Modeling for thin layer drying of black pepper (Piper nigrum) in a reverse air flow dryer

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Abstract and figures

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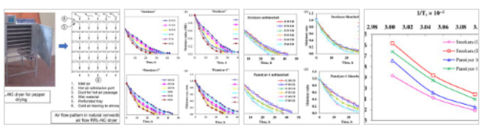

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ORIGINAL ARTICLE

Modeling for thin layer drying of black pepper (*Piper nigrum*) in a reverse air flow dryer

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Abstract

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Practical applications

Drying of harvested pepper is one of the most important unit operations during processing of green pepper. Sun drying is the conventional method followed for drying. The despiked pepper berries are dried under sun for 4–5 days to bring the moisture content below 11%. The process of blanching green pepper in boiling water for 1 min followed by mechanical drying could produce better quality dried product. A simple reverse air flow, natural convection mechanical dryer suitable for drying various agricultural produce at farm level was used for drying green pepper. The results of the study could be applied for gathering information related to the drying process in a mechanical dryer like the drying kinetics, effective moisture diffusivity and activation energy as well as the effect of blanching on these parameters.

KEYWORDS
black pepper, *Piper nigrum*, reverse flow drying, thin layer modeling

1 | INTRODUCTION

Black pepper is the whole dried fruit of the vine *Piper nigrum*. Black pepper is valued for its pungency and flavor, which is attributed by

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the presence of alkaloid piperine and the volatile oil (Ravindran et al., 2000). Two primary products of *P. nigrum* that are internationally traded are black pepper and white pepper. Black pepper is used directly as spice or it serves as raw material for the preparation of its derivatives namely essential oil, oleoresin, curry powder, etc.

Freshly harvested green pepper has moisture content of about 70% which should be brought to safer levels of <11% by adequate drying. The green color of matured pepper is due to the presence of chlorophyll pigment. During drying, enzymatic browning sets in and the phenolic compounds are oxidized by atmospheric oxygen under the catalytic influence of the enzyme phenolase and eventually turn black (Mathew, 1994). Blanching is known to augment the poly phenolase enzyme activity and thereby give a shining black color. It also reduces drying time (Bandyopadhyay et al., 1990). Black pepper is evaluated on the basis of its appearance, pungency level, aroma and flavor quality. The appearance of the berries is important for export and dark black color berries fetch the best price. Black pepper is a major foreign exchange earner for India and so it is important to maintain all aspects of quality including microbial load (Pruthi, 1992).

Processing plays an important role in determining the quality of black pepper (Joy et al., 2002). Among the different existing methods, the traditional method of sun drying is widely followed by native farmers. The quality of the black pepper can also be improved by a simple treatment of blanching. Bimi et al. (2004) reported that blanching by dipping the mature berries in boiling water for 1 min accelerated drying process. Blanching at 100°C for 5 min on Kamchay black pepper was reported by Mey et al. (2017) while blanching at 100°C for 10 min helped in better color development (Gu et al., 2013). Central Food Technological Research Institute in Mysore stated that blanching in boiling water for 1 min improved both color and quality (Thangaselvabal et al., 2008). This process of blanching followed by mechanical drying reduces the microbial load and produces uniform colored black pepper (Mey et al., 2017). Thomas and Paulose (2005) reported that natural convection reverse air flow mechanical driers are used by the farmers and cottage scale industrial units for heat sensitive products like spices during rainy season. These dryers are widely used for drying of coconut, *Garcinia cambogia*, nutmeg, mace, ayurvedic products, etc. The use of these dryers for black pepper is not studied. Hence, it was necessary to standardize the drying time of any particular product in this dryer based on the desired quality of the dried produce. The present study was conducted with the objective to investigate the effect of air temperature and blanching on drying kinetics of black pepper in a reverse flow drier and to evaluate the suitability of some thin layer drying models to explain the drying process in a reverse air flow mechanical dryer.

2 | MATERIALS AND METHODS

2.1 | Sample preparation

spikes were harvested during the month of January when one or two berries in the spike changes its color from green to orange red. The harvested spikes were threshed in a mechanical thresher (Wayanad model thresher, capacity 500 kg/h) and the separated berries we used for the experiment. The moisture content of the fresh pepper was determined by toluene distillation method (ASTA, 1968).

