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Effects of multilayer mechanical drying on the drying kinetics of white button mushroom *Agaricus bisporus*

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Abstract

In the present paper, drying kinetics of button mushroom slices affected by three different independent parameters, including temperature (45-65 ^{0}C), air velocities (1.0-5.4 m/s), and loading densities (26-52 kg/m^2) were investigated at 3 levels each. Four different dying models were applied to describe the drying kinetics of multilayer drying. Single layer drying was kept as control. The results indicated logarithmic model as the best model to characterize the drying kinetics of mushroom in both Multi and Single layer drying. The logarithimic model had the lowest root mean square error (RMSE), mean bias error (MBE) and chi-square. The highest effective moisture diffusivity (Deff) of 4.92×10^{-06} and 5.40×10^{-06} m^2/s was observed for multi and single layer drying respectively.

Keywords: Button mushroom, multilayer drying, drying kinetics, effective moisture diffusivity

1. Introduction

Mushrooms are unique group of macroscopic fungi, which lack chlorophyll. They are preferred for their delicious flavor, high protein content, low caloric value, vitamins, and minerals. Mushrooms contain 20 – 40% db protein and 37.9 - 41.0% db dietary fiber and no cholesterol and almost are free of fat Walde *et al.* (2006) [27]. The most commonly grown species are, *Agaricus bisporus* (white button mushroom), *Lentinus edodes* (Shitake or Japanese mushroom), *Pleurotus species* (Oyster mushroom), *Volvarella volvacea* (paddy straw mushroom), *Flammulna velutipis* (winter mushroom) and the *Auricularia polytricha* (Jew's ear mushroom). These sources of protein are considered more valuable than the cattle and fish. These have been the everlasting part of human diet, also consumed as a delicacy, as of its desirable taste, texture and aroma (Kalogeropoulos *et al.* 2013) [14]. Healing properties of mushrooms include enhancement of macrophage function and host resistance to various viral, bacterial, parasitic, and fungal infections; activation of a non-specific immune stimulation and reduction of blood glucose and blood cholesterol levels (Cheung 1998, Rajarathnam *et al.* 1998) [6, 21]. Mushroom has been initiating to prevent aromatase activity and suppress cell creating breast cancer. Mushroom can also be considered as effective means for disposal of agricultural waste such as hay, paddy straw etc., apart from its medicinal and nutritional value (Mandeel *et al.* 2005) [16].

Mushrooms are highly perishable due to their high moisture content. Deterioration of mushroom starts as the fruiting body matures, and after some time becomes objectionable for consumption. The sign of deterioration browning and veil opening; which are the major factors contributing loss of quality. Consequently, after the harvest, fresh mushrooms need to be processed properly to retard post-harvest losses prior to its consumption. There are number of techniques being used for the shelf life extension of button mushroom such as drying, by application of hydrogen peroxide and browning inhibitors (Sapers *et al.*, 2001; Thakur *et al.*,) [24] Amongst the numerous methods used for preservation, drying is a method in which food water activity is reduced by the removal of the water, thereby minimizing the microbiological and enzymatic activities. Mushrooms were traditionally dried under open sun, which resulted in poor-quality and unhygienic products. Being an energy-intensive operation, the major objective of any drying process is to produce a dried product of desired quality at maximum throughput, minimum cost, and optimized drying factors (Chua *et al.* 2001) [7].

The product can be dried in single or multiple layers. In the single-layer drying process, the sample is subjected to hot air under constant drying conditions. In a multilayer, the product can be thought of as several thin layers in which the humidity and temperature of the air entering and leaving each layer differ with time depending upon the phase of drying and moisture removed from each layer. Single layer drying has been verified as expensive and energy inefficient technique. Less quantity of product is dried in single-layer drying resulting in hotter outlet air whereas, in multilayer, a large quantity of product can be dried which will lead to the proper utilization of hot air and thereby resulting in lower energy wastage

In spite of substantial increases in the consumption and application of mushrooms, studies on mushroom dehydration are still lacking in the literature (Lee *et al.* 2008) [13], and only a limited number of works on the drying kinetics of mushrooms have been reported (Pal *et al.* 1997, Walde *et al.* 2006, Srivastava1 *et al.* 2009) [19, 27].

