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Thin layer modeling for drying of black pepper in an agricultural waste fired dryer

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Abstract
Black pepper (*Piper nigrum*) of Sreekara variety was dried in an agricultural waste fired reverse flow dryer and thin layer drying characteristics of blanched and unblanched pepper was studied. Blanching was done by dipping in boiling water for 1 min. The experimental data for moisture loss was converted to moisture ratios and fitted to nine thin layer drying models to describe the drying process mathematically. The results were compared for their goodness of fit in terms of coefficient of determination (R^2), root mean square error (RMSE), mean bias error (MBE) and mean square of deviation (χ^2). Diffusion approximation model was found most suitable to describe the drying process of black pepper. The unblanched pepper took 30 h and blanched pepper took 28 h to dry from moisture content of 178.55% to 9.56% and 9.29% d. b, respectively. The effective moisture diffusivity varied from 4.67 x 10^{-07} to 5.20 x 10^{-07} m^2s^{-1} for unblanched and blanched pepper.

Keywords: Black pepper, agricultural waste operated dryer, reverse air flow drying, thin layer modeling

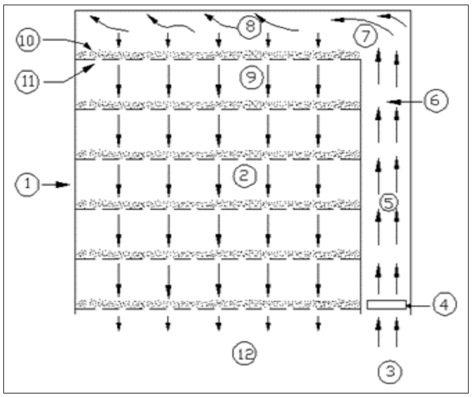
Introduction
Black pepper (*Piper nigrum*), the king of spices is one of the most important and widely used spice in the world. The pungency and flavour of black pepper makes it an important ingredient in many food preparations (Ravindran *et al.,* 2000) [13]. Black pepper is evaluated on the basis of its appearance, pungency level, Aroma and flavour quality. The appearance of the berries is important for export and dark brown to black colour fetches the best prices. Black pepper is a major foreign exchange earner for India and so it is important to maintain all aspects of quality including free of microbial contamination (Pruthi 1992) [14]. During the year 2019-20, India has exported 17,000 tonnes of pepper valued Rs. 57,37,034 lakhs to major buyers of Indian pepper like USA, UK, Italy, Germany and Canada (Spices Board, 2022) [14].
The aroma and flavour imparted by volatile oil is of great significance when black pepper is sold in domestic culinary purposes. Processing plays an important role in determining the quality of black pepper. Among the different existing methods followed, sun drying is widely adopted by native farmers. This process adds extraneous matter and microbes on the berries. The imposition of limits on filth, extraneous matter and microbial load by the importing countries has greatly increased the awareness of farmers to produce clean spices rather than cleaned spices.
Hot air drying using electric power is an alternative for sun drying, but the cost involved for such mechanical drying is very high. But, agricultural waste fired dryer is a viable technology for drying of spices. Blanching is yet another process that ensures black colour and quality to black pepper. The black shining product obtained after blanching is due to the activity of the enzyme phenolase, which catalyses the oxidation of colourless phenolic compounds to black polymeric compounds. Blanching followed by mechanical drying is efficient in reducing the microbial load and improving the quality of the processed black pepper. Hence the present study was conducted with the objective to investigate the effect of blanching on drying kinetics of black pepper in an agricultural waste operated reverse flow dryer and to evaluate the suitability of some thin layer drying models.

Materials and Methods
Black pepper of variety Sreekara was collected from the ICAR-Indian Institute of Spices Research, Experimental farm at Peruvannamuzhi, Kozhikode. Freshly harvested green pepper (1 kg) was blanched in boiling water for 1min and another 1 kg unblanched green pepper was used for the drying experiment. Drying of black pepper was carried out in a in an agricultural waste fired reverse flow dryer RRLT-NC dryer model no. 201 (Thomas and Paulose 2003) [16].

Pepper was spread in thin layers in the drying trays of the dryer and dried.

