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COMPARISON OF MATHEMATICAL MODELS AND THIN-LAYER DRYING KINETICS OF OYSTER MUSHROOM (*PLEUROTUS SPP*) UNDER FLUIDIZED BED DRYER WITH THE ACCELERATED AIR TEMPERATURE AND VELOCITY

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Abstract: Effect of drying air temperature and velocity on thin-layer drying characteristics of oyster mushroom (*Pleurotus spp*.) was investigated using a fluidized bed dryer. Mushrooms were dried at three air temperatures 45, 55 and 65ºC coupled with the air velocity of 2, 3.5 and 5 $m \cdot s^{-1}$. Dehydration of mushrooms occurred in falling rate period and temperature has significant (P=0.04) effect on drying. From the regression model, best quality of dried oyster mushroom was obtained at 65°C temperature and 5 ms^{-1} air velocity and it was validated with sensory characteristics in terms of colour, crispy texture, flavour and comparatively less shrinkage. To determine the drying kinetics, experimental moisture ratio data were fitted to seven thin-layer drying models. Among the models studied, Page model was found to be the best fitted model to describe the drying behavior of oyster mushroom. At any given air velocity, with the increase in drying air temperature led to an increase in effective moisture diffusivity ranged from 7.78×10^{-10} to $2.11 \times 10^{-9} m^2 \cdot s^{-1}$. Drying at 5 $m \cdot s^{-1}$ air velocity required minimum activation energy of 22.15 $kJ \cdot mol^{-1}$ to remove water during the drying process by diffusion. Rehydration ratios (RR) values (1.95-2.75) increased with increase in drying air temperature and velocity. The results obtained could be for making appropriate design and operations of industrial drying system for further processing of mushrooms to value added products.

Key words*: Oyster mushroom, drying kinetics, effective diffusivity, fluidized bed dryer, moisture ratio, sensory characters*

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INTRODUCTION

Mushrooms have been used throughout the world for many centuries as a good source of proteins, carbohydrates, lipids, and dietary fiber. Of the 2000 known species of mushrooms only 35 species are cultivated commercially. Cultivable mushrooms such as button mushroom (*Agaricus bisporus*), oyster mushroom (*Pleurotus spp.)*, milky mushroom (*Calocybe indica*), shitake mushroom (*Lentinus edodes*) and paddy straw mushroom (*Volvariella spp.*) are prized for their delicacy, nutritional and medicinal values [1]. Among these, oyster mushrooms grow on a wide variety of agricultural substrates in temperature ranging from 15 to 35ºC with 100% biological efficiency and are marketed in dried form worldwide. Due to their simplified and cheaper (1-1.5 times) cultivation practices compared to *Agaricus bisporus,* oyster mushrooms are believed to take over the mushrooms market of India in the near future. In addition to their pleasant flavour oyster mushrooms contain 20–30% protein, 57-65% non-starchy carbohydrates, minerals (Ca, Fe, Mg, P), vitamins, and low fat content (2–2.7%) making them an constituting excellent food supplement.

Moisture content of fresh mushrooms lies between 87-95% (w.b.) making it a perishable product leading to an extremely short shelf life. The quality of fresh mushrooms deteriorates if they are not marketed or processed immediately after harvesting [2]. Therefore, processing them to as table form requires special care when employing different preservation methods such as drying, canning, pickling and controlled environmental storage that improves shelf life [3]. Drying is an effective unit operation as it reduces bulk volume, facilitates better handling and storage by removing excess water necessary to inactivate microbial and enzymatic activities [4]. Dehydrated mushrooms are used in several food and medicinal formulations such as instant soups, pasta salad, snacks, stuffing, chocolates, biscuits, casseroles, meat and rice dishes, antioxidant capsules/tablets as food flavoring and anti-cancerous materials [5].

Oyster mushroom can be dried at (6-10% moisture content) by different methods such as sun, convective cabinet, fluidized bed and freeze drying depending upon harvest time, environmental condition and affordability [1]. Mushrooms are reported to be dried at temperatures ranging from 37.8–70°C with the finishing temperature up to 82.2°C alone or in combination with various blanching treatments [6].

Drying is cumulative effect of heat-mass transfer phenomenon that induces quality changes in dried food products. Hence, insight into the physical and thermal characteristics of food materials is essential to understand the drying mechanics [7]. Drying kinetics establish the relationship between drying parameters such as diffusion coefficients and moisture ratio to predict drying behavior. Thin layer drying, referred to as constant temperature drying, is a process where diffusion of water takes place from inside of the food material to the air–food interface and then to the air stream by convection. Therefore, thin-layer drying simulation is the most suitable approach to model drying of food materials. Mathematical models provides simple representations of complex drying process of geometrically different agricultural materials and have proven to be very useful for appropriate design, construction and operation of drying systems.