2. Materials and Methods

2.1. Materials and sample preparation

Experiment was carried out in department of Processing and Food Engineering, Punjab Agricultural University, Ludhiana to study the drying behavior of button mushroom. Fresh button mushroom with a 91.80 ± 0.5 (% wb) moisture content was procured from local market. It was cut manually into quarters, followed by dipping in 2% KMS water for 15 min to minimize losses of valuable compounds.

2.2 Experimental setup for drying

The experimental set-up for multilayer drying of button mushroom comprised of an experimental dryer (Make-SATAKE) with electrically heated hot air system capable of supplying air up to a temperature of 70 °C. A centrifugal blower capable of delivering air velocity up to 5.41 m/s was fitted in the dryer. The blower was powered with 0.75 kW, 1410 rpm, 3 phase, 230-Volt electric motor with a direct online starter. The hot air was sucked by the blower through the heaters and was thrown into the drying chamber. A total of 24 heaters (500W each) constituted the heating chamber. The heaters were vertically fitted in an aluminum chamber having rectangular cross section. Drying chamber for multilayer mechanical drying of button mushroom consisted of cubical boxes made of GI sheets with dimensions 20 cm X 11 cm X 6 cm. There were 24 chambers provided on the dryer but in order to maintain multilayer drying conditions and to meet the requirements for multilayer drying, the boxes were stacked one over the other. These boxes had a mesh at the bottom with approximate 1 mm hole diameter. The hot air enters the chamber from the bottom, passes through the product and leaves the chamber at the top.

2.3 Drying procedure

Pretreated button mushroom was kept for surface drying. The dryer was started half hour prior to actual drying so as to obtain steady state conditions. White button mushrooms were put into the drying boxes according to the desirable loading densities. Infrared thermometer was used to measure the temperature of product throughout drying. The relative humidity and temperature of the ambient and exhaust air were determined using thermo-hygrometer placed on the sample surface. At regular interval of 30 min all the parameters were recorded. The sample was dried up to 6.17 - 6.97% db moisture content. After drying, the sample was taken out, brought to room temperature, packed and stored. Three replications were taken for each experiment to get an average value.

2.4 Drying kinetics analysis

Data collected from multilayer drying was analyzed to obtain drying rate, drying time and moisture diffusivity. Drying rate was determined by moisture content (% db) decrease of the sample per unit time (min) as given by Brooker *et al.* (1997).

$$\frac{dM}{dT} = \frac{(M_i - M_{i+1})}{(t_{i+1} - t_i)} \tag{1}$$

Where,

dM/dT = drying rate, percent moisture loss per min (%/min),

M_i = Moisture content (% db) of sample at time t_i

M_{i+1} = Moisture content (% db) of sample at time t_{i+1}

Moisture ratio was calculated at different drying times (Brooker *et al.*, 1997)

$$MR = \frac{M - Me}{Mo - Me} \tag{2}$$

Where, M = Moisture content of sample at any time (%, db),

Me = Equilibrium moisture content (%, db) and

Mo = Initial moisture content (%, db).

2.5 Drying air conditions

The temperature of ambient, heated and exhaust air was measured with the help of Hygrometer. The product temperature was measured using infrared thermometer. The relative humidity of ambient, heated and exhaust air was recorded using Hygrometer (0 - 100%).

2.6 Drying model

The semi-theoretical and empirical models used to describe the drying kinetics of sample are shown in Table 1. Drying curves were fitted to the experimental data using these moisture ratio equations. Non-linear regression analysis was conducted to fit the mathematical models by the statistical package for social sciences (SPSS version 11.5). The adequacy of goodness of fit of various models was determined by various statistical parameters such as; coefficient of determination (R^2), chi-square (χ^2), mean bias error (MBE), root mean square error (RMSE) and were defined by the equations 3 to 6 (Gomez and Gomez, 1983).