The dryer (Fig.1.) produces hot air generated by burning of agricultural waste materials like coconut shell, husk etc. The overall dimensions of the dryer chamber are 120 x 60 x 60 cm. Hot air is generated by the burning of agricultural waste materials/ firewood. A specially designed furnace is incorporated for the burning of agricultural waste materials and to produce hot air. The duct for the passage of hot air is placed at the center of the dryer chamber and thereby dividing the dryer chamber into two compartments. Hot air is admitted into the duct rises upwards and enters into the two compartments equally through the opening provided. Suitable supports are placed to keep removable perforated trays in the dryer compartments. Provision was made to keep a total of 14 nos. of trays in the dryer chamber. Temperature of inlet air is controlled by adjusting the rate of burning of the fuel (Thomas and Paulose 2005) [17].

In a reverse air flow dryer, the hot air is made to flow in a downward direction through the material to be dried by an electrically operated fan or blower. The air flow pattern is shown in Fig. 1. Hot air is admitted from bottom through the duct in an upward direction and enters into the drying chamber at the top through the inlet port. The hot air after entering the dryer chamber displaces the air already present in the portion just below the top cover of the dryer chamber by pushing the air in a downward direction. In the dryer chamber except the bottom side all other sides are closed air tight. The wet material to be dried is kept in the dryer chamber. As the hot air comes into contact with the wet material the air temperature drops partially. The partially cooled air has a higher density when compared to the hot air occupying the layer just below the top cover. The denser air has a tendency to flow in a downward direction relative to the less dense air entering the dryer chamber. As the air flows in a downward direction through all the trays the air gets cooler and due to the further increase in air density flows downward. When the hot air reaches the bottom most trays the air is well cooled and humidified. From the bottom most tray, the humid air escapes into the atmosphere. The trays were removed periodically and the weight loss was recorded. The experiment was repeated three times.



1. Dryer outer cover 2. Drying chamber
3. Atmospheric air 4. Heater/hot air admission point
5. Hot air upward flow 6. Duct for hot air passage
7. Entry point to dryer chamber 8. Hotest air layer
9. Downward flow of semi cooled air 10. Wet material
11. Perforated tray 12. Cold air leaving to atmosphere

Fig 1: Schematic diagram for air flow inside a natural convection reverse air flow RRL-NC 201 biomass operated dryer

Mathematical modeling of drying curves

The moisture content data during drying were converted into moisture ratio and expressed by the following equation (Hayaloglu *et al.*, 2007) [10]:

$$\text{MR} = \frac{M - M_e}{M_o - M_e} \quad \ldots (1)$$

For long drying periods, the relative humidity of the drying air fluctuated continuously under agricultural waste fired drying conditions and hence the moisture ratio could be simplified (Diamante and Munro 1991) [5] to:

$$\text{MR} = \frac{M}{M_0} \quad \ldots (2)$$

Where, MR is the moisture ratio, M_0 is the initial moisture content in% d.b., M is the moisture at time t in% d.b., M_e is the equilibrium moisture content in% d.b. The moisture content data were converted into moisture ratio (MR) expression and curve fitting with drying time were carried for 8 drying models (Table 1). The highest value of coefficient of determination (r^2) and the lowest values of root mean square error (RMSE) mean bias error (MBE) and mean square of deviation (χ^2) were used to determine the best fit of the drying models (Togrul and Pehlivan 2002, Ertekin and Yaldiz 2004, Akpinar 2006) [18, 8, 2].

The statistical parameters were calculated as follows

$$\chi^2 = \sum_{i=1}^{N} \frac{\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - n} \quad \ldots (3)$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2\right]^{\frac{1}{2}} \quad \ldots (4)$$

$$\text{MBE} = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right) \quad \ldots (5)$$

where, $MR_{\exp,i}$ is the i^{th} experimentally observed moisture ratio, $MR_{pre,i}$ i^{th} predicted moisture ratio, N is the number of observations and n is the number of constants in the model. The parameters of all the models were estimated by using Sigma Plot 8.0 statistical software.