Several researchers have proposed thin layer drying simulations models for many agricultural products to generalize the drying curve and predict drying time of natural and forced convection drying systems. For example, apple [7], bamboo [8], banana peel [9], garlic [10], mango slices [11] and wheat [12] have been reported. Limited research on drying especially systematic studies on fluidized bed drying kinetics of oyster mushrooms is available in the literature [3]. Also proper investigation is prerequisite to enhance the efficiency of drying operation, design and construction of drying systems. Therefore, the objective of the this study was: (i) to investigate the effect of different drying air temperature and velocity on drying characteristics of oyster mushroom in a fluidized bed dryer (ii) to evaluate the suitable thin-layer model for describing the drying behavior (iii) to compute the effective moisture diffusivity, activation energy during drying of oyster mushroom and its quality evaluation through rehydration and sensory evaluation.

MATERIAL AND METHODS

Sampling and experimental setup

Freshly harvested oyster mushrooms of uniform maturity were obtained from the environmental controlled cropping unit of Directorate of Mushroom Research, Solan, India. Mushrooms were cleaned, sorted by size and their stipe's (stems) removed using sharp stainless steel knife. About 800 g of oyster mushroom sample of pileus (cap) diameter 75 – 80 mm and 7±1 mm thickness was selected for each drying experiment. The initial moisture content 92.32% (w.b.) of mushroom was measured using AOAC method [13] before starting the drying experiment. Drying kinetics of mushroom at three air temperatures 45, 55 and 65ºC and velocities 2.5, 3.5 and 5 $m \cdot s^{-1}$ was studied. The terminal velocity of above given size fresh mushroom was found to be 2 $m \cdot s^{-1}$; hence slightly higher air velocities were selected for thin-layer drying experiment. The laboratory scale cylindrical stainless steel fluidized bed dryer (Model: Retsch, TG 100, Germany) of 20 cm diameter and 314.28 cm^2 cross section area of plenum chamber was set at desired air temperature and velocity combination 1 h prior to start of experiment through proportional velocity and temperature controller. Pre-weighed mushroom sample was spread in thin layer of 8–10 cm thickness over perforated steel grit and dryer closed by wire mesh cloth cap. Loss in moisture content was measured continuously at every 30 min interval till constant weight was reached (using digital balance of 0.01 accuracy D'Arts-DG 25, India).The relative humidity of drying air was found between 23–41% and was not regulated. All experiments were performed in triplicates. The dried sample were collected from the grit, cooled at room temperature and subsequently packed in 500 g polypropylene bags to evaluate for rehydration and sensory qualities.

Drying kinetics and mathematical models for thin layer drying

To determine the most appropriate drying model, experimental data were fitted to different thin layer drying models (Tab. 1).

Moisture ratio *MR* of oyster mushroom samples during thin layer drying experiments in fluidized bed dryer were calculated using the following equation (1).

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{1}$$

where: M_i was initial moisture content, M_e equilibrium moisture content, and M_t was moisture content at time (t), all on dry basis (d.b.). During drying oyster mushroom samples were not exposed to uniform relative humidity and temperature throughout the process. Also values of M_e were relatively small as compared to M_i or M_t, and hence can be neglected.

Non-linear regression analysis was performed on drying data of *MR* versus drying time using SATISTICA 12 (StatSoft, Inc., USA) software package. Statistical parameters *viz.*, coefficient of determination (R^2)and goodness of fit determined by using chi-square (χ^2), mean bias error (*MBE*) and root mean square error (*RMSE*) values were used as selection criterion for best model fit [11, 14]. Model selection was based on higher R^2 value and lower χ^2, *MBE* and *RMSE* values. These parameters can be determined by using equations (2), (3) and (4).

Table.1. Mathematical models used for thin layer drying of oyster mushroom

Model	Mathematical equation	Reference
Newton/ Lewis	$MR = exp(-kt)$	[14]
Page	$MR= exp(-kt^n)$	[15]
Handerson and Pabis	$MR= aexp(-kt)$	[16]
Logarithmic	$MR=aexp(-kt)+c$	[1]
Two-term exponential	$MR=aexp(-kt) + (1-a) exp(-kat)$	[17]
Wang and Singh	$MR=1+at+bt^2$	[2]
Midilli *et al.*	$MR=aexp(-kt^n)+ bt$	[3]

Note: a, b, c, k, k_0, k_1, n are drying constants

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp} - MR_{pre})^2}{N - z} \tag{2}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N} (MR_{exp} - MR_{pre}) \tag{3}$$

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

Where, MR_{exp} is experimental moisture ratio, MR_{pre} is predicted moisture ratio, N is number of observations, z is number of drying constants.