$$R^2 = \frac{\sum_{i=1}^{n}\left(MR_i - MR_{pre,i}\right)\cdot\sum_{i=1}^{n}\left(MR_i - MR_{\exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(MR_i - MR_{pre,i}\right)^2\right]\cdot\left[\sum_{i=1}^{n}\left(MR_i - MR_{\exp,i}\right)^2\right]}} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{4}$$

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

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

Where, $MR_{exp,\ i}$ and $MR_{pre,i}$ are experimental and predicted dimensionless moisture ratios, respectively, N is number of observations and n is number of constants. The best model describing the drying characteristics of samples was chosen as the one with the highest coefficient of determination, the least mean relative error, reduced chi-square and RMSE (Sarsavadia *et al.*, 1999; Madamba, 2003; Sacilik *et al.*, 2006) [23, 15, 22].

Table 1: List of drying models

Model No	Model equation	Model name	References
1	$MR = exp(-kt)$	Newton	Lewis (1921)
2	$MR = exp(-kt^n)$	Page	Page (1949)
3	$MR = a\ exp(-kt) + b$	Logarithmic	Yagcioglu (1999)
4	M.R= a Exp (-kt)	Henderson and Pabis model	Ghodake *et al.* (2006)

2.7 Effective moisture diffusivity

When the moisture ratio starts decreasing continuously with increase in the drying time, it shows that the results can be interpreted by using Fick's diffusion model. For effective moisture diffusivity the shape of button mushroom slices were assumed as cylinder shape. Moisture transfers with negligible external resistance and uniform moisture distribution were taken into account. When the plot of logarithm of moisture ratio (ln MR) versus drying time is linear, the moisture diffusivity assumes an independent function of moisture content. Effective diffusivity evaluated by using moisture content can be described by the following equation (Crank, 1975) [8]:

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} = \frac{\mathrm{M_t}}{\mathrm{M_0}} = \frac{8}{\pi^2} \sum_{\mathrm{n}=1}^{\infty} \frac{1}{(2\mathrm{n}+1)} \exp\left[-\frac{(2\mathrm{n}+1)^2 \pi^2\, \mathrm{D\, t}}{4\,\mathrm{L}^2} \right] \quad (7)$$

Where, D is the effective moisture diffusivity (m^2/sec) and MR is the moisture ratio. Since the top surface of slice was only exposed to hot air, the radius of r, in Eq (8).

$$\mathrm{D} = \frac{r^2 \times \ln(0.692 \times M.R)}{5.78 \times t} \quad (8)$$

Linear regression analysis was employed to obtain values of diffusion coefficients for different drying conditions, from the slope of the straight lines obtained.

2.8 Heat utilization factor

Temperature and relative humidity of the air exhausted through layers was recorded. To calculate heat utilization factor Eq.9 given by Hall (1970) [11] was used. This defined the ratio of temperature decrease due to cooling of the air during drying and the temperature increase due to heating of air.

$$HUF = \frac{t_3 - t_2}{t_1 - t_2} \quad (9)$$

Where,

t_1 = Ambient air temperature (°C)

t_2 = Heated air temperature (°C)

t_3 = Exit air temperature/Outgoing air temperature (°C)

2.9 Coefficient of performance:

The coefficient of performance is expressed mathematically as given by Chakraverty (2010) [5].

$$COP = 1 - HUF \quad (10)$$

2.10 Specific energy consumption

Energy consumption was determined in terms of specific energy consumption (SEC, kWh/kg) that is defined as energy consumption per kilogram of product and is calculated by the following equation:

$$SEC\left(\frac{kWh}{kg} \right) = \frac{MP \times t}{W_o} \quad (11)$$

Where,

SEC = total energy consumed in each drying cycle (kWh/kg),

MP= the energy consumed by drier (kW),

t = the drying time (h) and

W_0 = initial weight of the sample (kg).

