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MATHEMATICAL MODELING OF THIN LAYER DRYING KINETICS OF SHATAVARI (ASPARAGUS RACEMOSUS) IN SOLAR CABINET DRYER INTEGRATED WITH PHASE CHANGE MATERIAL

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ABSTRACT

Mathematical models of thin-layer solar drying of medicinal plant Shatavari were studied and verified with experimental data. Seven different mathematical drying models were compared according to statistical parameters, i.e. coefficient of determination (R2), chi-square (χ^2) and root mean square error (RMSE). The best model describing the thin layer drying characteristics of Shatavari was set on the basis of the highest R2 values and the lowest RMSE values. The different thin layer drying models were applied for variation of moisture ratio with respect to drying time and was experimentally investigated in a sun drying and solar cabinet dryer. The objective of the study was the verification of models already developed and determined best ranked thin layer drying model for Shatavari. The Modified Henderson & Pabis model and Page model could satisfactorily describe the solar drying curve for sun and solar cabinet drying of Shatavari with coefficient of determination of 0.998 and 0.997 respectively.

Keywords: Thin-layer drying, Sun drying, Solar cabinet drying, Mathematical Model, Shatavari.

INTRODUCTION

Asparagus racemosus (family Asparagaceae; Liliaceae), is commonly known as Shatavari, Satawar or Satmuli in India, is a vital medicinal plant (Patil et al. 2019). Shatavari is a perennial much branched climbing herb found all over India, especially in tropical and sub-tropical parts and in Himalayan region upto 1400 m. It includes 300 species worldwide, and 22 species have been noted in India (Bopana & Saxena 2007). Shatavari is a plant with a woody stem that sends runners out, has needle like leaves, with small white flowers and having one hundred roots. The roots of Asparagus racemosus (Shatavari) are fleshy, whitish-brown in colour, slightly sweet in taste. It is an important herbal drug rich in steroids such as Shatavari I–VIII (Joshi et al. 2017). Root contains saponin, water soluble constituents 52.1 per cent, glucose 7 per cent and ash from dried root 4 per cent (Sharma et al. 2009). Shatavari is an indigenous medicinal plant used in Siddha and Homoeopathy medicines. It is estimated that in India, more than 500 tonnes of Shatavari roots are needed every year for various medicinal preparations (Dinabandhu2008). The roots of Asparagus racemosus (Shatavari) also has proved its effectiveness as a natural sex-stimulant, fertility promotion, phyto-estrogenic, hormone modulation in both male and female and medicine for gynecological disorders (Singh & Geetanjali 2016). Shatavari (Asparague racemosus) root and their different extracts have shown alterative, demulcent, aphrodisiac, antiseptic, anti-anxiety, cardio-protective, anti-diarrheal anti-depressant, neuroprotective, immunomodulatory, anti-bacterial, antiparasitic, antiepileptic, adaptogenic, antilithiatic, antihepatotoxic, ant-oxytocic and anti-cancer activity and also used for treatment and cure of stomach ulcers (Acharya et al. 2012, Goel et al. 2006, Dikasso et al. 2016, Kohli et al. 2022, Jalalpure et al. 2009, Muruganandan et al. 2001, Sairam et al. 2003 Sharma et al. 2013). It is a good source of folic acid that is vital for foetal neuronal growth and blood formation.Different scientific studies have proved its efficacy in a number of physical and mental ailments. (Alok Shashi et al. 2013). It has been utilized as a galactagogue, anodyne, antispasmodic, diuretic, aphrodisiac and nervine tonic (Zhang et al. 2019). Despite its nutritional and medicinal properties of Shatavari has a high moisture content so that it is highly perishable medicinal plant. Thus, it is suffered to quick spoilage with poor shelf-stable properties and demands preservation to reduce its postharvest losses (Kohli et al. 2017).

The aim of drying of medicinal plants are to increase the shelf life, protect from biological activities including microbial and enzymatic, and to reduce the weight and volume of the materials in order to facilitate packaging, transporting and storing (Simal et al. 2005). During the drying process, it is important to preserve the texture, color, flavor, and nutritional value of the product. This means reducing it to the safe level of moisture content, to minimize the quantity and losses during storage (Hall, 1980). The removal of moisture prevents the growth and reproduction of microorganisms like bacteria, yeasts and molds causing decay and minimizes many of the moisture-mediated deteriorative reactions (Van Arsdel 1965). Drying also reduces physical and chemical changes during storage. Since it is a highly energy-intensive process, new drying techniques and driers are needed with minimum energy cost (Oladejo et al. 2021).

