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Thin layer modeling for drying of nutmeg mace (*Myristica fragrans)* in reverse air flow dryer

E Jayashree

Abstract

Nutmeg and mace are the two important spices derived from the same fruit of nutmeg (*Myristica fragrans).* Nut is the seed of the fruit and mace is the outer aril surrounding the nut. The mace from the freshly harvested fruit is removed from the nut and processed separately. Drying of two treatments of nutmeg mace *ie.* blanched and unblanched mace from nutmeg variety '*Viswasree*' was done at temperatures of 50, 55 and 60 °C in a reverse air flow, natural convection mechanical dryer. 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 five 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). Page model was found most suitable to describe the drying process of nutmeg mace. The unblanched mace took 330, 240 and 210 min and blanched took 300, 210 and 180 min to dry from moisture content of 186.5 to 5.2% (db) at air temperatures of 50, 55 and 60 °C respectively. The effective moisture diffusivity varied from 1.59×10^{-08} to 2.82×10^{-08} m^2s^{-1}. The activation energy was higher for unblanched than for blanched nutmeg mace and was found to vary from 47.56 to 52.77 kJ/mol.

Keywords: Nutmeg, mace, reverse air flow, drying, thin layer modeling

Introduction

Nutmeg and mace are the two important spices derived from the same nutmeg fruit (*Myristica fragrans)* and are commercially considered as spices. The spice nutmeg is the dried kernel of the seed and mace is the dried aril surrounding it. Ratio of mace to nutmeg is 1:8. Fruits are collected from the tree by hand or with hooked sticks or allowed to fall naturally on the ground and are gathered every day (Krishnamoorthy, 1987) [19].

The spices in their ground form are mainly used in the food processing industry, principally in the seasoning of meat products, they are also used in soups, sauces, baked goods and spice mixes. They are also used in the perfumery and pharmaceutical industries.

Freshly harvested nutmeg is processed after removing the outer pericarp which is also called as the rind. The nut and the mace are dried separately. Drying to optimum moisture level without losing the inherent qualities especially colour is a pre-requisite for long storage and better price. Colour plays an important role in deciding the commercial value of nutmeg mace and its scarlet red colour is due to the presence of pigment pigment lycopene (Gopalakrishnan *et al*., 1980) [13]. This pigment is highly sensitive to heat and light. During drying, scarlet-red colour of nutmeg mace changes to light red or reddish brown colour.

Conventionally, nutmeg mace is dried in the sun or in the kitchen fireplace utilising the heat from the stove or on clay '*kurdis*' spread over fire. In these conventional methods, it is difficult to control the temperature of drying, which has profound influence on the colour of the nutmeg mace. The dried nutmeg mace so obtained does not possess uniform red colour. Also, about 2-3% of the nutmeg mace gets charred in the process. Sun drying is difficult and very slow in many areas because of the active monsoon during the harvesting season (Amaladhas *et al*., 2004) [2].

Hot air mechanical drying is the only alternate viable alternate technology for drying of nutmeg mace. A mild blanching and subsequent drying of nutmeg mace at 50 °C in a cross flow dryer helped in retention of colour and general quality of nutmeg mace (Gopalakrishnan *et al*., 1980) [13].

Dried mace is of great importance in international trade and is used in the preparation of its extractives and volatile oils. The pale-yellow essential oil which is volatile fraction obtained by steam distillation is used as a flavouring essence and in perfumery.

Drying to optimum moisture level without losing the inherent qualities especially the colour is a prerequisite for long storage and better price. Colour also plays an important role in deciding the commercial value of mace and it has been established that its scarlet red colour is due to the pigment lycopene (Gopalakrishnan *et al*., 1980) [13]. During drying, the mace loses about 60 per cent of its weight as moisture (Gopalakrishnan, 1992) [12]. If drying is delayed, mace becomes highly susceptible to mould and insect contamination.

Farmers and cottage scale industrial units use natural convection reverse air flow dryers for drying nutmeg mace and other heat sensitive products (Thomas and Paulose, 2005)32. Hence the present study was conducted with the objective to investigate the effect of air temperature and blanching on drying kinetics of nutmeg mace in a reverse air flow dryer and to evaluate the suitability of some thin layer drying models to describe the drying process.