Determination of effective moisture diffusivity and activation energy

Drying in general occurs in two periods, constant rate period followed by falling rate period. Effective moisture diffusivity at constant moisture content can be estimated using methods of slopes techniques. Hence Fick's second law of unsteady state diffusion was used assuming that oyster mushroom is of slab geometry, moisture migration occurred due to internal diffusion at constant temperature and negligible shrinkage. Simplified solution of Fick's second law for food material of slab geometry which describes thin layer drying process as shown in Eq. (5).

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \tag{5}$$

Where, D_{eff} is the effective diffusivity (m^2s^{-1}), t is the drying time (s), and L is the half slab thickness (m).

The effective moisture diffusivity (D_{eff}) can be calculated from the slope of the normalized plot of ln(*MR*) versus time (*t*), using the following equation (6) [16]:

$$D_{eff} = \frac{-Slope\ 4L^2}{\pi^2} \tag{6}$$

As the D_{eff} value changes with moisture content of the drying material, sometimes it is not possible to get a linear relationship for the entire moisture content range i.e. a single D_{eff} value to represent the entire drying range. Hence, as explained by [2], the entire plot of ln(*MR*) versus drying time (*t*) was divided into two portions when needed so that it could be well represented by two linear relationships with higher R^2 value. Therefore, two D_{eff} values one for initial and another for later stages of drying were obtained.

Activation energy is termed as the minimum energy that must be supplied to break water-solid and/or water-water interactions, and to move the water molecules from one point to another in the solid. Activation energy of drying can be obtained from the linearized form of Arrehenius equation (7). Slope from the plot of ln(D_{eff}) versus 1/T yields E_a and from the intercept D_o is estimated [18]:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (7)$$

Where, D_0 is the pre-exponential factor of the Arrhenius equation ($m^2 \cdot s^{-1}$), E_a is the activation energy ($kJ \cdot mol^{-1}$), R is the universal gas constant (8.314 kJ mol⁻1·K^{-1}), and T is the absolute air temperature (K).

Rehydration characteristics and sensory analyses

Rehydration ratio (RR) of dried oyster mushroom samples of various treatments was calculated as the rehydrated mass to the dehydrated mass 30 days after dehydration. A sample of 5 g of the dried mushroom was kept in a 250 ml beaker containing 150 ml of boiling distilled water. The contents were boiled for 15 minutes for rehydration. After that excess water from the mushroom samples were removed and rehydration ratio (*RR*) was determined. Triplicate measures were done and average value was taken.

Quantitative descriptor analysis (*QDA*) method was used for sensory profiling of dehydrated oyster mushrooms. Organoleptic quality of dried mushrooms was inspected with the help of 10 semi-trained consumer panel of different age group. Descriptors used for sensory analysis were developed during initial sessions in which different samples were presented to the panelists. The panelists were asked to describe the samples with as many spontaneous descriptive terms (viz., colour, flavour, texture, overall acceptability, off flavour etc.) as they found suitable for application. The common descriptors chosen by at least one third of the panel were compiled along with some significant descriptors found in literature were used [8]. Quality attributes were scored using a 9-point Hedonic scale of 1-9 (1= dislike extremely, 9= like extremely), score of 5.5 and above considered as acceptable.

Statistical analyses

The data obtained in the present study was subjected to factorial CRD statistical analysis. The critical difference (C.D.) value at 5% level of probability was compared for making the comparison among different treatments. Drying kinetics and moisture ratio value were plotted against time in the MS Excel (Version, 2007). Sensory values were analyzed statistically and mean value for each descriptor for various treatments is plotted in spider chart using MS Excel. The statistical significance of the terms in the regression equation was examined by analysis of variance (ANOVA) with SATISTICA 12 (StatSoft, Inc., USA).

RESULTS AND DISCUSSION

Drying characteristics of the oyster mushroom

The typical drying curves describe drying characteristics of oyster mushroom at different air temperatures and velocities in fluidized bed dryer are shown in Fig.1 a and b. The initial moisture content of 92.32% (w.b.) of mushroom sample was decreased to final moisture content ranging from 6.1–9.6% (w.b.) with drying time ranging from 150–330 min depending on drying condition used. Drying time was reduced with increase of drying air temperature and velocity. For example oyster mushroom dried at higher air temperature of 65ºC and 5 ms^{-1}air velocity required lowest drying time of 150 min to obtained final moisture content of 6.1% (w.b.) for safe storage. It is evident that drying air temperature and velocity had important effect on moisture movement and reduction in drying time. These results showed inverse relationship between air temperature and drying time are corroborated with findings of drying in milky mushrooms [2] and raw mango slices [11].