Thin layer drying models have found widest application because of their ease of use and do not require evaluation of many models parameters. Thin layer drying equations describe drying phenomena in a unified manner and estimate drying time of several products and generalize drying curves (Karathanos & Belessiotis 1999). Thin layer drying models for agricultural products related to moisture content of the material at any given point in time and drying parameters (Midilli et al. 2002, Togrul & Pehliavan 2002). Dried product quality entirely depends on different unit operations involved in drying process (Ertekin & Yaldiz 2004). Drying kinetics and modeling of several fruits and vegetables have been studied by countless researchers, jujube (Wang, et al., 2021), banana (Macedo, et al., 2020), green apple peel (Alibas et al. 2020), mango (Shende et al. 2020), lemon (Ozcan et al. 2021), apricots (Togrul & Pehliavan 2002) mint leaves (Doymaz 2006 and Kannan et al., 2021), sweet potato (Onwude et al. 2021), Cuminum cyminum (Zomorodian et al. 2010) and tomato (Al-Hilphy et al. 2021) etc. but limited information is available on drying kinetics of Shatavari root. The present work ascertains the effect of drying of Shatavari root in sun and Solar cabinet dryer integrated with phase change material and evaluates different thin layer drying model.

MATERIALS AND METHODS

Sample preparation

Freshly harvested Shatavari roots were procured directly from farmer's field. The discolored, diseased or damaged Shatavari were sorted out. The samples were washed properly in running water to remove the adhering impurities and the sample was spread on a plastic filter tray to drain out the excess water. Further the samples were peeled with the help of knife. Peeling helps tuber to dry early. In case of Shatavari as the length of roots were longer, they were cut into small pieces of about 6-7 cm immediately after peeling for drying (Patil et al. 2019). The initial moisture content of Shatavari roots was determined by oven drying method (Ranganna 1986).

Drying of shatavari

Sun Drying:

Sun drying was done by spreading the Shatavari roots samples in a single layer in the dish. A 0.35 m height from the ground was maintained in order to avoid contamination of dust (Akpinar 2010).

Drying experiment was conducted between 9.00 a.m. to 18.00 p.m. Open sun drying of Shatavari was conducted at temperature range 25 to 36°C. During the experiment, the observations were recorded at a regular interval of time. The overall 9 hrs of drying during daytime was considered.

Solar Cabinet Drying:

A solar cabinet dryer having 10 kg capacity integrated with PCM as heat storage material has been developed and tested for Shatavari. The solar collector system was facing south tilted at an angle of 45° from the horizontal is connected to food cabinet having five trays. The sample was distributed and loaded equally on five trays. Drying was conducted at constant air velocity of 1.0 m/s from 9:00 h till getting constant weight of sample. The temperature range of 35 to 65°C with corresponding average solar radiation 555 W/m2 and average ambient temperature of 30°C.

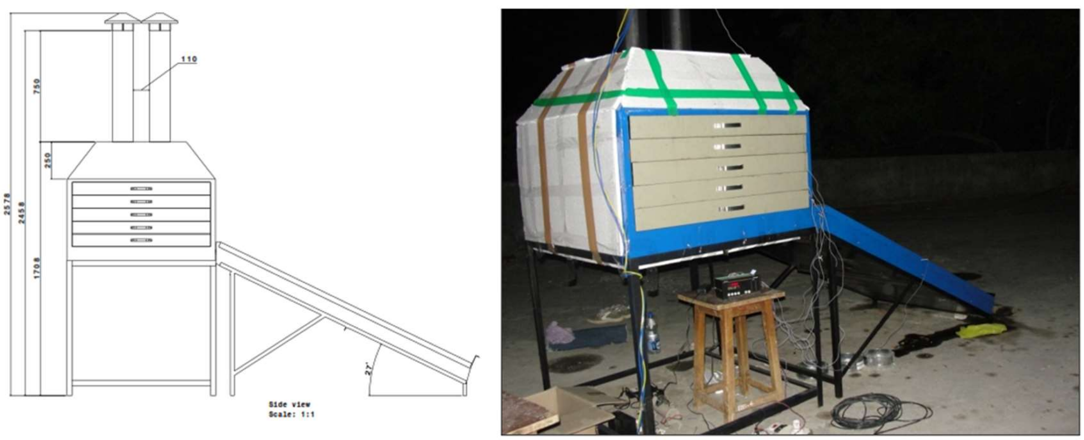

Figure1: Experimental set of Solar cabinet dryer with phase change material

2.3 Drying characteristics

The drying depends on simultaneous heat and mass transfer phenomena and factors dominating each process determine the drying behavior of the product. The drying rates were computed from the experimental data and drying characteristics curves i.e. moisture content (db) vs drying time, drying rate and moisture ratio vs drying time.