Materials and Methods

Method

Nutmeg mace from the variety '*Viswasree*' (Fig. 1) was collected from ICAR-Indian Institute of Spices Research, Experimental farm at Peruvannamuzhi. About 1000 g of nutmeg mace at a moisture content of 65.10% (w.b) was taken in a perforated sieve holder and blanched in boiling water (100 °C) for 1 min and another 1000 g of unblanched nutmeg mace was used for each of the drying temperature experiment. After blanching the moisture content of the mace increased to 74.36% (w.b). Nutmeg mace was spread in thin layers on the wire mesh drying trays of size 470 × 475 × 25 mm of the dryer and dried at three different temperatures of 50, 55 and 60 °C. The trays were removed periodically and the weight loss was recorded. The experiment was repeated three times.

Experimental setup and dryer details

Drying of nutmeg mace was carried in a reverse air flow dryer (Model: RRLT-NC Dryer Model 101). This model was designed for the mechanical drying of small quantities of material at farm level (Thomas and Paulose, 2003) [31]. Natural convection dryers are the simpler forms of dryers that can be used by the farmers and cottage scale industrial units for the drying of heat sensitive materials. The overall dimensions of the dryer were 600 × 600 × 600 mm. The duct for the passage of hot air was placed on one side of the dryer chamber. Six numbers of removable wire mesh trays were provided. An electrical heater of 500 watts was placed in the duct itself for the generation of hot air. A thermostat was provided to regulate the air temperature. Hot air was admitted from bottom through the duct in an upward direction and enters into the drying chamber at the top through the inlet port (Fig. 2). As the air flows in a downward direction through all the trays loaded with the materials to be dried, 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 bottommost tray, the humid air escapes into the atmosphere.

Selection of appropriate thin layer model

The moisture content data during drying were converted into moisture ratio and expressed by the following equation:

$$\mathrm{MR} = \frac{M - M_e}{M_o - M_e} \qquad \ldots (1)$$

For long drying periods the moisture ratio can be simplified according to Doymaz (2004b) [6], to:

$$\mathrm{MR} = \frac{M}{M_0} \qquad \ldots (2)$$

where, MR is the moisture ratio, M_0 is the initial moisture content in % db, M is the moisture at time t in % db, M_e is the equilibrium moisture content in % db. To select a suitable model for understanding and describing the drying process of nutmeg mace, curve fitting of moisture ratio with drying time was carried for five drying models (Table 1). The highest value of coefficient of determination (R^2) and the lowest values of mean square of deviation (χ^2), root mean square error (RMSE) and mean bias error (MBE) were used to determine the best fit of the drying models (Hayaloglu *et al.*, 2007) [15]. The statistical parameters were calculated as follows:

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

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

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

where, $MR_{\exp,i}$ is the i^{th} experimentally observed moisture ratio, $MR_{pre,i}$ is the 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.

Moisture diffusivity

Fick's second law was used to describe the moisture diffusion during concentration of drying of nutmeg mace spread in the form of thin slabs as follows (Crank, 1975) [4]:

$$\mathrm{MR} = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2}\left[\sum_{n=1}^{n=\infty} \frac{1}{(2n+1)^2} \exp\left(\frac{-(2n+1)^2 \pi^2}{4} \frac{D_{eff}\, t}{h^2}\right)\right] \qquad \ldots (6)$$

where MR is the moisture ratio, M_0 is the initial moisture content in % db, M is the moisture at time t in % db, M_e is the equilibrium moisture content in % db, D_{eff} is the effective moisture diffusivity in m^2h^{-1}, t is the concentration time in min and h is the thickness of infinite slab 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) [11].

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2}{4}\frac{D_{eff}t}{h^2}\right) \quad \ldots (7)$$

The above equation is in the form of

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{M}{M_0} = Ae^{-kt} \quad \ldots (8)$$

where, the constant

$$A = \frac{8}{\pi^2} \quad \text{and} \quad k = \frac{\pi^2 D_{eff}}{4h^2}.$$

By linearizing the Eq. (8)

$$\ln(MR) = \ln\left(\frac{M}{M_0}\right) = \ln A - kt \quad \ldots (9)$$

The effective moisture diffusivity of nutmeg mace was 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 slab to be dried from one face is assumed to be half the total thickness h, where h = h/2 in m. Hence the slope is taken as

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

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

Activation Energy

In convective heating the effective moisture diffusivity coefficient is dependent on temperature and can be described by Arrhenius equation (Kashaninejad *et al.*, 2007)18. The activation energy for diffusion was estimated by using the equation

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

where, D$_{eff}$ is the effective moisture diffusivity in m^2/s, D$_0$ is the constant in Arrhenius equation in m^2/s, Ea 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 is D$_0$ from which the activation energy E$_a$ can be calculated.