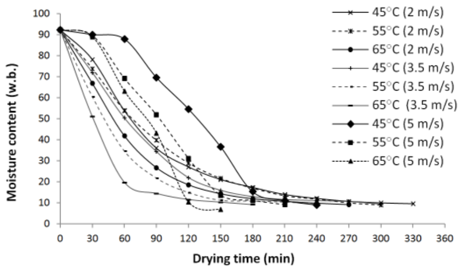

Figure 1(a). Variation in moisture content (w.b.) of oyster mushroom at different air-temperature and air-velocities in fluidized bed dryer

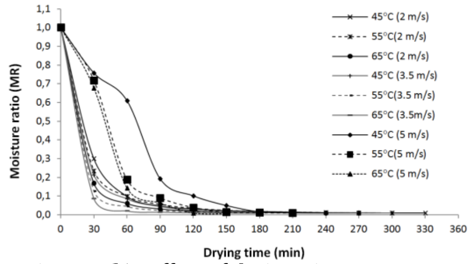

Figure 1(b). Effect of drying air-temperatures and air-velocities on moisture ratio of oyster mushroom

Drying of mushroom for 45, 55 and 65ºC at 2, 3.5 and 5 $m \cdot s^{-1}$ followed falling rate profile. Mushroom dried at 2 $m \cdot s^{-1}$ and 3.5 $m \cdot s^{-1}$ air-velocities, moisture content (w.b.) reduces in two stages i.e. initially at faster rate and then slowly with increase in drying time for different temperatures. However, moisture content (w.b.) of mushroom dried at 5 $m \cdot s^{-1}$ reduces slowly during initial stage, then decreases rapidly and again slowly decreases at the end of process with increase of drying time. Similar decreasing trends of moisture ratio with increase of drying time were observed for all drying treatments. The rate of moisture loss was higher at higher air temperatures and velocities resulted in substantial reduction total drying time with the increase in drying air temperature and velocity. Thus drying curves for all treatments indicated that entire drying process took place in the falling rate period. It is revealed that drying process was mainly controlled by physical diffusion mechanism governing moisture movement in the interior of mushrooms. These findings are consistent with previous studies by various researchers to explain thin layer drying behavior for different perishable fruits and vegetables [3, 9, 16].

$$MR = 0.014297 – 0.000445\ V\ (ms^{-1}) – 0.000034\ T(ºC) – 0.000084 V\ T \qquad (8)$$

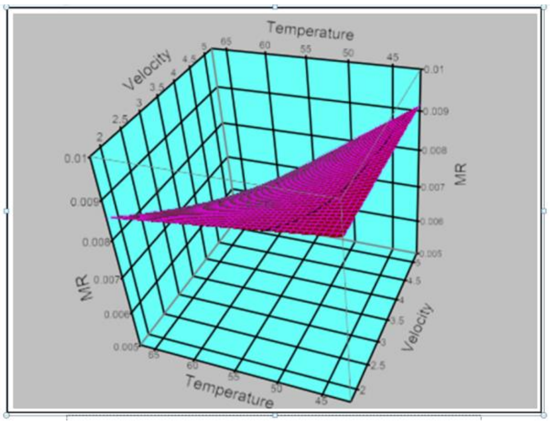

Figure 2. Surface plot showing the influence of drying air-temperature and air-velocity on moisture ratio of oyster mushroom

Drying at high temperature is not recommended due to detrimental effects on food constituents like proteins, vitamins, minerals, color, texture etc. A multiple lineal regression test was carried out using JMP 10.0 (Cary, NC, USA) on moisture ratios for the oyster mushroom resulted in equation (8). Fig. 2 illustrates the combined effect of drying air temperature and velocity evident that drying air temperature (*T*) has significant ($p=0.04$) effect on drying. The lowest moisture ratio of 0.006 was obtained at 65°C and 5 $m \cdot s^{-1}$ velocity with higher desirability of 0.67 and indicating the best quality of dried oyster mushroom.

Evaluation of the mathematical models

The moisture ratio data of oyster mushroom dried at different air temperatures (45, 55 and 65ºC) and velocities (2, 3.5 and 5 $m \cdot s^{-1}$) were fitted into different thin layer drying models listed in Table 1 to evaluate their suitability to describes the drying process in fluidized bed dryer. The summarized results of drying model constants, coefficient of determination (R^2) and statistical parameters calculated from nonlinear regression analysis were presented in the Tab. 2. The higher values of R^2 and lower values of χ^2, *RMSE* and *MBE* were used as selection criteria for best model fit. From Table 2 it was found that R^2values are > 0.93 for Henderson, Newton, Page, and Two-Term exponential models indicating the best fit. It was also observed that Logarithmic model (R^2> 0.99) at 2 and 3.5 $m \cdot s^{-1}$ air-velocity and Wang and Singh model (R^2> 0.95) at 5 $m \cdot s^{-1}$ air-velocity are fitted best for mushroom dried at all drying temperatures. However, Page model gave highest values of R^2 (0.9846 to 0.9999) and lowest values of χ^2 (0.00001 to 0.00255), *RMSE* (0.0031 to 0.0445) and *MBE* (–0. 0005 to 0.0006) for all drying air temperatures and velocities. This model fitted well to the experimental and predicted values of moisture ratio. The linear relationship at 45º slope from the origin between predicted and experimental values of moisture ratio indicated that predicted model is a good fit for the actual drying data (Fig. 3). Hence Page model was suggested as the best model to explain thin layer drying behavior of oyster mushroom under fluidized bed condition. These results are similar with observations of air-drying of bamboo [8] and mango slices [11]. But inferences from this study are different from that of [3] for drying of oyster mushroom in convective hot dryer for which drying kinetics was explained by the Midilli *et al*. model [3].