2.2 | Blanching as pretreatment

Blanching of pepper was done by taking 1 kg of pepper berries in a muslin cloth and immersing it in a stainless vessel containing boiling water for 1 min. The two varieties were blanched separately. Both blanched and unblanched pepper berries of the two varieties were used for the drying experiments.

2.3 | The equipment used

2.3.1 | Reverse air flow dryer

Drying of black pepper was carried out in a reverse air flow drier (Model: RRLT-NC Drier Model 101, Anna Industries). This model was designed for the mechanical drying of small quantities of material at farm level (Thomas & Paulose, 2003). The overall dimensions of the dryer were 60 cm × 60 cm × 60 cm. The duct for the passage of hot air was placed on one side of the drier chamber. Seven numbers of removable perforated trays were provided. An electrical heater of 500 W was placed in the duct itself for the generation of hot air and a thermostat was provided to regulate the air temperature. Graphical abstract of drying fresh pepper in RRL-NC dryer is shown in Figure 1.

2.3.2 | Principle of a reverse air flow dryer

In a reverse air flow dryer the hot air is made to flow in a downward direction through the material to be dried unaided by any fan or blower. 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 drier chamber displaces the air already present in the portion just below the top cover of the drier chamber by pushing the air in a downward direction. In the drier chamber except the bottom side all other sides are closed air tight. The wet material to be dried is kept in the drier 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 the downward direction

Two varieties of freshly harvested black pepper viz. Sreekara and Panniyur-1 obtained from ICAR-Indian Institute of Spices Research, Experimental Farm, Kozhikode, Kerala were used for the study. The through the trays, the air gets cooler with the absorption of moisture and there is an increase in air density. Thus when the hot air reaches the bottom most tray, the air is well cooled and humidified. From the bottom most tray the humid air escapes into the atmosphere.

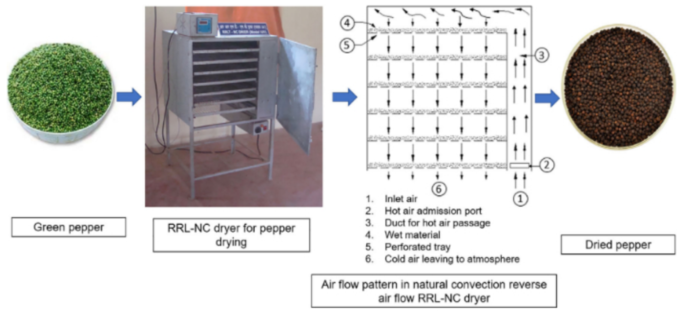

FIGURE 1 Graphical abstract of fresh pepper drying in RRL-NC dryer

2.4 | Experimental procedure

One kilogram of each variety, i.e., Sreekara and Panniyur-1 was blanched in boiling water for 1 min and another 1 kg each of unblanched green pepper was used for the experimental studies on drying of black pepper. The blanched and the unblanched pepper of both the varieties were spread separately in thin layer on the drying trays of the dryer and the experiments were done at three varying temperatures of 50°C, 55°C, and 60°C. The trays were removed periodically and the weight loss was recorded. The experiment was replicated three times.

2.5 | Fitting drying characteristic curves

The moisture content data at different experimental mode during drying were converted into moisture ratio (MR) and expressed by the following equation (Hayaloglu et al., 2007):

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

For long drying periods the moisture ratio can be simplified according to Doymaz (2004a), to:

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

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.

2.6 | Mathematical modeling

The moisture content data were converted into moisture ratio expression and curve fitting with drying time were carried for five drying models (Table 1). Nonlinear regression procedure was performed on all drying runs to estimate the parameters associated with the five selected models using the software Sigma Plot (ver. 6.0). The coefficient of determination R^2 was the primary criterion for selecting the best equation to describe the drying curve. In addition, the reduced Chi-square (χ^2), Root Mean Square Error analysis (RMSE) and Mean Bias Error (MBE) were calculated to evaluate the efficiency of fitting a model to the experimental data. The highest value of R^2 and the lowest values of χ^2, RMSE and MBE were used to determine the best fit (Akpinar, 2006; Ertekin & Yaldiz, 2004; Togrul & Pehlivan, 2003).