Results and Discussions

Drying kinetics of nutmeg mace

The time required to dry unblanched nutmeg mace from an initial moisture content of around 186.5% db to the final moisture content of around 5.2% db was 330, 240 and 210 min at 50, 55 and 60 °C of drying air temperature, respectively. In case of blanching, the time required for drying was 300, 210 and 180 min for the above temperatures respectively (Fig.3). Amaladhas *et al*., (2004) [2] reported that unblanched and blanched nutmeg mace dried in 4 h and 3.5 h respectively in an agricultural waste fired dyer at average drying temperature of 50 °C. Blanching of mace followed by drying yielded good quality product. Blanching in 75 °C hot water for 2 min, reduced the drying time by 12.5% and enhanced the colour (lycopene) by 22.06%. Blanched mace acquired a uniform deep red colour with a glossy appearance (Amaladhas *et al*., 2004) [2]. During drying, the initial scarlet red colour of mace is changed from light red to reddish brown colour. Kumar *et al*., (2017) [20] reported that mace dried in a mechanical dryer showed better colour than other methods of drying, like drying of mace under close vicinity of 60 watt burning bulbs or oven drying and sun drying. In case of drying less than 60 watt burning bulbs slight bleaching of colour was observed owing to its high temperature of 72 to 76 °C during drying, whereas oven dried mace showed dark brown colour. Prolonged exposure of materials to sunlight or to higher temperature also resulted in change in colour of the product. Srinivas and Mathew (2018) [29], studied the sun drying of mace and reported that the moisture content of nutmeg mace decreased from 66.67% (d.b.) to 6.28% (d.b.) in 16 h. Jayashree and Joseph (2023) [16] reported that mechanical drying of nutmeg mace at 55 °C could reduce the moisture content of nutmeg mace from 225.32 (d.b.) to 4.36% (d.b.) in 6 h and yield good quality mace.

Curves of moisture ratio versus drying time for different drying air temperatures showed that the moisture ratio of nutmeg mace reduced exponentially as the drying time increased (Fig. 4). A plot between the drying rate and the average moisture content of nutmeg mace at different drying air temperatures showed that drying rate was more for nutmeg mace dried at higher temperature than the nutmeg mace dried at lower temperatures for the same average moisture content. At higher temperatures, the relative humidity of the drying air was less compared to drying air at lower temperatures. Because of this, the difference in the partial vapour pressure between nutmeg mace and the surrounding higher temperature drying air environment was more, compared to the difference in partial vapour pressure between nutmeg mace and the surrounding lower temperature drying air environment. Hence, the moisture transfer rate was more with higher temperature drying air. Similarly, drying rate in blanched nutmeg mace was more compared to unblanched nutmeg mace for the same drying air temperature.

Blanching, prior to drying improved the drying rate and this might be due to rupturing of membrane and making mace tender and thus facilitating faster removal of moisture. Similar observations were also reported by Sharma *et al.* (2015) [27] and Thakur *et al.* (2010).

Nutmeg mace did not exhibit a constant rate period of drying (Fig. 3). The entire drying took place in the falling rate period. Drying in falling rate period indicates that, internal mass transfer occurred by diffusion. Similar results have been reported for drying of apricots (Doymaz (a), 2004) [5] and chillies (Kallimullah and Kailappan, 2006) [17]. The constant drying rate period was absent due to the quick moisture removal from the outer surface of nutmeg mace. At the beginning, when moisture content was high, drying rate was very high, and as moisture content approached to equilibrium moisture content, drying rate was very low. This is in agreement with the results of the study on onions (Mazza and Maguer, 1980) [23] and lettuce and cauli-flower leaves (Lopez *et al*., 2000) [21].

Modeling of drying curves

Moisture ratio data of blanched and unblanched nutmeg mace dried at different temperatures were fitted to five thin layer drying 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) [8], but Page model gave comparatively higher R^2 values in all the drying treatments (0.989-1.0) and also the RMSE (0.006-0.032), MBE (-0.007-0.001) and χ^2 (0.05 x 10^{-3} - 1.21 × 10^{-3}) values were lower. Hence Page model may be assumed to represent the thin layer drying behaviour of nutmeg mace in a reverse flow dryer. The predicted moisture ratios are in good agreement with the observed values and therefore it can be concluded that Page model is relatively better than other five models (Fig. 4) in describing the drying characteristics of both blanched and unbalanced nutmeg mace. The results are in agreement with the observations made by other authors for eggplant (Akpinar and Bicer, 2004) [1], green beans (Doymaz, 2005) [7], kiwi fruit (Simal *et al.*, 2005) [28].