Moisture content

Initial moisture content of sample was determined by the hot air oven drying method (Ranganna, 1986). The percentage moisture content was determined by using following formula,

$$M.C.(\text{wb}) = \frac{(W_1 - W_2)}{W_1} \times 100 \quad \ldots 1$$

$$M.C.(\text{db}) = \frac{(W_1 - W_2)}{W_2} \times 100 \quad \ldots 2$$

Where,

W1= weight of sample before drying, g

W2= weight of bone dried sample, g

Drying rate

The drying rate (g h-1100g-1 of bone dry weight) of produce sample during drying period was determined (Doymaz 2006).

$$\text{Drying rate } (DR) = \frac{\Delta \mathrm{W}}{\Delta \mathrm{t}} \quad \text{...3}$$

Where,

ΔW= Weight loss in one hour interval (g 100g-1of bdm)

Δt = Difference in time reading (h)

Moisture ratio

The moisture content of Shatavari samples during thin layer drying were expressed in terms of moisture ratios (MR). The most widely used thin layer models in the drying process of agricultural products are the semi-empirical and the empirical models. The solar drying curves of Shatavari samples drying were fitted with different moisture ratio equations (Table 1). The moisture ratio of the produce was computed by using the initial moisture content (IMC) and equilibrium moisture content (EMC) (Midilli 2001, Erenturk et al. 2004).

$$\text{Moisture Ratio } (M.R.) = \frac{(\mathrm{M} - \mathrm{M}_e)}{(M_0 - \mathrm{M}_e)} \quad \text{... 4}$$

Where,

M = Moisture content, %

Me = Equilibrium moisture content, %

M0 = Initial moisture content, %

Mathematical modelling

The coefficient of determination (R2) was used as primary criteria for selecting the model that best fit the experimental data. In addition, the best fit of the experimental data was also selected based on various statistical parameters such as the reduced chi-square (χ2) as the mean square of the deviations between the experimental and predicted values for the models and root mean square error analysis (RMSE). To get the best fit of the experimental data, the coefficient of determination should be higher and the χ2 and RMSE should be lower (Perumal 2007, Kamil 2006). The statistical parameters were calculated by using the following relationships:

$$R^2 = \frac{\left[\sum_{i=1}^{N}\left(MR_{pre,i} - \sqrt{MR_{pre,i}}\right)^2\right]}{\left[\sum_{i=1}^{N}\left(MR_{exp,i} - \sqrt{MR_{exp,i}}\right)^2\right]} \quad \ldots 5$$

$$\chi^2 = \frac{\left[\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]}{N-n} \quad \ldots 6$$

$$R_{MSE} = \sqrt{\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]} \quad \ldots 7$$

Where,

$MR_{exp,i}$ = the i^{th} experimentally observed moisture ratio

$MR_{pre,i}$ = the i^{th} predicted moisture ratio values

N = the total number of observations

n = the number of constants in the model.

Table 1: Mathematical Models applied to solar drying curves

Sr. No.	Model Name	Model
1.	Lewis	M.R. = $exp(-a.x)$
2.	Page	M.R. = $exp(-a.x^b)$
3.	Henderson-Pabis	M.R. = $a.exp(-b.x)$
4.	Logarithmic	M.R. = $a.exp(-b.x) + c$
5.	Two term	M.R. = $a.exp(-b.x) + c.\ exp(-d.x)$
6.	Modified Henderson and Pabis	M.R.=$a.exp(-b.x) + c.\ exp(-d.x) + e.exp(-f.x)$
7.	Wang and Singh	M.R. = $1+a.x+b.x^2$

(a, b, c, d & f = Model coefficients, x= Drying time, min.)

In the equations, a, b, c, d, e and f are the model coefficients. Non-linear regression method was utilized to fit the data for the selected drying models. For evaluating the goodness of fit, three statistical indicators were used in addition to R2. The model having the highest R2 and the lowest Root Mean Squares Error (RMSE), χ2and Mean Bias Error (MBE) was determined as the best fit model. The mathematical modelling of thin layer drying of Shatavari was done by using STATISTICA.