Determination of effective moisture diffusivity

Transport of water in food material is an important physical process. Water is transported with in the food materials by a combination of several mechanisms depending on the physical structure of the product and external drying conditions. The prevalent mechanisms are molecular diffusion and capillary flow. Molecular diffusion is used widely for estimation of effective moisture diffusivity of foods although water may be transported by mechanisms other than diffusion. It is assumed that the driving force for all water transport is the moisture gradient. Fick's second law was used to describe the moisture diffusion during drying of spherical objects as follows (Crank 1975) [4]:

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{M}{M_o} = \frac{6}{\pi^2}\left[\sum_{n=1}^{n=\infty}\frac{1}{n^2}\exp\left(\frac{-n^2\pi^2}{6}\frac{D_{eff}t}{R^2}\right)\right] \quad \ldots (6)$$

Where MR is the moisture ratio, M_0 is initial moisture content in% d.b, M is moisture content at time t in% d.b, M_e is equilibrium moisture content in% d.b, D_{eff} is effective moisture diffusivity in m^2h^{-1}, t is the drying time in h and R is the thickness of spherical pepper to be dried from top and bottom parallel surfaces in m.

For long drying periods, Eq. (6) can be simplified to the following form by taking n=0 (Geankoplis, 2003) [9].

$$MR = \frac{M}{M_o} = \frac{6}{\pi^2}\exp\left(\frac{-\pi^2}{6}\frac{D_{eff}t}{R^2}\right) \quad \ldots (7)$$

The above equation is in the form of

$$MR = \frac{M}{M_o} = Ae^{-kt} \quad \ldots (8)$$

where, the constant $A = \frac{6}{\pi^2}$; and $k = \frac{\pi^2 D_{eff}}{6R^2}$. By linearizing the Eq. (8)

$$\ln(MR) = \ln\left(\frac{M}{M_o}\right) = \ln A - kt \quad \ldots (9)$$

The effective moisture diffusivity of black pepper can be calculated using the method of slopes. A plot of ln (M/ M_0) versus drying time gives a straight line with a slope. Assuming that drying occurs from top and bottom parallel faces, thickness of the sphere to be dried from one face is assumed to be half the total thickness, where R = R/2 in m. Hence the slope is taken as:

$$\text{Slope} = k = \frac{2\pi^2 D_{eff}}{3R^2} \quad \ldots (10)$$

From Eq. (10) the effective moisture diffusivity D_{eff} can be calculated.

Results and Discussion

Drying kinetics

Drying characteristic curves of blanched and unblanched Sreekara variety black pepper are presented in Fig. 2. It is apparent that moisture content decreases continuously with drying time. The time required to dry unblanched pepper from an initial moisture content of around 178.55% d.b. to the final moisture content of around 9.56% d.b. was 30 h. In case of blanching the time required to dry from an initial moisture content of around 178.55% d.b. to the final moisture content of around 9.29% d.b. was 28 h. Curves of moisture ratio versus drying time for drying black pepper showed that moisture ratio of black pepper reduced exponentially as the drying time increased. Umamaheswari *et al.*, (2002) [19] have studied a firewood operated dryer for curing of cardamom and reported that curing time was 26 h when firewood was used as fuel and when LPG was used as fuel the time extended to 45 h.

As indicated in the curves of drying rate verses time, there was no constant rate period in drying of black pepper. All the drying process occurred in the falling rate period. In the falling rate period, the material surface was no longer saturated with water and drying rate was controlled by diffusion of moisture from the interior of solid to the surface. Thomas and Paulose (2001) [15] have studied the use of RRL-201 dryer for drying of *Garcinia combogia* and reported that the time required for drying varied from 36 h for thinner varieties to 48 h for thicker varieties and the dried product did not have any smoke smell and taste.