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 1.59 x 10^{-08} to 2.82 x 10^{-08} $m^2\ s^{-1}$. The results showed that blanching pre-treatment has increased the moisture diffusivity for all the temperature treatments.

The increase in drying rate with increase in drying temperature has led to the higher diffusion coefficient. This is because higher air-drying temperatures resulted in greater vapour gradients at the food surface which invariably lead to a higher rate of moisture evaporation at the food/air interface. This higher moisture evaporation rate caused a higher rate of moisture diffusion from the internal regions of the pepper to the surface which increased the diffusion coefficients. The increase in moisture diffusivity value, D_{eff} with increase in temperature is similar to observations for dried pestil (Maskan *et al*. 2002) [22] and *Capsicum annuum* (Ertekin 2002) [10]. In these reported cases, samples that were blanched had higher drying rates than the untreated ones. Similar results of influence of blanching pretreatment on increase in moisture diffusivity during air drying has been found in blanched mango slices (Goyal *et al.*, 2006) [14], apricots (Doymaz (a) 2004) [5].

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 (Fig. 5). From the plot, diffusivity constant (D_0) and activation energy (E_a) were calculated Table 4. The activation energy was found to vary from 47.56 to 52.77 kJ/mol and was higher for unblanched than for blanched nutmeg mace. The activation energy is in reasonable agreement with the data presented by other authors, for example 28.36 kJ/mol for carrot (Doymaz(b) 2004) [6], 57.00 kJ/mol for prune (Sabarez and Price, 1999) [26] and 82.93 kJ/mol for mint (Park *et al*., 2002) [25]. Drying of fresh and blanched nutmeg mace of '*Viswasree*' variety was carried in a reverse air flow natural convection dryer at varying temperatures of 50, 55 and 60 ºC. Page model was found most suitable to describe the drying process of nutmeg mace mathematically. The unblanched nutmeg mace took 330, 240 and 210 min and blanched took 300, 210 and 180 min to dry from moisture content of 186.5 to 5.2% (db) at air temperatures of 50, 55 and 60 ºC respectively. The effective moisture diffusivity varied from 1.59 × 10^{-08} to 2.82 × 10^{-08} $m^2 s^{-1}$. The activation energy was higher for unblanched than for blanched nutmeg mace and was found to vary from 47.56 to 52.77 kJ/mol.

Table 1: Empirical thin layer drying kinetic models

S. No.	Model name	Model	Reference
1.	Page	$MR = \exp(-kt^n)$	Lopez *et al*. (2000) [21]
2.	Diffusion approximation	$MR = a \exp(-kt) + (1 - a)\exp(-kbt)$	Togrul and Pehlivan (2003) [33]
3.	Overhults	$MR = \exp[-(kt)^n]$	Overhults *et al*. (1973) [24]
4.	Two term exponentials	$MR = a \exp(-kt) + (1-a)\exp(-kat)$	Ertekin and Yaldiz (2004) [9]
5.	Newton	$MR = \exp(-kt)$	Ayensu (1997) [3]

Table 2: Values of model constants and statistical parameters

Model	Treatment	Temp, ºC	k	n	a	b	r^2	RMSE	MBE	χ^2
Page	Unblanched	50	0.002	1.251	-	-	0.989	0.032	-0.007	1.21 x 10^{-3}
		55	0.036	0.776	-	-	0.994	0.022	-0.003	0.60 x 10^{-3}
		60	0.026	0.937	-	-	1.000	0.006	0.001	0.05 x 10^{-3}
	Blanched	50	0.003	1.192	-	-	0.995	0.021	-0.004	0.55 x 10^{-3}
		55	0.031	0.840	-	-	0.996	0.018	-0.002	0.45 x 10^{-3}
		60	0.055	0.768	-	-	0.999	0.009	-0.001	0.11 x 10^{-3}
Diffusion approximation	Unblanched	50	0.187	-	-0.081	0.038	0.979	0.043	-0.017	2.49 x 10^{-3}
		55	0.225	-	0.209	0.045	0.997	0.016	-0.002	0.41 x 10^{-3}
		60	0.308	-	0.067	0.062	1.000	0.006	0.001	0.06 x 10^{-3}
	Blanched	50	0.196	-	-0.084	0.040	0.990	0.029	-0.005	1.17 x 10^{-3}
		55	0.252	-	0.162	0.050	0.998	0.015	-0.002	0.36 x 10^{-3}
		60	0.28	-	0.254	0.056	1.000	0.003	-0.001	0.01 x 10^{-3}
Overhults	Unblanched	50	0.006	1.251	-	-	0.989	0.032	-0.007	1.21 x 10^{-3}