3. Results and Discussion

3.1 Moisture content

Moisture content of fresh white button mushroom was about 91.80 ± 0.5 (% wb). Moisture content decreased with the drying time for all the samples irrespective of the combinations of temperature, air velocity and loading densities as shown in Fig.1. There was steep decline in the moisture content during initial period of 120 mins of drying; followed by gradual decline. For removal of moisture content from 1340.28 to 6.17% db, maximum drying time of 810 min was recorded for 45 ^{0}C, 1 m/s and 52 Kg/m^2 and minimum drying of 210 min was recorded for 65 ^{0}C, 5.4 m/s and 26 Kg/m^2. The decrease in moisture content increased with temperature and air velocity whereas opposite trend was observed for loading density. The increased temperature resulted in decreased moisture content during the initial period where, sensible heat followed by latent heat of vaporization were transferred to the product, which directly influenced the moisture content there by increasing the rate of evaporation Mihalcea *et al.* (2016) [18]. An increase in air velocity persuades the enhancement of convective heat transfer coefficient, which is a function of Reynolds Number and enables evaporation of water from the product. At the same time, the external resistant produced by boundary layer is reduced with increasing air velocity due to better heat transfer to the samples Bansal (2013) [4], Garg (2012) [10], Aral and Bese (2016) [1]. With the increase in loading density exposure of air passing through each layer reduces, lowering moisture removal irrespective of temperature and air velocity. As drying air, enters it passes through each layer and gains moisture but in turn reduces the drying air temperature and resulting in insufficient removal of moisture. This is the reason that removal of moisture was much slower at higher loading density 52 kg/m^2. An important observation was that there was not much difference in change in moisture content at loading densities of 26 and 39 kg/m^2. This showed that multilayer drying up to 39 kg/m^2 loading density can have a comparable decrease in moisture. Similar trends were also observed by Garg (2012) [10]. Comparatively, multilayer drying resulted in capacity enhancement by 2.34 times to that of single layer drying, alternatively it took 4.3 times more time to that of multilayer drying, to dry the same amount of product in single layer drying.

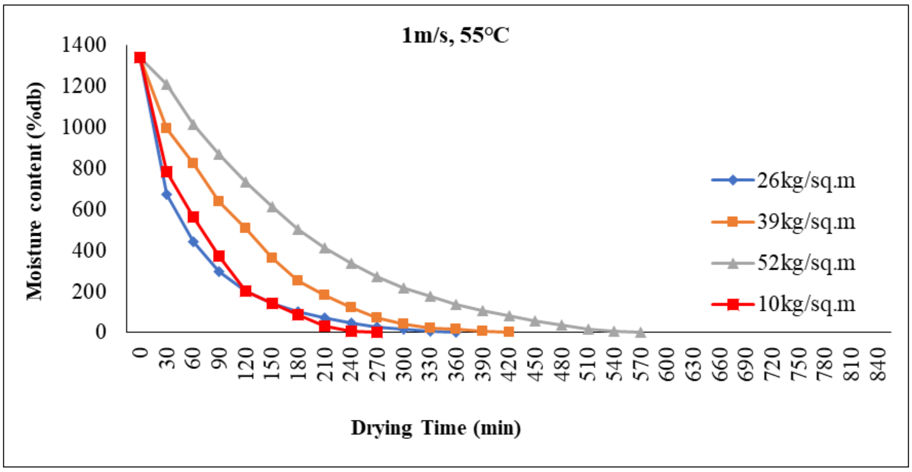


Fig 1: Moisture content (% db) versus drying time (min)

3.2 Drying Rate

The initial drying rates were different for all the combinations of temperatures, air velocities and loading densities. As drying progressed, initially there was sharp rise in drying rate, reaching its peak value; thereafter the drying rate decreased sharply became very slow towards the end of drying as shown in Fig. 2. Decline in moisture content was relatively slower in multilayer drying compared to single layer drying. Because in the beginning, the hot air crossed first layer, removed moisture from that layer which is added to air and in turn reduction in air temperature took place due to heat utilization which caused decrement of drying in second and subsequent layers. The highest drying rate of 17% db/min was recorded for 65 ^{0}C, 5.4m/s and 26 kg/m^2 and was lowest of 4.70% db/min for 45 ^{0}C, 1m/s and 52 kg/m^2. The drying rate decreased with decrease in available free moisture owing to lower driving force and lower moisture diffusion from center to the surface of the dried product. The overall drying took place in falling rate period and generally two period were observed, with a short accelerating period at the beginning of drying. The effect on drying rate is well documented in the literature on drying of various food product (Simal *et al.*, 2000, Akpinar *et al.*, 2003, Senadeera *et al.*, 2003) [2, 25]. Drying rate increased at the beginning and decreased towards the end with temperature and air velocity, whereas it increased with loading density. Comparatively, multilayer drying showed lower drying rates than that of single layer drying indicating that at lower loading densities, the drying was faster, due to the faster rate of drying in single layer drying. Case hardening of the product were observed in single layer drying which was not seen in the case of multilayer drying.