TABLE 1 Thin layer drying models

Model name	Model	Reference
Page	$MR = \exp(-kt^n)$	Lopez et al. (2000)
Overhults	$MR = \exp[-(kt)^n]$	Overhults et al. (1973)
Diffusion approximation	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Togrul and Pehlivan (2003)
Logarithmic	$MR = a\exp(-kt) + c$	Doymaz (2004a)
Newton	$MR = \exp(-kt)$	Ayensu (1997)

The statistical parameters were calculated as follows:

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

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

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

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 (ver 6.0) statistical software.

2.7 | Determining the diffusion coefficient of the effective moisture

Fick's second law was used to describe the moisture diffusion during drying of spherical objects as follows (Crank, 1975):

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

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., D_{eff} is the effective moisture diffusivity in m^2/s, t is the drying time in s, and R is the thickness of spherical pepper to be dried from top and bottom parallel surfaces in m. For long drying periods, Equation (6) can be simplified to the following form by taking $n = 0$ (Geankoplis, 2003).

equation (Okos et al., 1992). The activation energy for diffusion was estimated by using the equation:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT}\right) \quad (11)$$

where D_{eff} is the effective moisture diffusivity in m^2/s; D_0 is the constant in Arrhenius equation in m^2/s; E_a is the activation energy in kJ/mol; R is the universal gas constant (8.31×10^{-3}) in kJ/mol K; T is the drying temperature in K. The activation energy can be determined by plotting ln D_{eff} versus $1/T$. The slope of the line is $-E_a/R$ and the intercept equals to D_0, from which the activation energy E_a can be calculated.

3 | RESULTS AND DISCUSSION

3.1 | Effect of drying air temperature

The time required to dry unblanched pepper, variety Sreekara from an initial moisture content of around 180.89% d.b. to the final moisture content of around 9.4% d.b. was 42, 34, 26 h at 50°C, 55°C, and 60°C

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

The above equation is in the form of

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

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

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

The effective moisture diffusivity of 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 R, where $R = R/2$ in m. Hence the slope is taken as

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

From which the effective moisture diffusivity D_{eff} can be calculated for a particular concentration conditions.

2.8 | Activation energy

In natural conventional heating the effective diffusivity coefficient is dependent on temperature and can be described by Arrhenius of drying air temperature, respectively. In case of blanching, the time required for drying was 36, 30, and 24 h at drying air temperatures of 50°C, 55°C, and 60°C, respectively (Figure 2a). In case of drying variety Panniyur-1 time required to dry unblanched pepper from an initial moisture content of around 197.62% d.b. to the final moisture content of around 9.35% d.b. was 44, 36, 28 h at 50°C, 55°C, and 60°C of drying air temperatures, respectively. Whereas, for blanched pepper, the time required was 37, 32, and 26 h for the same of drying air temperatures, respectively (Figure 2c). Thus, blanching reduced the drying time and the rate of moisture removal was higher during drying in blanched pepper. Shreelavaniya et al. (2017) reported that drying of black pepper in was much faster Solar-Biomass Hybrid Dryer (S-BHD) and took only 12 h to dry from initial moisture content of 434.8% (d.b) to final moisture content of 9.4% (d.b) whereas in case open sun drying (OSD), it took 84 h to obtain the final moisture content of 12.10% (d.b). Zhang et al. (2016) studied the effect of drying temperature and reported that the drying time required to reduce the moisture content of debittered apricot kernels from the initial moisture content of 44.6% ± .5% (d.b) to the final moisture content of 2.3% ± .7% (d.b) was 220, 200, 150, and 110 min at drying temperatures of 60°C, 80°C, 100°C, and 120°C, respectively. The results clearly indicated a pronounced effect of drying temperature on the drying time of the product.