		55	0.014	0.776	-	-	0.994	0.022	-0.003	0.60 x 10^{-3}
		60	0.021	0.937	-	-	1.000	0.006	0.001	0.04 x 10^{-3}
	Blanched	50	0.007	1.192	-	-	0.995	0.021	-0.004	0.55 x 10^{-3}
		55	0.016	0.840	-	-	0.996	0.018	-0.002	0.45 x 10^{-3}
		60	0.023	0.768	-	-	0.999	0.009	-0.001	0.11 x 10^{-3}
Two Term exponential	Unblanched	50	1.899	-	0.003	-	0.971	0.048	-0.003	2.78 x 10^{-3}
		55	0.055	-	0.192	-	0.994	0.023	-0.001	0.67 x 10^{-3}
		60	0.296	-	0.064	-	1.000	0.007	0.001	0.05 x 10^{-3}
	Blanched	50	3.252	-	0.002	-	0.986	0.036	-0.002	1.56 x 10^{-3}
		55	0.077	-	0.166	-	0.997	0.016	-0.001	0.35 x 10^{-3}
		60	0.067	-	0.248	-	0.998	0.013	0.001	0.25 x 10^{-3}
Newton	Unblanched	50	0.006	-	-	-	0.975	0.048	-0.004	2.48 x 10^{-3}
		55	0.013	-	-	-	0.978	0.043	0.001	2.05 x 10^{-3}
		60	0.020	-	-	-	0.999	0.010	0.003	0.11 x 10^{-3}
	Blanched	50	0.007	-	-	-	0.986	0.035	-0.002	0.01 x 10^{-3}
		55	0.015	-	-	-	0.989	0.031	0.001	1.09 x 10^{-3}
		60	0.021	-	-	-	0.988	0.034	0.007	1.33 x 10^{-3}

Table 3: Effective moisture diffusivity for drying of mace

Temperature, °C	**Moisture diffusivity D_{eff}, m^2s^{-1}, x 10^{-8}**
Unblanched mace	
50	1.59
55	2.00
60	2.87
Blanched mace	
50	1.56
55	2.43
60	2.82

Table 4: Diffusivity constant and activation energy for various treatments

Treatments	**Diffusivity constant, m^2/s**	**Activation energy, kJ/mol**
Unblanched mace	1.68	52.77
Blanched mace	-0.16	47.56