RESULT AND DISCUSSION

Drying characteristics of Shatavari

The drying experiments were carried out on typical sunny days in the month of December. The moisture content of Shatavari was reduced from 362.79 per cent (db) to 14.22 per cent (db) in open sun drying in 20 h, whereas moisture content was reduced to 15.81 per cent (db) in 15 h when dried in solar dryer (Figure 2). The drying time of Shatavari was reduced by 5 h when dried in solar dryer as compare to the open sun drying. It was also observed that the maximum moisture removal had taken place from 362.79 to 105.30 per cent (db) in 9 h in open sun drying whereas up to 100.83 per cent in 7 h in solar dryer and followed by falling rate period.

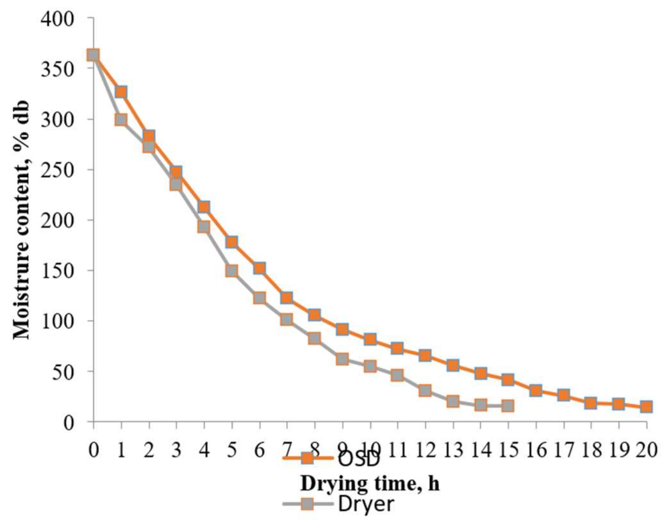

Figure 2: Variation of moisture content of Shatavari in solar dryer and open sun drying

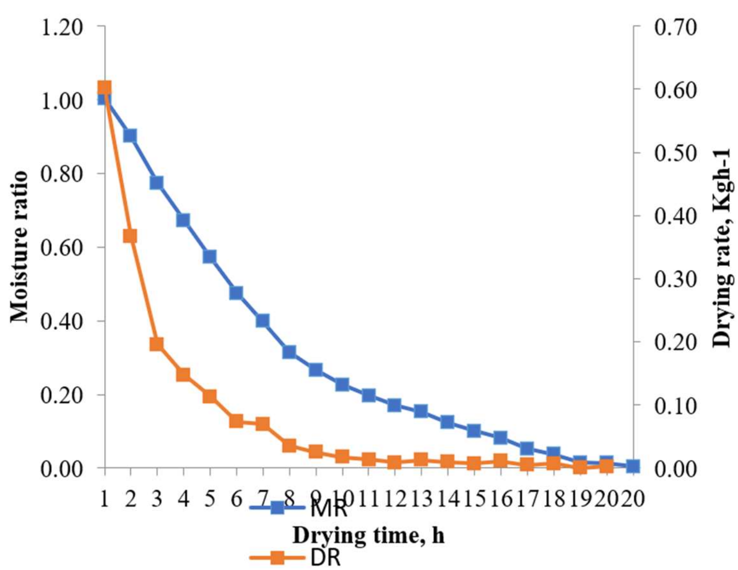

Figure 3: Variation of moisture ratio and drying rate of Shatavari in open sun drying

The drying rate varied from 0.6028 to 0.0023 g/100g bdm/min and 1.0713 to 0.0003 g/100g bdm/min in open sun drying and solar dryer respectively (Figure 3 and 4). The drying rate during initial hours was found to be higher in the solar dryer (1.0713 g/100g bdm/min) following open sun drying (0.6028 g/100g bdm/min). The corresponding average moisture ratio for open sun drying and the solar dryer varied from 1.00 to zero. The drying rate decreased with increase in drying time (Figure 3 and 4). There was rapid moisture removal from Shatavari during initial 3 h of drying in solar dryer and 5 h in open sun drying. This was the first falling rate period during which the free moisture is removed. After 3h of drying in solar dryer, the drying rate further decreases slowly, this was second falling rate period during which bound moisture is removed. The drying results are in confirmation with the research findings recorded regarding drying rate and moisture content vs drying time for drying of onion in packed bed thermal storage natural convection solar crop dryer (Jain 2007).