Table.2. Model coefficients on drying of oyster mushrooms at different temperatures and velocities

Model	Temp. ºC	Velocity (ms^{-1})	Constants and coefficients				R^2	χ^2	RMSE	MBE
Newton/ Lewis			*k*							
	45	2.0	0.0391				0.9977	0.00019	0.0132	0.0100
	55	2.0	0.0448				0.9942	0.00050	0.0213	0.0137
	65	2.0	-0.057				0.9972	0.00027	0.0155	0.0110
	45	3.5	-0.0484				0.9961	0.00034	0.0177	0.0116
	55	3.5	-0.0666				0.9980	0.00022	0.0139	0.0102
	65	3.5	-0.0806				0.9992	0.0001	0.0094	0.0075
	45	5.0	-0.0142				0.9401	0.00868	0.0878	-0.0088
	55	5.0	-0.0212				0.9509	0.00721	0.0794	-0.0061
	65	5.0	-0.0233				0.9430	0.01005	0.0916	-0.0098
Page			*k*	*n*						
	45	2.0	0.0758	0.8192			0.9987	0.00012	0.0100	0.0059
	55	2.0	0.1867	0.6062			0.9997	0.00003	0.0048	0.0020
	65	2.0	0.2518	0.5789			0.9997	0.00003	0.0050	0.0023
	45	3.5	0.1864	0.6241			0.9997	0.00003	0.0049	0.0024
	55	3.5	0.4285	0.5154			0.9998	0.00004	0.0051	0.0017
	65	3.5	0.8369	0.3590			0.9999	0.00001	0.0031	0.0006
	45	5.0	0.0004	1.7829			0.9846	0.00255	0.0445	-0.0005
	55	5.0	0.0003	2.1059			0.9935	0.00112	0.0290	0.0143
	65	5.0	0.0002	2.2233			0.9964	0.00079	0.0229	0.0101