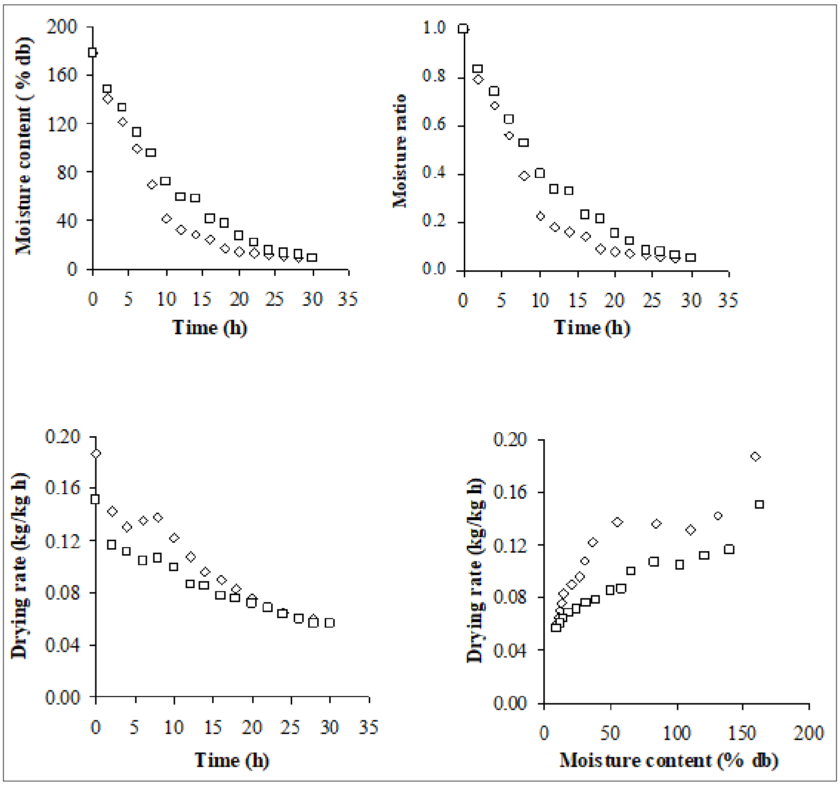
In the graph of moisture content verses drying rate, at the beginning of drying process, when moisture content was high, drying rate was also very high and as moisture content approached to equilibrium moisture content, drying rate was very low. Balakrishnan *et al.*, (1998) [3] reported that conventional kiln dryer took about 20 h to dry cardamom from 80% to 10% moisture content (w.b) at the air temperature of 40-45 ^oC.

Modeling of drying curves

Moisture ratio data of black pepper dried in agricultural waste fired dryer were fitted to 9 thin layer models and the values of r^2, RMSE, MBE and χ^2 are summarized in Table 2. In all the cases, the values of r^2 were greater than 0.90 indicating a good fit (Erenturk *et al*., 2004) [7], but diffusion approximation model gave comparatively higher r^2 values in all the drying treatments (0.990 and 0.995) and also the RMSE (0.030 and 0.020), MBE (0.004 and -0.006) and χ^2 (0.001 and 0.0005) values were lower for blanched and unblanched Sreekara pepper respectively. Hence, diffusion approximation model may be assumed to represent the thin layer drying behaviour of black pepper in agricultural waste fired furnace. The predicted moisture ratios are in good agreement with the observed values and therefore it can be concluded that Diffusion approximation is relatively better than other 8 models (Fig. 3). Akpinar *et al.*, (2003) [1] compared eleven thin layer drying models to study drying characteristics of red pepper and found that the drying process was best described by diffusion approximation model.

Effective moisture diffusivity

Effective moisture diffusivity was calculated using slopes derived from ln MR versus time (Fig. 4). The effective moisture diffusivity for drying black pepper was 5.20 x 10^{-07} m^2s^{-1} for blanched and 4.67 x 10^{-07} m^2s^{-1} for unblanched Sreekara pepper. The estimated moisture diffusivity is comparable with the reported values of 1.5 x 10^{-9} m^2/s for raisin (Lomauro *et al.*, 1985) [10], 2.64 x 10^{-9} to 5.71 x 10^{-9} m^2/s for green beans (Doymaz 2005) [6].



--◊-- blanched --□-- unblanched

Fig 2: Drying characteristics blanched and unblanched black pepper

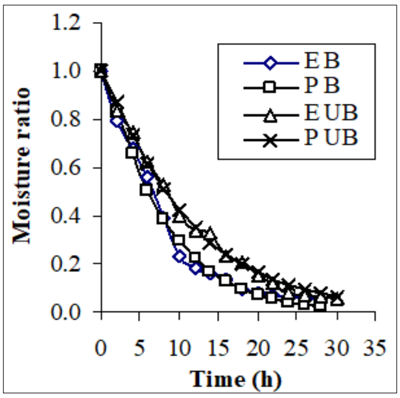


Fig 3: Predicted and observed moisture ratio for drying of black pepper (EB: Expected blanched; PB: Predicted blanched; E UB: Expected unblanched; PUB: Predicted unblanched)