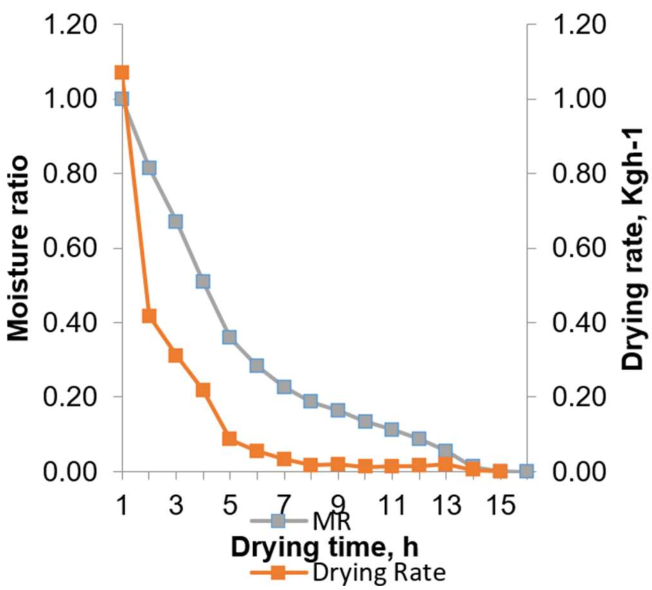

Figure 4: Variation of moisture ratio and drying rate of Shatavari in solar dryer

Mathematical Modelling

The moisture content data were converted to moisture ratio related to the drying period were fitted for the mentioned thin layer drying models. As there was not any appearance of the constant rate period in drying curves, those models that better define the drying in falling rate period were used. The best ranked thin layer drying model with higher coefficient of determination (R2) and lower chi-square █(χ^2@)) and root mean square error (RMSE) value was selected (Togrul & Pehlivan 2002, Demir et al. 2010, Erenturk et al. 2004 and Goyal et al. 2007). The sample of Shatavari dried in open sun and dryer were analyzed to identify the best ranked thin layer model and are summarized in Table 2. All the models gave satisfactory results with high coefficient of determination (R2) was found greater than 0.98 except logarithmic model. Among all models revealed the best fit equation and good correlation between the attributes of moisture ratio and drying time of sample.

Table 2: Thin layer drying models for drying of Shatavari in open sun drying and solar dryer

Sr. No.	Model name	Sun Drying				Solar Cabinet Dryer			
		R^2	x^2	MBE	RMSE	R^2	x^2	MBE	RMSE
1	Lewis model	0.9849	0.0029	-0.0041	0.0520	0.9908	0.00187	-0.0010	0.0419
2	Page model	0.9863	0.0026	-0.0064	0.0495	0.9977	0.00046	-0.0032	0.0208
3	Henderson & Pabis	0.9863	0.0026	-0.0009	0.0494	0.9939	0.00125	0.0053	0.0342
4	Logarithmic	0.5643	0.0652	0.0000	0.2478	0.9976	0.0728	0.0000	0.2613
5	Two term	0.9863	0.0026	-0.0009	0.0494	0.9976	0.00049	0.0020	0.0215
6	Modified Henderson & Pabis	0.9982	0.0022	-0.0041	0.0458	0.5403	0.00049	0.0020	0.0215
7	Wang and Singh	0.9031	0.0008	0.0014	0.0277	0.9393	0.01209	0.0000	0.1065

It was observed that the best ranked thin layer drying model for Shatavari in open sun drying was Modified Henderson & Pabis model. The drying constants for best fit logarithmic equations for Shatavari are a=1.1192, b=0.0036, c=-0.0601, d=9.5850, e=-0.0592 and f=0.9589. The value of R2 obtained for above best fitted model in solar dryer was 0.9982 (Figure 5).