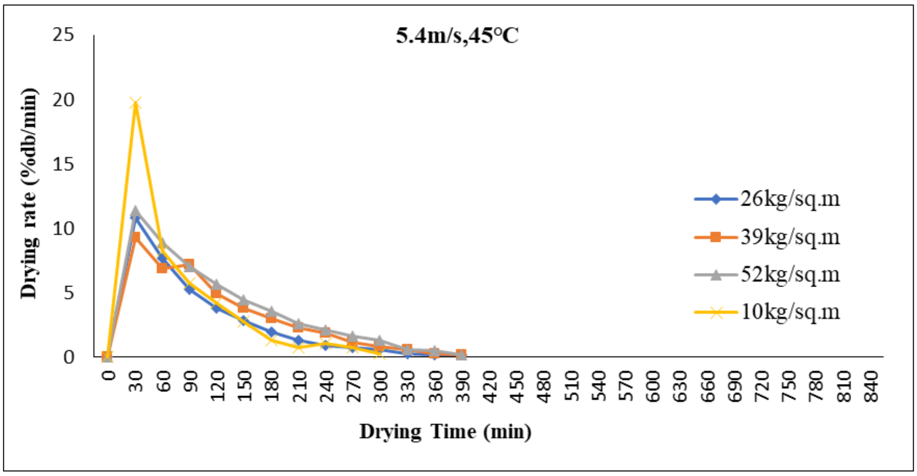


Fig 2: Drying rate (% db/min) versus drying time (min)

3.3 Temperature of outgoing air

Temperature of ambient air was 28-33 ºC and the temperature of the entering hot air were 45^0 C, 55^0 C and 65^0 C. The temperature of outgoing air in the beginning of drying ranged between 28 – 30 °C indicating high utilization of heat for removal of moisture and availability of more free moisture. At the end of drying temperature ranged between 44.09 – 63 °C due to fully dried product. In combination of 65 ^{0}C, 1 m/s, and 26 kg/m^2 the outgoing air temperature increased quickly to reach its peak value in 5.50 h; in combination 45 ^{0}C,1 m/s, and 52 kg/m^2 on the other hand temperature of outgoing air increased slowly to reach its peak value in 13.5 h; The reason for high temperature increase of the outgoing air in former was due to fact that the product was exposed to the incoming hottest air (65 ^{0}C) and lesser volume of the product (26 kg/m^2); resulting in quick drying; whereas in later large volume of the product resulted in drop of outgoing air temperature. The temperature of outgoing air increased with air velocity whereas opposite trend was observed for loading density. Comparatively, multilayer drying showed lower temperature of outgoing air than that of single layer drying indicating higher utilization of heat and high availability of free moisture.

3.4 Relative humidity of outgoing air

The initial value of relative humidity ranged between 82-86% and declined at a faster rate and finally reaching to 16 - 28% at the end of drying. For 45 ^{0}C, 1m/s, and 26 kg/m^2 the relative humidity of outgoing air and reached a lower value of 24% after 6.5 h of drying. Whereas for 45 ^{0}C, 1m/s, and 52 kg/m^2 it reached a value of 17.4% in 13.5 h. This Indicates that in samples having low loading densities, the decrease in relative humidity with drying time was fast compared to high loading densities as indicated by Fig.3. This may be due to addition of moisture to the drying air as evaporation of moisture proceeds after initial warming of the product. Furthermore, due to the high initial moisture content of the product, the drying air absorbed more moisture from lower layers and became saturated before reaching to the top layer of the product. Relative humidity decreased with temperature and air velocity whereas increasing trend was observed for loading densities. Comparatively, multilayer drying showed higher relative humidity of outgoing air than that of single layer drying indicating that at higher loading densities relative humidity decreased slowly.

