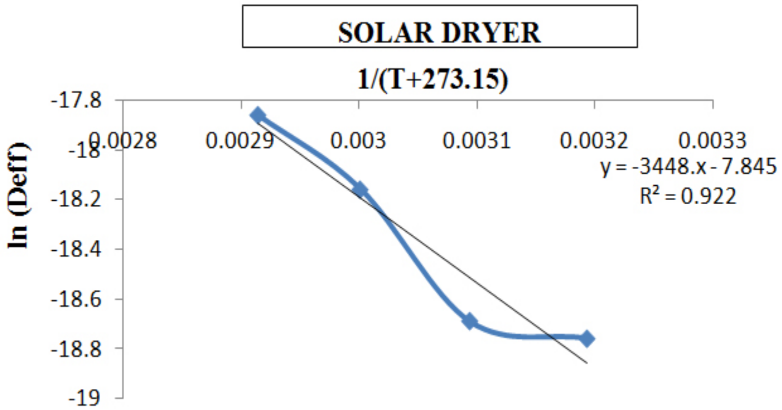

Fig 10: Effective diffusivity vs reciprocal of absolute temperature for solar dryer

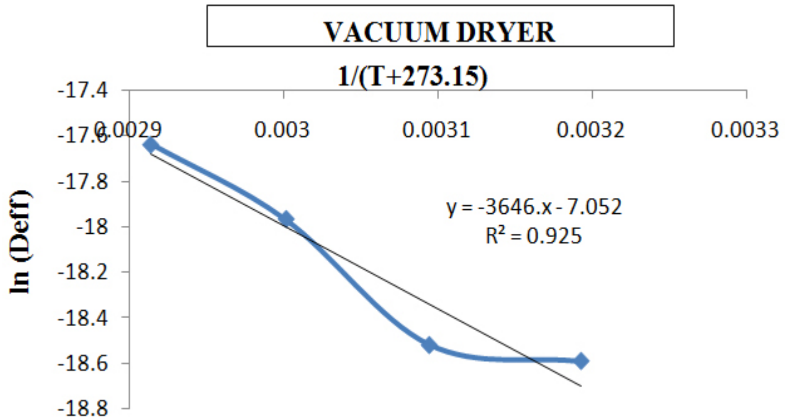

Fig 11: Effective diffusivity vs reciprocal of absolute temperature for vacuum dryer

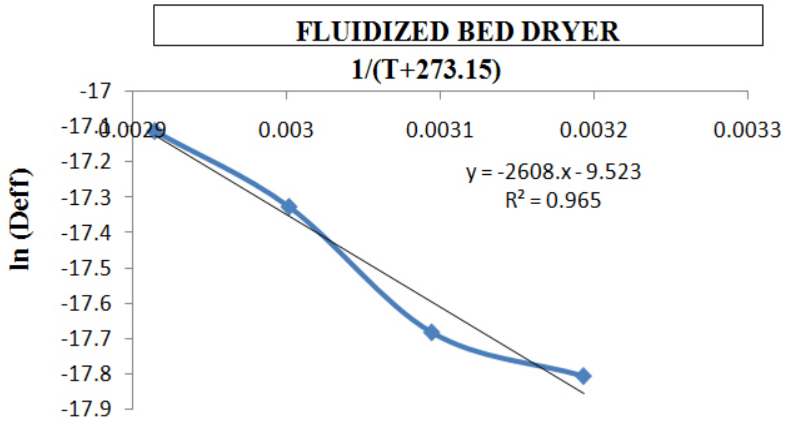

Fig. 12: Effective diffusivity vs reciprocal of absolute temperature for fluidized bed dryer

As there was absence in constant rate period in complete drying of *Asparagus* roots, so the models which describe the falling rate period phenomenon of drying were only attempted. The standard error of estimation was less in Page's model for all conditions of experiments as well as the coefficient of determination was high but very closely near to logarithmic model in 16 experiments. Therefore, on the basis of R^2 and SEE values, both the logarithmic model and the page's model were observed to be more satisfactory compare to other two models for experimental data. To analyze further about the validity of one these two models namely the logarithmic and the Page's models, the variation of moisture ratio with time for observed and predicted values were plotted. This is because of the fact that for best fit drying model, the latter part of the moisture ratio curve is more important that initial part of the curve. The residual of observed and predicted MR (MR in the logarithmic and the Page's models) are compared. Standard error of estimation of moisture ratio for the sample set was minimum for Page's model followed by logarithmic model. Therefore the Page's model was selected as the best fit curve. The value of statistical parameters for drying models is shown in Table 3 and the value of the regression coefficient for drying models are shown in Table 4.