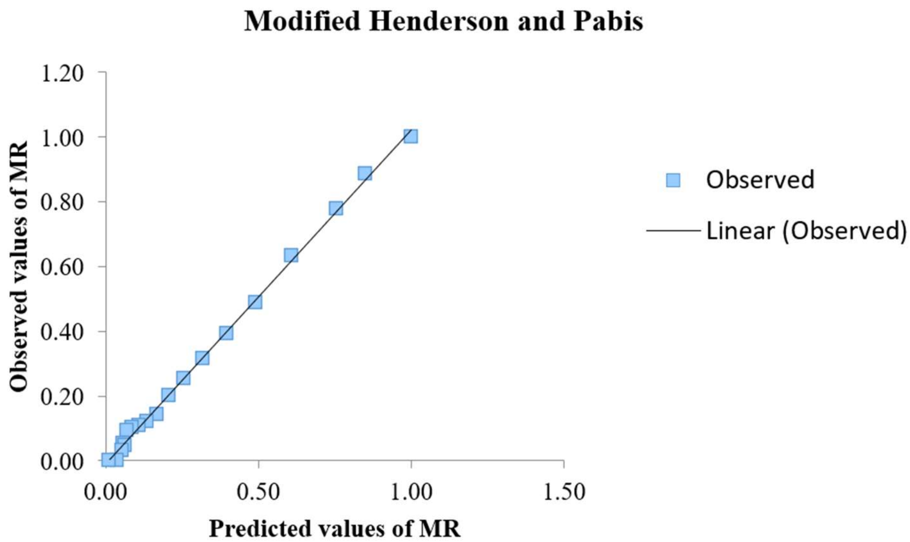

Figure 5: Experimented and predicted values of MR best fitted to Modified Henderson and Pebis model for Shatavari dried in open sun drying

It was observed that, the best ranked thin layer drying model applicable to the variation of moisture ratio with drying time of Shatavari in solar dryer was Page model. The drying constants for Shatavari are a=0.0007, b=1.2514. The value of R2 obtained for above best fitted model in open sun drying was 0.9977 (Figure 6).

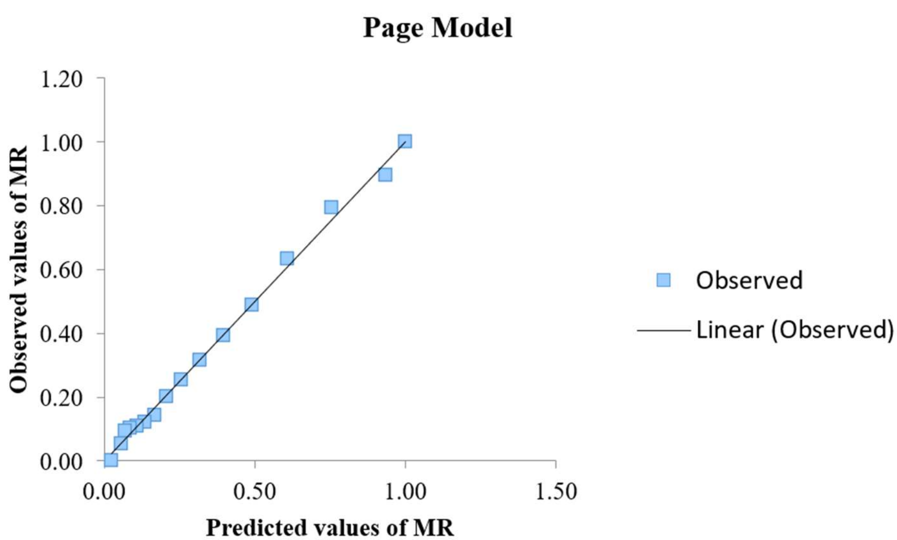

Figure 6: Experimented and predicted values of MR best fitted to Page model for Shatavari dried in solar dryer

CONCLUSIONS

In this present study, the effects of the sun drying and solar cabinet drying for drying of asparagus roots were investigated. The results demonstrated that the drying conditions significantly affected the kinetics and quality of dried Shatavari. The drying of Shatavari roots was done at constant weight loss until the final moisture content reaches to 14.22 per cent (db) in open sun drying in 20 h, whereas 15.81 per cent (db) in 15 h when dried in solar dryer. From the drying data drying characteristics viz, drying time, moisture content, drying rate and moisture ratio were determined. Modified Henderson & Pabis model and Page model had the highest R2 and the lowest χ^2 and RMSE values for sun drying and solar cabinet dryer for Shatavari. The value of R2, χ^2, and RSME was found 0.998, 0.0022 and 0.0458 in Modified Henderson & 0.997, 0.00046 and 0.020 Pabis model in sun drying and in solar cabinet drying respectively.

ABRIVIATION

OSD	:	Open Sun Drying
DR	:	Drying Rate
MR	:	Moisture Ratio
Pre	:	Predicted
Exp	:	Experimentally

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