Handerson and Pabis			*a*	*k*						
	45	2.0	0.9979	0.0391			0.9977	0.00021	0.0132	0.0101
	55	2.0	0.9961	0.0447			0.9943	0.00055	0.0213	0.0140
	65	2.0	0.9988	0.0570			0.9972	0.00030	0.0155	0.0111
	45	3.5	0.9973	0.0483			0.9961	0.00038	0.0176	0.0118
	55	3.5	0.9994	0.0666			0.9980	0.00025	0.0139	0.0102
	65	3.5	0.9999	0.0806			0.9992	0.00013	0.0094	0.0075
	45	5.0	1.0707	0.0150			0.9456	0.00900	0.0837	-0.0179
	55	5.0	1.0533	0.0220			0.9505	0.00788	0.0769	-0.0129
	65	5.0	1.0478	0.0241			0.9459	0.01194	0.0892	-0.0183
Logarithmic			*a*	*k*	*c*					
	45	2.0	0.9847	0.0411	0.0148		0.9997	0.00003	0.0049	0.0000
	55	2.0	0.9775	0.0483	0.0206		0.9979	0.00022	0.0127	0.0000
	65	2.0	0.9838	0.0607	0.0157		0.9992	0.00009	0.0081	0.0000
	45	3.5	0.9817	0.0515	0.0169		0.9986	0.00015	0.0105	0.0000
	55	3.5	0.9853	0.0710	0.0145		0.9995	0.00007	0.0067	0.0000
	65	3.5	0.9886	0.0856	0.0114		0.9999	0.00001	0.0020	0.0000
	45	5.0	1.1692	0.0116	-0.1185		0.9597	0.00779	0.0721	0.0000
	55	5.0	0.8479	0.8000	0.1521		0.6120	0.07975	0.2233	0.0000
	65	5.0	1.1467	0.019	-0.1089		0.9576	0.01246	0.0789	0.0000
Two-Term exponential			*a*	*k*						
	45	2.0	0.4434	0.0648			0.9986	0.00013	0.0102	0.0072
	55	2.0	0.3522	0.0958			0.9969	0.00029	0.0155	0.0103
	65	2.0	0.3864	0.1127			0.9983	0.00018	0.0121	0.0089
	45	3.5	0.3605	0.1018			0.9980	0.00020	0.0127	0.0088
	55	3.5	0.4114	0.1246			0.9986	0.00017	0.0116	0.0086
	65	3.5	0.4512	0.1398			0.9994	0.00010	0.0084	0.0066
	45	5.0	0.0015	9.2180			0.9399	0.00996	0.088	-0.0096
	55	5.0	0.0018	12.0147			0.9507	0.00845	0.0796	-0.0065
	65	5.0	0.0018	12.7625			0.9428	0.01262	0.0917	-0.0102
Wang and Singh			*a*	*b*						
	45	2.0	-0.010836	0.000025			0.5215	0.04301	0.1893	-0.0488
	55	2.0	-0.011803	0.00003			0.5327	0.04490	0.1917	-0.0488
	65	2.0	-0.013307	0.000038			0.5256	0.05080	0.2016	-0.0499
	45	3.5	-0.011956	0.000031			0.5056	0.04776	0.1977	-0.0504
	55	3.5	-0.014961	0.000048			0.5667	0.05238	0.2019	-0.0481
	65	3.5	-0.019613	0.000083			0.7073	0.04796	0.1851	-0.0391
	45	5.0	-0.010152	0.000025			0.9732	0.00444	0.0588	0.0058
	55	5.0	-0.013633	0.000044			0.9559	0.00755	0.0753	-0.0015
	65	5.0	-0.01648	0.000066			0.9711	0.00637	0.0652	0.0061
Midilli et al.			*a*	*–k*	*n*	*b*				
	45	2.0	0.406686	0.000000	0.000000	-0.001673	0.4009	0.06732	0.2118	0.0000
	55	2.0	1.000062	-0.161048	0.64808	0.000031	0.9999	0.00001	0.0024	0.0002
	65	2.0	1.000000	-2.756115	1.113188	0.000095	0.9634	0.00523	0.0560	0.0202
	45	3.5	1.000000	-2.470894	0.770042	0.000095	0.9390	0.00758	0.0694	0.0252
	55	3.5	1.000000	-3.009014	1.424586	0.000097	0.9792	0.00352	0.0442	0.0159
	65	3.5	1.000000	-3.23332	1.66698	0.000110	0.9911	0.00244	0.0324	0.0112
	45	5.0	0.972627	-0.00024	1.920892	0.000046	0.9854	0.00339	0.0434	0.0001
	55	5.0	0.956234	0.004363	1.064802	-0.016259	0.9376	0.01604	0.0895	-0.0006
	65	5.0	0.820284	0.0000	0.0000	-0.006716	0.8052	0.08595	0.1693	0.0000

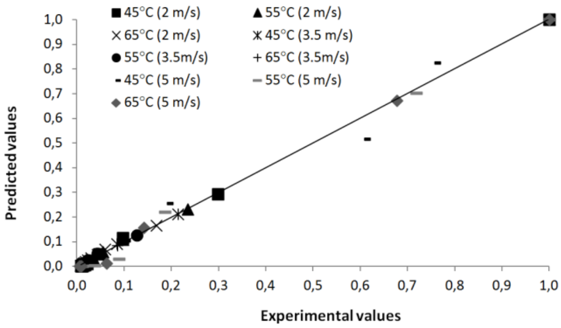

Figure 3. Comparison of experimental and predicted moisture ratio with page model

Computation of effective diffusivity and activation energy

The effective moisture diffusivity (D_{eff}) of oyster mushroom dried at different air temperatures and velocities were computed from the method of gradients of graphs [11]. The straight line relationship between ln (*MR*) versus drying time (*t*) were depicted to determine the values of effective moisture diffusivity by slope of the best fit using Eq. (7). The best-fit regression equations, coefficient of correlation (R^2) and corresponding D_{eff} values for different drying air temperatures and velocities during first and second falling rated drying period are given in Table 3. This table shows drying air temperatures and velocities greatly affected the effective moisture diffusivity of the oyster mushroom. At any given air velocity a rise in drying temperature led to an increase in effective moisture diffusivity. The D_{eff} values obtained at 2 and 3.5 $m \cdot s^{-1}$ air velocities ranged from 7.24×10^{-10}–2.11×10^{-9} and 7.78×10^{-10}–2.89×10^{-9} $m2 \cdot s^{-1}$, increased with air velocity for the first falling rate and almost same for second falling rate for mushroom dried at all air temperatures. At 5 $m \cdot s^{-1}$ air velocity, comparatively lower D_{eff} values of 2.44–4.02 $\times 10^{-9}$ $m2 \cdot s^{-1}$ were found as drying process exhibited in single falling rate. This is attributed to the heat energy transferred at lower rate to oyster mushroom for higher air velocity as result of higher turbulent flow created under fluidized bed condition [10]. Also all these D_{eff} values are found within the range of 10^{-9}–10^{-10} $m^2 \cdot s^{-1}$ as similar to previous report for most food, fruits and vegetable materials. Many studies performed on different perishable fruits and vegetables under similar drying air temperature and velocity conditions showed D_{eff} values to lie between 2.05–7.80×10^{-9} $m^2 \cdot s^{-1}$ for kachkal banana peel [9], 2.62–$4.39 \times 10^{-10} m^2 \cdot s^{-1}$ for raw mango slices [11] and 6.59– 1.93×10^{-10} $m^2 \cdot s^{-1}$ for spinach [16].