Table 3: Statistical parameters for drying models

Temp. (°C)	Dryers	Exponential model		Page's model		Generalized Exponential model		Logarithmic model	
		R^2	SEE	R^2	SEE	R^2	SEE	R^2	SEE
40	Vacuum	0.9984	0.0172	0.9989	0.0149	0.9985	0.0177	0.9991	0.0147
	Tray	0.9828	0.0645	0.9976	0.0254	0.9855	0.0628	0.9983	0.0233
	Solar	0.9969	0.0235	0.9989	0.0143	0.9972	0.0236	0.9999	0.0047
	Fluid	0.9889	0.0560	0.9995	0.0131	0.9901	0.0579	0.9957	0.0427
50	Vacuum	0.9985	0.0169	0.9996	0.0086	0.9987	0.0168	0.9995	0.0116
	Tray	0.9898	0.0499	0.9985	0.0207	0.9911	0.0495	0.9992	0.0164
	Solar	0.9961	0.0268	0.9981	0.0199	0.9963	0.0276	0.9997	0.0078
	Fluid	0.9911	0.0502	0.9992	0.0168	0.9919	0.0527	0.9964	0.0392
60	Vacuum	0.9993	0.0133	0.9998	0.0058	0.9993	0.0138	0.9995	0.0134
	Tray	0.9929	0.0412	0.9986	0.0198	0.9937	0.0415	0.9994	0.0142
	Solar	0.9982	0.0206	0.9989	0.0179	0.9984	0.0218	0.9984	0.0244
	Fluid	0.9946	0.0388	0.9988	0.0202	0.9949	0.0413	0.9985	0.0250
70	Vacuum	0.9983	0.0204	0.9988	0.0185	0.9984	0.0220	0.9984	0.0246
	Tray	0.9957	0.0326	0.9985	0.0194	0.9960	0.0341	0.9996	0.0120
	Solar	0.9970	0.0283	0.9996	0.0116	0.9972	0.0299	0.9981	0.0275
	Fluid	0.9982	0.0236	0.9999	0.0061	0.9982	0.0260	0.9993	0.0194

Table 4: Regression coefficient for drying models

Temp.	Dryers	Exponential model	Page's model		Generalized Exponential model		Logarithmic model	
(°C)		K	K	n	A	k	a	k	C
40	Vacuum	0.00539	0.00739	0.9412	0.9894	0.00533	0.9750	0.0057	0.0221
	Tray	0.00454	0.00047	1.4093	1.0632	0.00481	1.3526	0.0027	-0.3350
	Solar	0.00532	0.00983	0.8864	0.9808	0.00523	0.9369	0.0063	0.0652
	Fluid	0.00815	0.00104	1.4135	1.0413	0.00844	1.1562	0.0064	-0.1337
50	Vacuum	0.00608	0.00976	0.9104	0.9843	0.00598	0.9580	0.0066	0.0371
	Tray	0.00549	0.00103	1.3102	1.0447	0.00572	1.2194	0.0038	-0.2079
	Solar	0.00618	0.01165	0.8796	0.9828	0.00607	0.9437	0.0073	0.0606
	Fluid	0.00908	0.00148	1.3685	1.0331	0.00936	1.1189	0.0074	-0.1009
60	Vacuum	0.00963	0.00608	1.0943	1.0094	0.00972	1.0188	0.0094	-0.0121
	Tray	0.00611	0.00164	1.2548	1.0341	0.00630	1.1448	0.0047	-0.1370
	Solar	0.00828	0.00538	1.0866	1.0122	0.00838	1.0150	0.0083	-0.0034
	Fluid	0.01009	0.00285	1.2609	1.0207	0.01026	1.0861	0.0085	-0.0780
70	Vacuum	0.01227	0.01848	0.9133	0.9918	0.01218	0.9913	0.0122	0.0006
	Tray	0.00754	0.00304	1.1774	1.0194	0.00767	1.0954	0.0061	-0.0943
	Solar	0.00989	0.00365	1.2060	1.0175	0.01003	1.0479	0.0091	-0.0368
	Fluid	0.01496	0.00529	1.2304	1.0081	0.01505	1.0370	0.0137	-0.0327

Discussion

The present study concludes that the drying of *Asparagus* was carried out only in the falling rate stage which shows that the moisture removed from the product was governed by diffusion phenomenon. The drying was fast in case of the fluidized bed dryer. Page's model was best for prediction of the data. The drying time of *Asparagus* decreases and the effective diffusivity increases as the air temperature was increased.The highest effective diffusion was found to be 3.70×10^{-8} m^2/s for a fluidized bed dryer at temperature 70 °C. The lowest effective diffusion was 7.14×10^{-9} m^2/s for a solar dryer at temperature 40 °C.Activation energy was found to 11.797 kJ/mol for tray dryer, 21.687 kJ/mol for fluidized bed dryer, 28.667 kJ/mol for solar dryer 30.318 kJ/mol. This activation energy is the main basic consideration for the design of any drying system and calculation of required drying energy.

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