Fig 1a: Nutmeg fruit ready for harvest **Fig 1b:** Nutmeg seed with mace

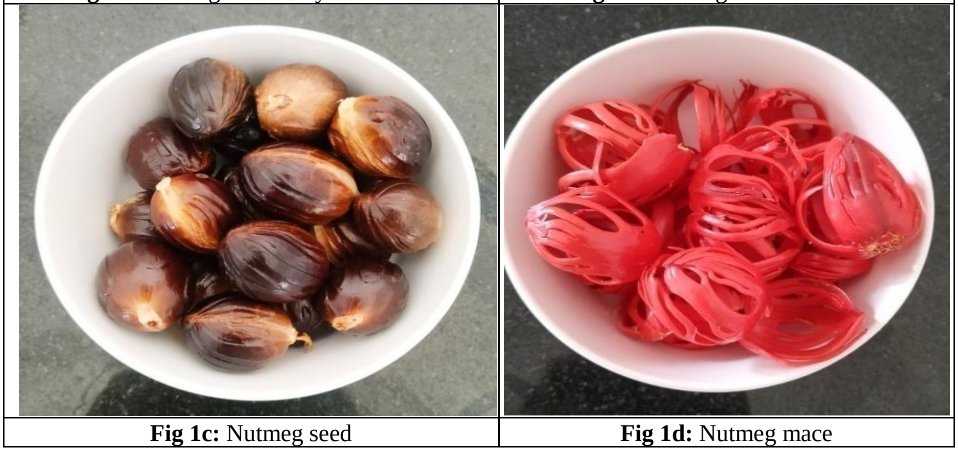

Fig 1c: Nutmeg seed **Fig 1d:** Nutmeg mace

Fig 1: Nutmeg fruit and its components

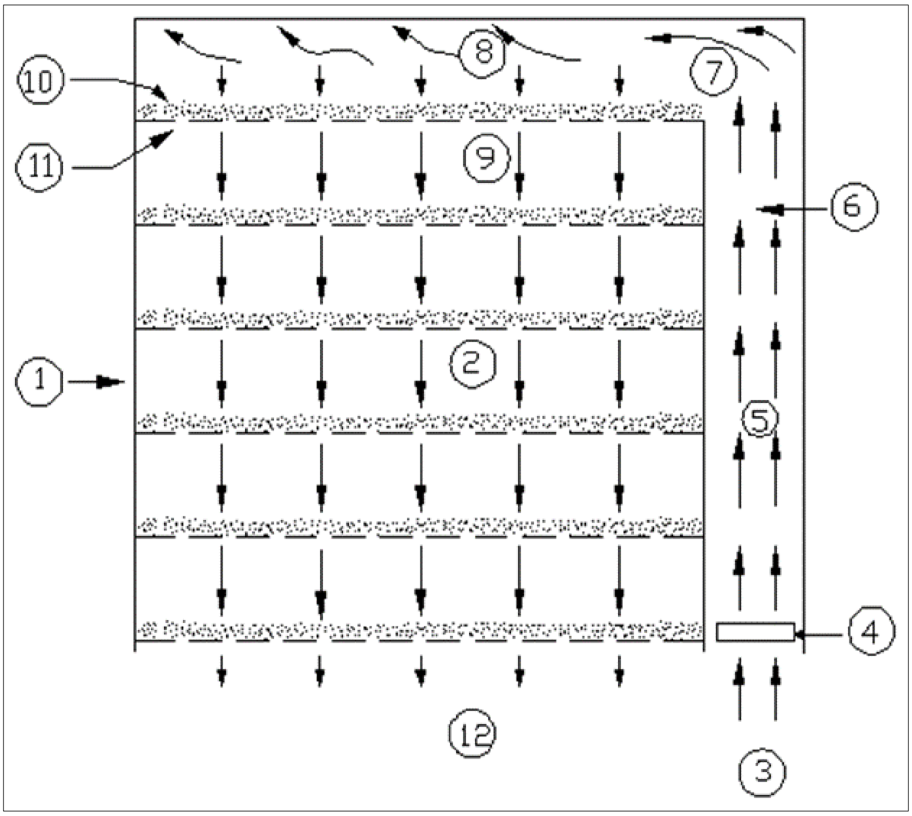

Fig 2: Schematic diagram of drying in Natural convection reverse air flow RRL-NC dryer

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. Hottest air layer
9. Downward flow of semi cooled air
10. Wet material
11. Perforated tray
12. Cold air leaving to atmosphere