Table.3. Comparison of effective moisture diffusivity equation,
R^2 and D_{eff} values for oyster mushroom at different temperatures and velocities

Temp. (ºC)	Velocity (ms^{-1})	1st falling rate			2nd falling rate		
		Equations	R^2	Deff ($\times 10^{-9}$)	Equations	R^2	Deff ($\times 10^{-10}$)
45	2.0	$y = -0.0195x - 0.7307$	0.9020	2.11	$y = -0.0036x - 3.5932$	0.9482	3.89
55	2.0	$y = -0.0240x - 0.5031$	0.9361	2.59	$y = -0.0059x - 3.0521$	0.9768	6.38
65	2.0	$y = -0.0384x - 0.2963$	0.9549	4.15	$y = -0.0067x - 3.1150$	0.8986	7.24
45	3.5	$y = -0.0267x - 0.5062$	0.9468	2.89	$y = -0.0036x - 3.6883$	0.9231	3.89
55	3.5	$y = -0.0412x - 0.3830$	0.9365	4.45	$y = -0.0058x - 3.4626$	0.8089	6.27
65	3.5	$y = -0.0648x - 0.1674$	0.9782	7.00	$y = -0.0072x - 3.5540$	0.9434	7.78
45	5.0	$y = -0.0226x + 0.3510$	0.9747	2.44	-	-	-
55	5.0	$y = -0.0252x - 0.0288$	0.9655	2.72	-	-	-
65	5.0	$y = -0.0372x + 0.3154$	0.9724	4.02	-	-	-

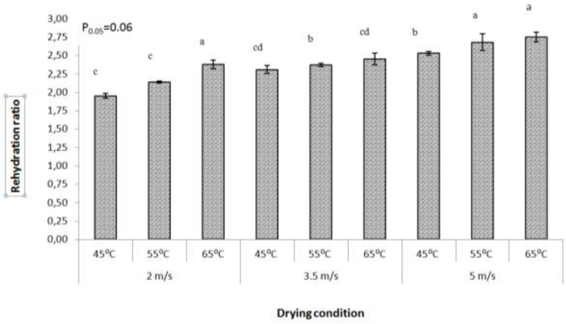

Figure 4. Effect of different air temperatures and velocity
on rehydration ratio of oyster mushroom

Activation energy (E_a) of 30.17 and 39.17 kJ·mol^{-1} during initial stage were higher as compared to later stage, which were 27.91and 31.07 kJ·mol^{-1} for different drying temperature (45, 55 and 65º C) at 2 and 3.5 m·s^{-1} air velocities, respectively. Mushroom dried at different temperatures for 5 m·s^{-1} gave minimum value 22.15 kJ·mol^{-1} of activation energy to detach and move the water during the drying process. These activation energy values of oyster mushroom lie in the range of activation energy for mulberry (21.2 kJ·mol^{-1}) and grapes (40.14 kJ·mol^{-1}) [1, 14]. Similarly lesser activation energy requirement for drying at higher air velocities was observed for garlic sheets under semi-fluidized/fluidized bed condition [10] at different air-temperature.

Rehydration ratio

The rehydration characteristics of dried products are widely used as the quality index. It is evident from Fig. 4 that rehydration ratio was increased under high air temperature coupled with high air velocity and it was relatively poor with low temperature and slow air velocity. The rehydration ratio (RR) values ranged between 1.95-2.75. A highest value of *RR* (2.75) was obtained with 65ºC and 5.0 m·s^{-1} indicating the superior quality of mushroom. In practice, most changes caused by pre-drying and drying treatments are irreversible, and rehydration cannot be considered as simply as a process reversible to dehydration [8]. Higher rehydration displayed by high temperature might be due to the faster drying process that cause less cellular and structural changes in the final product while, the poor rehydration ratio poor in low temperature was due to longer time for drying, poor texture of the product caused by poor RH maintenance and fluctuation in air flow.

Sensory quality of dried mushroom

Acceptability of dehydrated products by the consumer is highly dependent on its sensory attributes. In addition, to visual appearance, colour, flavour and textural attributes are critical in determining their degree of acceptance. It was observed that 65°C with the air velocity of 5 m•s^{-1} recorded highest scores for almost all sensory quality parameters at the end of drying (Fig. 5). Mushroom colour changed from creamy whitish to yellow is preferred as the best quality and it was obtained when mushroom was dried at 65ºC and 5 m•s^{-1} during fluidized condition. However, the colour turned brown with higher temperatures and lower air velocity drying condition. Off flavor was due to over burning at higher temperature and lower velocity condition. The best colour of the dried product might be due to faster drying of mushroom under such an environment as described by [8] on different fruits.