Thamkaew et al. (2020) reported a decrease in the drying time for all drying methods after the blanching process. Suchana et al. (2021) studied the effect of blanching pepper berries in boiling water for 1–5 min and indicated that the drying time was negatively correlated to blanching time for both sun and mechanical drying methods. Furthermore, blanching reduced the final moisture content of the dried product to 12.30% (1 min blanched and sun dried) to 5.33% (for 1 min blanched and mechanically dried at 60°C) while for unblanched pepper the corresponding values were 13.79% and 7.31%. Thus, blanching reduced the final moisture content of the dried product and this

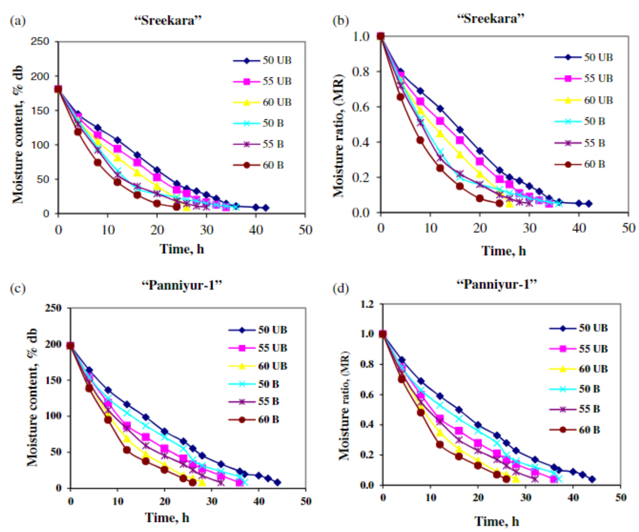

FIGURE 2 Drying characteristics of black pepper varieties (Sreekara and Panniyur-1) at different temperatures. (a) Moisture content vs drying time. (b) Moisture ratio vs drying time. (c) Moisture content vs drying time. (d) Moisture ratio versus drying time

could be due to the partial breakage of cell wall of the pepper which increased the drying rate and decreased the final moisture content (Weil et al., 2017). The result was in line with the studies conducted by Rocha et al. (1993) for basil and Sledz et al. (2016) for parsley, where higher drying rate for steam blanched product was reported than the unbleached product.

Curves of moisture ratio versus drying time for different drying air temperatures showed a reduction in moisture ratio as the drying time increased (Figure 2b,d). In these curves, an increase of drying rate, given by the curve slope, with increase in temperature was observed. Shreelavaniya et al. (2017) reported a strong liner relationship between moisture ratio and drying time for black pepper drying in Solar Biomass Hybrid Dyer ($R^2 = .982$) and open sun drying process ($R^2 = .978$). The results are in agreement with the reports quoted for green peas Thakur (2008), garlic (Madamba et al., 1996) and cauliflower leaves (Lopez et al., 2000).

3.2 | Modeling of drying curves

Moisture ratio data of blanched and unblanched black pepper dried at different temperatures were fitted to 5 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 >.90 indicating a good fit (Erenturk et al., 2004), but Logarithmic model gave comparatively higher R^2 values in all the drying treatments (.9948–.9995) and also the RMSE (.0041–.0211), MBE (.011–.020 × 10^{-3}) and χ^2 (.0001–.0006) values were lower. The predicted moisture ratios were in good agreement with the observed values for both the varieties of black pepper under blanched and unblanched conditions. Thus, Logarithmic model was capable of representing the thin layer drying behavior of black pepper in a reverse flow drier in the temperature range 50–60°C and was relatively better than other five models. The performance of this model at different drying temperatures for blanched and unblanched black pepper for varieties Sreekara and Panniyur-1 is shown in Figure 3. In the study conducted by Shreelavaniya et al. (2017) on modeling the drying characteristics of black pepper, the logarithmic model recorded the highest value for R^2 (.9996) and lowest RMSE (.0072) and χ^2 (.0000519) in open sun drying process. Similar observations for the use of Logarithmic model have been reported for drying of whole figs (Xanthopoulos et al., 2007); peach slice (Kingsly et al., 2006); white mulberry (Doymaz, 2004a); shelled and unshelled pistachio (Midilli & Kucuk, 2003) and single apricot (Togrul & Pehlivan, 2003).