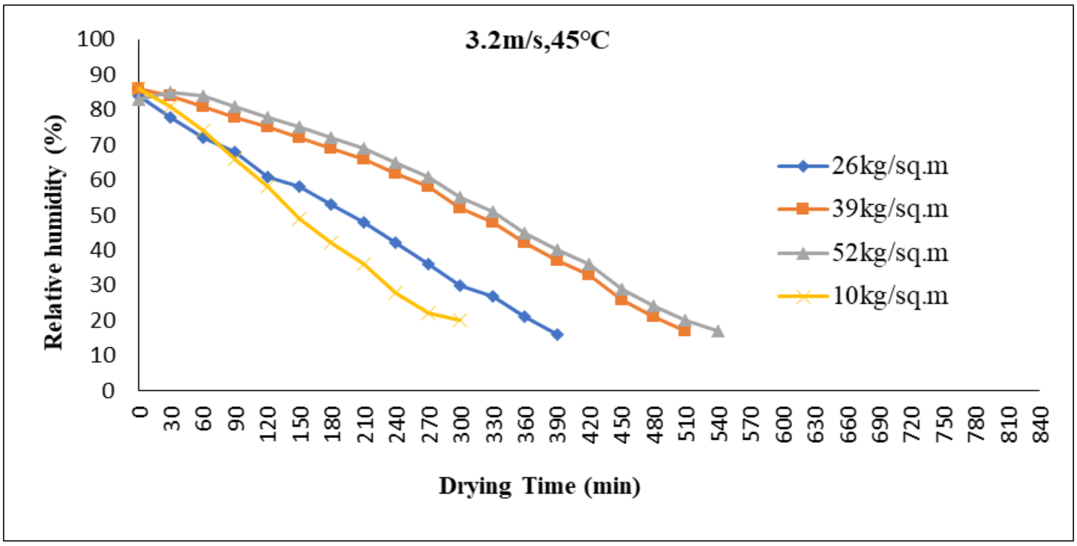


Fig 3: Relative humidity (%) versus drying time (min)

3.5 Temperature of product

Quality of product is temperature dependent, owing to the sensitivity of nutrients to temperature; higher the temperature of the product more is deterioration of the quality and less is the product suitable for storage. Temperature causes micro structure damage comparatively leads to product shrinkage (Hebbar *et al.*, 2004; Reis, 2014; Vega-Galvez *et al.* 2012). The product prior to drying were cool, compared to the hot drying air initial temperature of product was between 28 – 30 °C and it increased at a faster rate reaching a temperature of 44 – 63 °C at the final stage of drying. The trend showed that as the temperature and air velocity of air increased the temperature of product also increased; while loading density showed opposite trend for temperature of product. Comparatively, multilayer drying showed lower temperature of product than that of single layer drying.

3.6 Heat utilization factor

HUF showed a rapid decreasing trend for all combinations, followed by more or less constant towards the end of drying. When the hot inlet air comes in contact with the product, heat is transferred to the product resulting in evaporation of moisture from it and in turn lowering the temperature of the air; lower the temperature of outgoing air, more is the heat being utilized. The initial and final HUF remained between 0.95 - 0.98 and 0.02 - 0.24, respectively. The high value of HUF indicates higher heat utilization during drying or conversely less wastage of heat. It was observed that the HUF decreased with temperature and air velocity while increased with loading density. HUF was observed to be more in multilayer drying than in single layer.

3.7 Coefficient of performance

COP showed a rapid increasing trend for all combinations, followed by more or less constant towards the end of drying. The initial and final COP remained between 0.05-0.02 and 0.98- 0.96, respectively. It was observed that COP was higher towards the end of drying. The lower the value of COP, higher is the being utilized during drying or conversely less wastage of heat. It was observed that COP increased with temperature and air velocity while as opposite trend was observed for loading density. It was observed that COP of dryer was higher during multilayer drying as compared to single layer.