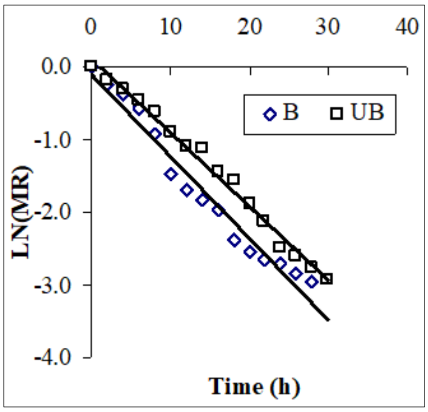


Fig 4: Effective moisture diffusivity for drying of black (B: blanched; UB: unblanched)

Table 1: Thin layer drying models

Model name	Model	Reference
Newton	MR = exp(-kt)	Ayensu (1997)
Henderson and Pabis	MR = a exp(-kt)	Henderson and Pabis (1961)
Page	MR = exp $(-kt^n)$	Lopez *et al* (2000)
Modified Page	MR = exp$[-(kt^n)]$	Babalis *et al* (2006)
Overhults	MR = exp$[-(kt)^n]$	Overhults *et al* (1973)
Logarithmic	MR = a exp(-kt) + c	Doymaz (2004a)
Diffusion approximation	MR = a exp(−kt) + (1 − a)exp(−kbt)	Togrul & Pehlivan (2003)
Wang and Singh	MR = 1 + at + bt^2	Ertekin & Yaldiz (2004)
Two term Exponenetial	MR = a exp(−kt) + (1 − a)exp(−kat)	Ertekin & Yaldiz (2004)

Table 2: Values of model constants and statistical parameters

Model	Treatment	K	n	a	b	c	r^2	RMSE	MBE	χ^2
Newton	B	0.121	-	-	-	-	0.985	0.036	0.002	0.001
	UB	0.088	-	-	-		0.993	0.025	-0.002	0.001
Henderson and Pabis	B	0.125	-	1.030	-	-	0.987	0.035	-0.001	0.001

	UB	0.090	-	1.023	-	-	0.994	0.023	-0.004	0.001
Page	B	0.090	1.132	-	-	-	0.989	0.031	0.005	0.001
	UB	0.066	1.115	-	-		0.996	0.017	-0.002	0.001
Modified Page	B	0.779	0.156	-	-	-	0.985	0.036	0.002	0.002
	UB	0.664	0.133	-	-	-	0.993	0.025	-0.002	0.001
Overhults	B	0.119	1.133	-	-	-	0.989	0.031	0.005	0.001
	UB	0.087	1.115		-	-	0.996	0.017	-0.002	0.002
Logarithmic	B	0.124	-	1.031	-	-0.002	0.987	0.035	-0.000	0.002
	UB	0.076	-	1.076	-	-0.072	0.997	0.017	-0.000	0.001
Diffusion approximation	B	0.439	-	-0.232	0.326	-	0.990	0.030	0.004	0.001
	UB	0.559	-	-0.086	0.169	-	0.995	0.020	-0.006	0.001
Wang and Singh	B	-	-	-0.089	0.002	-	0.984	0.038	-0.004	0.002
	UB	-	-	-0.068	0.001	-	0.995	0.022	-0.004	0.001
Two term Exponenetial	B	41.152	-	0.003	-	-	0.985	0.036	0.002	0.002
	UB	30.554	-	0.003	-	-	0.993	0.025	-0.003	0.001

(B: blanched; UB: unblanched)

Conclusion

Black pepper was dried in agricultural waste fired flue gas, a reverse air flow, natural convection mechanical dryer. Two treatments for freshly harvested pepper– blanching (by dipping in boiling water for 1 min) and unblanched (fresh pepper) was used for the drying experiment. The experimental data for moisture loss was converted to moisture ratios and fitted to nine thin layer drying models to describe the drying process mathematically. Diffusion approximation model was found most suitable to describe the drying process of black pepper. The unblanched pepper took 30 h while blanched pepper took 28 h to dry from moisture content of 178.55% to 9.56% and 9.29% (d.b), respectively. The effective moisture diffusivity varied from 4.67×10^{-07} to 5.20×10^{-07} m^2s^{-1} for unblanched and blanched pepper, respectively.

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