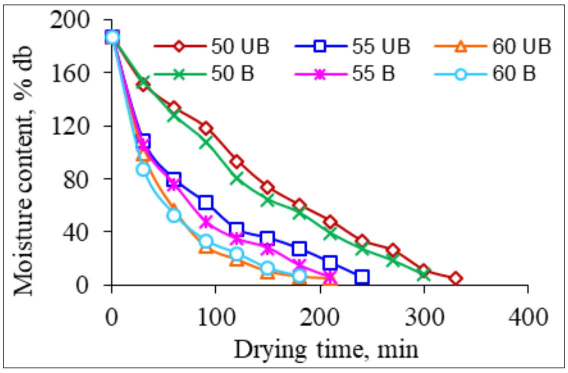

Fig 3a: Moisture content vs. Drying time

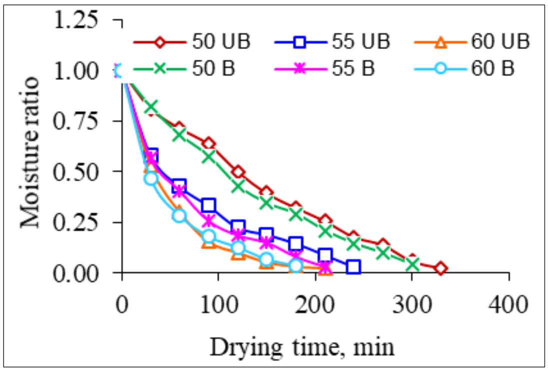

Fig 3b: Moisture ratio vs. Drying time

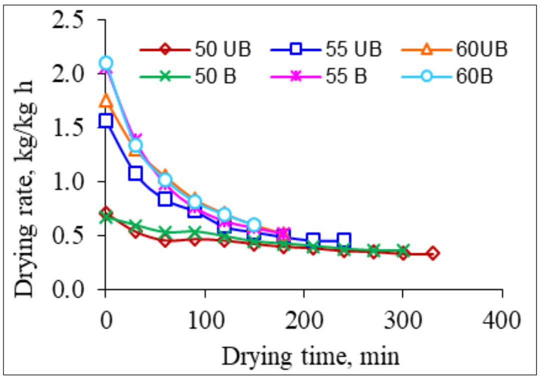

Fig 3c: Drying rate vs. Drying time

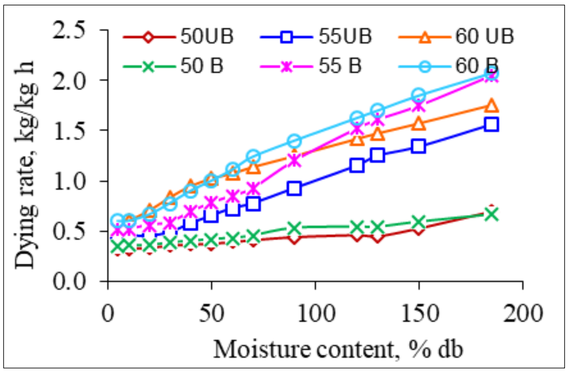

Fig 3d: Drying rate vs. Moisture content

Fig 3: Drying characteristics curves of blanched and unblanched nutmeg mace

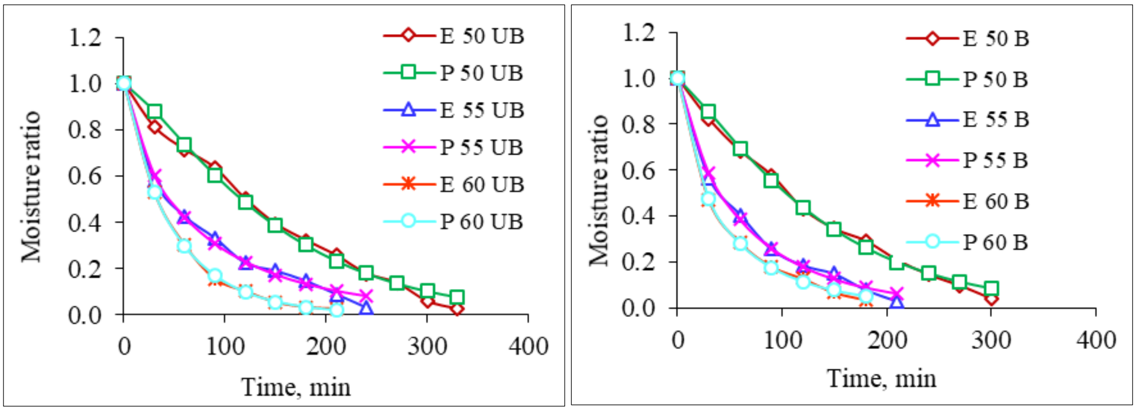

Fig 4a: Unblanched mace (UB) **Fig 4b:** Blanched mace (B)

Fig 4: Predicted and observed moisture ratio for drying of unblanched mace (E: Expected, P: Predicted)

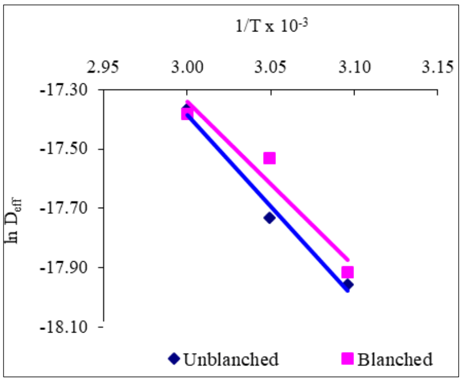

Fig 5: Arrhenius type relationship between effective moisture diffusivity and reciprocal of absolute temperature

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