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TABLE 2 Values of model constants and statistical parameters

Model	Treatment	Temp. °C	*k*	*n*	*a*	*b*	*c*	r^2	RMSE $\times 10^{-2}$	MBE $\times 10^{-3}$	$\chi^2 \times 10^{-3}$
Page	Sreekara UB	50	.022	1.307	–	–	–	.992	2.7	−6.2	.8
		55	.033	1.239	–	–	–	.990	3.0	−6.5	1.1
		60	.043	1.209	–	–	–	.985	3.8	−6.2	1.9
	Sreekara B	50	.070	1.082	–	–	–	.996	1.9	2.5	.4
		55	.069	1.114	–	–	–	.998	1.4	−.6	.2
		60	.086	1.127	–	–	–	.999	1.1	−2.2	.2
	Panniyur-1 UB	50	.026	1.218	–	–	–	.993	2.4	−5.3	.7
		55	.054	1.077	–	–	–	.997	1.7	−2.1	.3
		60	.059	1.161	–	–	–	.999	.9	−1.5	.1
	Panniyur-1 B	50	.040	1.124	–	–	–	.987	3.3	−5.7	1.3
		55	.065	1.060	–	–	–	.997	1.7	−2.5	.4
		60	.073	1.135	–	–	–	.998	1.3	−.2	.2
Overhults	Sreekara UB	50	.055	1.307	–	–	–	.992	2.7	−6.2	.8
		55	.063	1.239	–	–	–	.990	3.0	−6.5	1.1
		60	.074	1.209	–	–	–	.985	3.8	−6.2	1.9
	Sreekara B	50	.085	1.082	–	–	–	.996	1.9	−1.1	.4
		55	.091	1.114	–	–	–	.998	1.4	−.6	.2
		60	.113	1.127	–	–	–	.999	1.1	−2.2	.2
	Panniyur-1 UB	50	.049	1.218	–	–	–	.993	2.4	−5.3	.7
		55	.066	1.077	–	–	–	.997	1.7	−2.1	.3
		60	.087	1.161	–	–	–	.999	.9	−1.5	.1
	Panniyur-1 B	50	.057	1.124	–	–	–	.987	3.3	−5.7	1.3
		55	.076	1.060	–	–	–	.997	1.7	−2.5	.4
		60	.099	1.135	–	–	–	.998	1.3	−.2	.2
Diffusion approximation	Sreekara UB	50	.109	–	−5.203	.881	–	.999	2.7	−5.6	.9
		55	.122	–	−3.041	.835	–	.999	3.0	−5.1	1.2
		60	.141	–	−2.505	.819	–	.986	3.7	−4.5	2.2
	Sreekara B	50	.693	–	−.101	.137	–	.996	1.7	1.8	.4
		55	.249	–	−.276	.437	–	.998	1.4	−1.4	.3
		60	.188	–	−3.011	.873	–	.999	1.0	−2.1	.2
	Panniyur-1 UB	50	.091	–	−4.164	.875	–	.994	2.3	−5.0	.7
		55	.593	–	−.049	.118	–	.996	1.8	−2.5	.5
		60	.155	–	−2.877	.850	–	.999	.8	−1.0	.1
	Panniyur-1 B	50	.097	–	−2.582	.854	–	.988	3.2	−5.4	1.3
		55	.627	–	−.034	.126	–	.996	1.8	−2.8	.5
		60	.251	–	−.406	.497	–	.998	1.3	−.3	.3
Logarithmic	Sreekara UB	50	.036	–	1.279	–	−.279	.995	2.0	.013	.5
		55	.037	–	1.332	–	−.348	.998	1.3	.020	.2
		60	.038	–	1.470	–	−.489	.996	2.0	.013	.6
	Sreekara B	50	.086	–	1.028	–	−.009	.995	2.1	.011	.6
		55	.083	–	1.059	–	−.052	.998	1.4	.013	.3
		60	.098	–	1.079	–	−.078	1.000	.4	.011	.0
	Panniyur-1 UB	50	.032	–	1.258	–	−.266	.999	1.3	.015	.2
		55	.056	–	1.085	–	−.090	.998	1.0	.016	.2
		60	.073	–	1.107	–	−.100	1.000	.7	.012	.1
	Panniyur-1 B	50	.037	–	1.233	–	−.259	.995	2.1	.011	.6