3.8 Specific energy consumption

The trend of specific energy consumption for different combinations of temperatures, air velocities and loading densities are presented in Fig 4. Specific energy consumption is the energy required to evaporate 1 kg of moisture. The minimum required energy for starting the process of drying is known as the activation energy. Proper selection of input variables is important for the minimizing specific energy consumption. Energy consumption showed a downward trend with temperature and air velocity and an upward trend with increasing loading density. It indicates that due to the higher amount of product, the time taken for drying was more, which directly initiated the higher energy consumption. The highest energy consumption of 52 kWh/kg was observed for 45 ^{0}C, 1 m/s & 52 Kg/m^2 and the lowest 16 kWh/kg was observed in 65 ^{O}C, 5.4 m/s & 26 Kg/m^2.

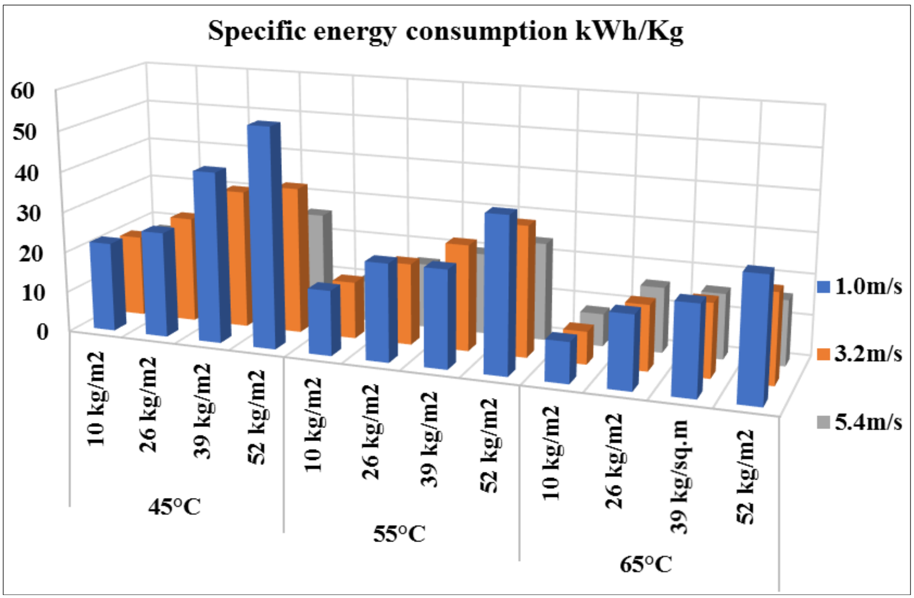
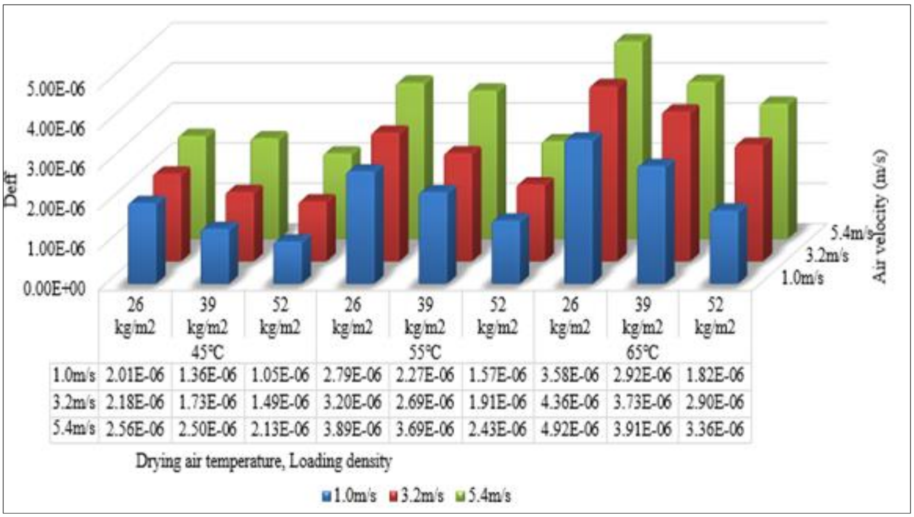


Fig 4: Effect of temperature, air velocity and loading density on specific energy consumption in multilayer and single layer drying

3.9 Effective moisture diffusivity for drying process

Variation in ln (MR) against drying time plot for the various range of temperature, air velocity and loading density was used to calculate the effective moisture diffusivity; Deff, had coefficient of determination greater than 0.97. Though values obtained are within the suitable range for food products (10^{-12} to 10^{-6} m^2/sec) reported in literature (Zogas *et al.*, 1996 and Maskan *et al.*, 2002) [28, 17].