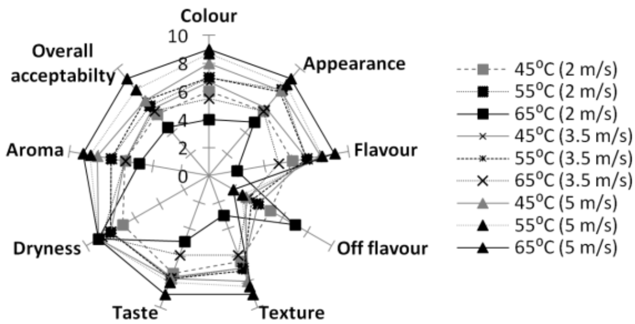

Figure 6. Quantitative descriptor analysis of oyster mushroom at variable air temperature and velocity

Texture of dried samples as revealed by scores of dryness was better with the same drying condition. Rapid and controlled loss of moisture, maintained the cell structure due to uniform heat transfer (65ºC) with the accelerated air velocity (5 $m \cdot s^{-1}$) which could be a probable factor for contributing high texture scores. Similarly, all other positively contributing sensory characteristics like flavor, aroma, after taste and over all acceptability of dried mushroom were also scored higher in high temperature with more air velocity. Off-flavor is mainly attributed to presence of phenolic compounds, degradation of quality components like sugar, acid and carotenes which might have got oxidized during drying [8].

CONCLUSIONS

From the study it was concluded that drying time reduced with the increase of drying air temperatures and velocities. The entire drying process of oyster mushroom occurred in the falling rate period. The mushroom dried at 65ºC and 5 $m \cdot s^{-1}$ was dried faster and gave the best quality in term of colour, texture, flavour and comparatively less shrinkage along with better rehydration ratio. Among the all models considered for this study; Page model explained drying process better than all other tested models. The effective moisture diffusivity ranged from $7.78 \cdot 10^{-10}$ to $2.11 \cdot 10^{-9}$ $m^2 \cdot s^{-1}$ with higher values at higher drying temperature for any given velocity. In addition, drying at 5 $m \cdot s^{-1}$ air velocity required minimum activation energy of 22.15 $kJ \cdot mol^{-1}$ to detach and move the water during the drying process by diffusion. The finding of this study will be helpful to optimize the drying process for oyster mushroom under fluidized bed heating system and would provide processing parameters for up scaling the oyster mushroom drying process and efficient utilization of dehydration systems.

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POREĐENJE MATEMATIČKIH MODELA I KINETIKE SUŠENJA BUKOVAČE (*PLEUROTUS SPP*) U TANKOM FLUIDIZOVANOM SLOJU SA UBRZANOM TEMPERATUROM I BRZINOM VAZDUHA

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Sažetak: Ispitivan je uticaj temperature i brzine vazduha na karakteristike sušenja tankog fluidizovanog sloja bukovače (*Pleurotus spp*.). Pečurke su sušene na tri temperature vazduha 45, 55 i 65ºC, kombinovane sa brzinama vazduha od 2, 3.5 i 5 ms^{-1}. Trajanje dehidracije pečurki se smanjivalo i temperatura je imala značajan (P=0.04) uticaj na sušenje. U regresionom modelu, najbolji kvalitet sušene bukovače postignut je pri temperaturi od 65°C i brzini vazduha od 5 ms^{-1}, a ocenjen je prema senzornim karakteristikama: boja, hrskava tekstura, ukus i komparativno manje kalo. Za određivanje kinetike sušenja, eksperimentalne vrednosti vlažnosti su poređene sa sedam modela sušenja tankog sloja. Među analiziranim modelima, Page model je najbolje opisivao tok sušenja bukovače. Pri svakoj brzini vazduha, povećanje temperature dovelo je do povećanja efektivne difuzivnosti vlage u interval od 7.78×10^{-10} do 2.11×10^{-9} m^2s^{-1}. Sušenje strujom vazduha brzine 5 ms^{-1} zahtevalo je minimalnu energiju aktivacije od 22.15 KJ mol^{-1} za odstranjivanje vode difuzijom tokom sušenja. Odnosi rehidracije (RR) (1.95-2.75) povećali su se sa povećanjem temperature i brzine vazduha. Dobijeni rezultati se mogu koristiti za pravljenje odgovarajućih konstrukcija i operacija industrijskih sistema sušenja gljiva radi dalje prerade i dobijanja prozvoda veće vrednosti.

Ključne reči*: bukovača, kinetika sušenja, efektivna difuznost, suušč fluidiziranog sloja, odnos vlažnosti, senzorne karakteristike*

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