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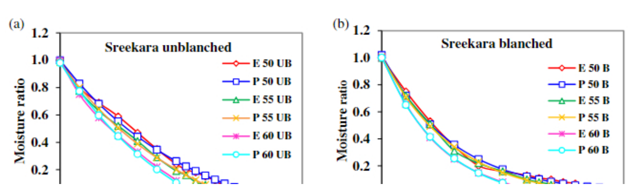
TABLE 2 (Continued)

Model	Treatment	Temp. °C	*k*	*n*	*a*	*b*	*c*	r^2	RMSE $\times 10^{-2}$	MBE $\times 10^{-3}$	$\chi^2 \times 10^{-3}$
		55	.064	–	1.071	–	−.080	.999	1.1	.0	.2
		60	.090	–	1.068	–	−.060	.997	1.6	.0	.4
Newton	Sreekara UB	50	.058	–	–	–	–	.973	4.8	−4.8	2.5
		55	.066	–	–	–	–	.978	4.5	−4.8	2.2
		60	.076	–	–	–	–	.976	4.8	−3.4	2.6
	Sreekara B	50	.087	–	–	–	–	.994	2.3	.4	.6
		55	.093	–	–	–	–	.995	2.1	−2.4	.5
		60	.116	–	–	–	–	.996	2.1	−3.6	.5
	Panniyur-1 UB	50	.051	–	–	–	–	.982	3.9	−3.5	1.6
		55	.067	–	–	–	–	.995	2.0	−1.9	.5
		60	.089	–	–	–	–	.994	2.5	−2.6	.7
	Panniyur-1 B	50	.058	–	–	–	–	.983	3.8	−3.5	1.5
		55	.076	–	–	–	–	.996	1.9	−2.5	.4
		60	.101	–	–	–	–	.995	2.4	−1.8	.6



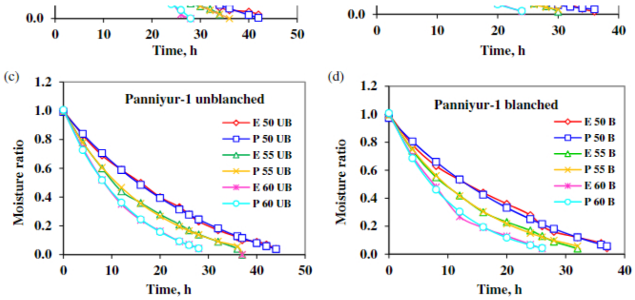


FIGURE 3 Comparisons of experimental and predicted dimensionless moisture ratio for the best model (logarithmic) at the three working temperatures for two varieties of black pepper. (a) MR versus time for Sreekara(unblanched). (b) MR versus time for Sreekara(blanched). (c) MR versus time for Panniyur-1(unblanched). (d) MR versus time for Panniyur-1(blanched). B, blanched; E, estimated; MR, moisture ratio; P, predicted; UB, unblanched

3.3 | Effective moisture diffusivity

The effective moisture diffusivity for different drying treatment is given in Table 3. Drying at higher temperatures gave the highest D_{eff} values. The values ranged from 3.28×10^{-7} to 6.44×10^{-7} m²/s. The results show that pretreatment has affected the moisture diffusivity. It is also found that blanching pre-treatment has increased the moisture diffusivity for all the temperature treatments. Similar results

of influence of pretreatment on moisture diffusivity during air drying has been found in blanched mango slices (Goyal et al., 2006) and apricots (Doymaz, 2004b).