The effect of temperature, air velocity and loading density on Effective moisture diffusivity on drying of button mushroom is shown in Fig 5. With increase in temperature and air velocity, the effective diffusivity increased due to the increase in the vapor pressure inside the sample. The highest D_{eff} of 4.92x $10^{-6}$$m^2$/sec was recorded for sample having 65 ^{0}C, 5.4 m/s and 26 kg/m^2 and lowest of 1.05 x $10^{-6}$$m^2$/ sec for 45 ^{0}C, 1 m/s and 52 kg/m^2 combinations. This incline in Deff was due to increased heat energy reported to enhance the activity of the water molecules leading to higher moisture diffusivity. Similar results of moisture diffusivity during air drying had been found in lateral studies like in apricots, peach slices, tomatoes, ginger, mushroom (Pala *et al.* 1996; Kingsly *et al.* 2007; Doymaz 2007; Garg 2012) [20, 12, 9, 10]. In single layer drying D_{eff} ranged between 2.76 x 10^{-6} m^2/ sec to 5.40x $10^{-6}$$m^2$/ sec compared to 1.05 x $10^{-6}$$m^2$/ sec to 4.92x $10^{-6}$$m^2$/sec in multilayer drying.



	26 kg/m2	39 kg/m2	52 kg/m2	26 kg/m2	39 kg/m2	52 kg/m2	26 kg/m2	39 kg/m2	52 kg/m2
		45°C			55°C			65°C	
1.0m/s	2.01E-06	1.36E-06	1.05E-06	2.79E-06	2.27E-06	1.57E-06	3.58E-06	2.92E-06	1.82E-06
3.2m/s	2.18E-06	1.73E-06	1.49E-06	3.20E-06	2.69E-06	1.91E-06	4.36E-06	3.73E-06	2.90E-06
5.4m/s	2.56E-06	2.50E-06	2.13E-06	3.89E-06	3.69E-06	2.43E-06	4.92E-06	3.91E-06	3.36E-06

Fig 5: Effective moisture diffusivity at different temperature, air velocity and loading density during multilayer drying

3.10 Validation of drying models

In order to evaluate the performance of convective drying models, the values of statistical parameters for all the experiment runs were compared and model coefficients for each model were calculated using non-linear regression techniques of SPSS version 11.5. All the models showed higher R^2 value (> 0.90). It was also observed that the error term χ^2 minimum value of 0.0001 for all the models at combination of 45 ^{0}C, 1 m/s and 26 kg/m^2. Whereas, the maximum value of χ^2 0.0983 was observed for page model for the combination of 65 ^{0}C, 1 m/s, and 52 Kg/m^2. Minimum MBE and RMSE values of -0.058 and 0.0001 respectively were observed for logarithmic model showing higher adequacy of fit between experimental and predicted data with highest R^2 value ranging from 0.993 - 0.999 for describing the drying kinetics. The results were supported by the distribution of residuals (%) v/s MR showing random pattern for all the models. It was concluded that for each combination of temperature, air velocity and loading density, logarithmic model showed better distribution of residuals followed by page model. In Single layer drying logarithmic model was also best fitted for describing the drying kinetics with minimum MBE and RMSE values of -0.035 and 0.0003 respectively. Similar results were also reported by Bansal (2011).

4. Conclusions

It can be concluded that multilayer drying can be proved beneficial for capacity enhancement, as in the present study multilayer drying enhanced capacity of dryer by 2.34 times to that of single layer drying, alternatively it took 4.3 times more time to that of multilayer drying, to dry the same amount of product in single layer drying.

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