3.4 | Activation energy

The plot depicting the relationship between ln (D_{eff}) and 1/T was found to be a straight line in the range of temperatures investigated, indicating Arrhenius dependence (Figure 4). From the plot, diffusivity constant (D_0) and activation energy (E_a) were calculated Table 4. The activation energy was found to vary from 39.45 to 44.05 kJ/mol and was higher for unblanched than for blanched black pepper. The E_a value has been studied for other products and is found to be 35.43 kJ/mol for green beans (Doymaz, 2005) and 37.76 kJ/mol for chilies (Kaleemullah & Kailappan, 2006).

TABLE 3 Effective moisture diffusivity for drying of black pepper

Variety	Treatment	Temp, °C	Diffusivity, D_{eff}, m²/s
Sreekara	Unblanched	50	3.73×10^{7}
		55	4.20×10^{7}
		60	5.15×10^{7}
	Blanched	50	4.34×10^{7}
		55	5.18×10^{7}
		60	6.97×10^{7}
Panniyur-1	Unblanched	50	3.70×10^{7}
		55	4.40×10^{7}
		60	5.93×10^{7}
	Blanched	50	4.14×10^{7}
		55	4.94×10^{7}
		60	6.44×10^{7}

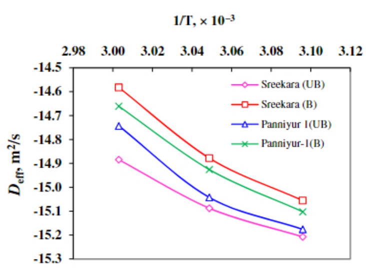


FIGURE 4 Arrhenius type relationship between effective moisture diffusivity and reciprocal of absolute temperature. B, blanched; UB, unblanched

4 | CONCLUSION

The study on drying of two black pepper varieties Sreekara and Panniyur-1 was carried in a reverse air flow natural convection drier at varying temperatures of 50°C, 55°C, and 60°C. Blanching of fresh pepper in boiling water for 1 min was followed as pretreatment. The drying time required to reduce the moisture content from 180.89 to 9.4% (d.b) at drying air temperatures of 50°C, 55°C, and 60°C for variety Sreekara (unblanched) was 42, 34, and 26 h while Sreekara (blanched) took 36, 30, and 24 h, respectively. In case of Panniyur-1, the unblanched pepper took 44, 36, and 28 h and the blanched pepper took 37, 32, and 26 h to dry from moisture content of 197.62 to 9.2% (d.b.) for the same temperatures. Logarithmic drying model was found most suitable for describing the drying process of black pepper mathematically in a reverse flow dryer. The effective moisture diffusivity varied from 3.28×10^{-7} to 6.44×10^{-7} m²/s. The activation energy was higher for unblanched than for blanched black pepper and varied between 39.45 and 44.05 kJ/mol. The study could give information related the drying kinetics, effective moisture diffusivity and activation energy as well as the effect of blanching on these parameters.

NOMENCLATURE

A	constant
D_0	constant in Arrhenius eqution (m²/s)
D_{eff}	effective moisture diffusivity (m²/s)
E_a	activation energy (kJ/mol)
k	constant
M	moisture at time t (% d.b.)
M_0	moisture content (% dry basis [d.b.])
M_e	equilibrium moisture content (% d.b.)
MR	moisture ratio (dimensionless)
$MR_{exp,i}$	ith experimentally observed moisture ratio (dimensionless)
$MR_{pre,i}$	ith predicted moisture ratio (dimensionless)
n	number of constants in the model
N	number of observations

TABLE 4 Diffusivity constant and activation energy for various treatments

Variety	Treatment	Diffusivity constant, m²/s	Activation energy, kJ/mol
Sreekara	Unblanched	−4.4762	44.05
	Blanched	.668	40.12
Panniyur1	Unblanched	−.8219	42.20
	Blanched	−.4215	39.45

R	thickness of spherical pepper (m)	
R	universal gas constant (8.31×10^{-3}) in kJ/mol K	
t	drying time (h)	
T	absolute temperature (K)	

AUTHOR CONTRIBUTIONS

Ettannil Jayashree developed the original idea and the protocol, abstracted and analyzed data, wrote the manuscript and is the guarantor. Thondiath John Zachariah contributed to the development of the protocol and contributed towards writing the manuscript.

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CONFLICTS OF INTEREST

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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