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RESEARCH PAPER

Mathematical modelling of osmo-convective dehydration of button mushroom *(Agaricus bisporus)* slices

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SUMMARY : The drying characteristics of mushroom slices were investigated in an experimental axial flow dryer and modelled at various air temperatures of 45, 55, 65, 75 and 85°C and velocity of air such as 1.0, 1.5 and 2.0 m/s. The entire drying process took place in the falling rate period. The average effective moisture diffusivity $(D_{eff})_{avg}$ values of osmo-convectively dried mushroom samples varied considerably with moisture content and air drying temperature from 1.392 x 10^{-9} to 4.671 x 10^{-9}, 1.435 x 10^{-9} to 4.814 x 10^{-9} and 1.570 x 10^{-9} to 4.919 x 10^{-9} m^2/s for air velocity of 1.0, 1.5 and 2.0 m/s, respectively. The six thin-layer drying models Exponential, Henderson and Pabis, Page, Modified page, Logarithmic and Power law models were applied and validated on the basis of determination of coefficient (R^2), reduced mean square (χ^2) of the deviation, and root mean square error (E_{RMS}) between the observed and predicted values of moisture ratios. Page model was found to be the most satisfactory than the other models.

Key Words : Mushroom, Osmo-convective, Diffusivity, Moisture ratio, Modelling

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Today, mushroom cultivation is one of the biggest money spinning enterprises in the world and mushroom is an important horticultural cash crop. Its production has tremendous scope as an income generating activity. Mushroom being an indoor crop does not require arable land, except for some non-agricultural land to build infrastructure for preparation of substrate, raising of crop, preparation of spawn and post harvest handling, hence, it is of great importance for landless and marginal farmers. But post-harvest problems of mushroom arise due to its high moisture content (*i.e.* about 90 per cent) and respiration at a very fast rate. This accelerates deteriorative changes, with the result product becomes high perishable with the shelf life of 1-2 days only under ambient temperature and humidity (Lal Kaushal and Sharma, 1995). Loss of texture, development of off flavour and discolouration results in poor marketable quality and restricts trade of fresh mushrooms. Besides they grow in flushes and every 8-10 days, they are harvested in batches. In between the flushes, the production comes down quite low. The demand, therefore, never coincides with supply. In the peak period of harvesting due to the gluts in the market, owing to highly perishable nature, ensuring income security to farmers and bring nutritional security, its preservation in the form of more stable products is of great importance.

For these reasons, several dehydration methods or combinations of methods can be used including osmo-convective drying, microwave drying, solar drying, hot-air, freeze drying, osmotic dehydration, spray drying, impregnation vacuum, etc. Among these, application of osmo-convective drying for vegetables improves the quality of final product (dried vegetables). Hence, osmotic dehydration is used as a

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pre-treatment before hot-air drying of mushrooms (Shukla and Singh, 2007 and Dehkordi, 2010) because it has the advantage of improving nutritional, sensorial and functional aspects of foods, without changing its colour, texture and aroma. Besides, the osmotic dehydration minimizes the thermal damage on colour, flavour and prevents enzymatic browning that is the main critical factor on the quality of mushrooms.

Keeping all above mentioned points in view, the thin layer drying behaviour of mushroom slices in an osmo-convective drying has been investigated and various drying models have been validated.

EXPERIMENTAL METHODS

Mushroom of *Agaricus bisporus* variety, having about (89-91 per cent) moisture content (wb), was procured on daily basis from All India Co-ordinated Research Project on Mushroom, Rajasthan College of Agriculture, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan. Freshly harvested, firm, dazzling white, mature mushrooms of uniform size were manually sorted and medium sized were selected as the raw material for all the experiments. They were thoroughly washed under tap water to remove adhering impurities. They were then pat dried on a blotting paper, and then cut into 5±0.5 mm thick slices with the help of sharp stainless steel knife. The brine solution of desired concentration was prepared by dissolving the required quantity of salt (w/v) in tap water.

In the process of osmotic dehydration, a sample was placed in the hypertonic solution and due to concentration difference water comes out from sample to solution. Simultaneously transports of solids take place from solution to sample and vice versa. The mass transport in terms of water loss, mass reduction and solid gain were studied. Osmotically dehydrated product, generally, may not have moisture content low enough to be considered as shelf stable. It is therefore, needed it to be further air dried to obtain a shelf stable product *i.e.* stable with respect to prevention of microbial growth and enzymatic colour changes (Islam and Flink, 1982). Hence, the product obtained from the optimized levels of the osmotic dehydration was then air-dried in axial flow dryer at various air temperatures of 45, 55, 65, 75 and 85°C and velocity of air such as 1.0, 1.5 and 2.0 m/s.

Theoretical consideration:

Mathematical modelling of drying curves:

The moisture ratio of mushroom slices during convective drying experiment was calculated using the following equation:

$$MR = \frac{M - M_e}{M_0 - M_e}$$

where, MR is moisture ratio (dimensionless), M is moisture content (g water per g dry matter) at specified time, M_0 is initial moisture content (g H_2O/g dry matter) and M_e is equilibrium moisture content (g H_2O/g dry matter).

Six thin layer drying equations listed in Table 1 were tested to select the best model to describe convective drying of mushroom slices. Modelling of drying behaviour of different agricultural products often requires the statistical methods of regression and correlation analysis. Linear and non-linear regression models are important tools to find the relationships between different variables, especially, those for which no established empirical relationship exists. In this study, the relationships of the constants of the best suitable model with the various drying temperature and air velocity levels were also determined.

The regression analysis was performed using SYSTAT-8.0 software. The coefficient of determination (R^2) was primary criterion for selecting the best equation to describe the drying model. In addition to this, the goodness of fit was determined by reduced mean square of the deviation (χ^2) and root mean square error (E_{RMS}). For quality fit, R^2 value should be higher and close to one and ÷² *and* E_{RMS} values should be low (Erketin *et al.*, 2004). The above parameters were calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(M_{R,exp,i} - M_{R,pre,i}\right)^2}{N - z}$$

$$E_{RMS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{R,pre,i} - M_{R,exp,i}\right)^2\right]^{1/2}$$

where, $M_{R,exp,i}$ and $M_{R,pre,i}$ are the experimental and predicted dimensionless moisture ratios, respectively; N is the number of observations and z is the number of drying constants.

Table A : Mathematical models used under drying study

Model equation	Name	Reference
$MR = \exp(-kt)$	Exponential	Liu and Bakker-Arkema (1997)
$MR = \exp(-kt^n)$	Page	Zhang and Litchfield (1991)
$MR = \exp(-kt)^n$	Modified page	Overhult *et al.* (1973)
$MR = a\exp(-kt)$	Henderson and Pabis	Henderson and Pabis (1961)
$MR = At^B$	Power law	Chandra and Singh (1995)
$MR = a + b\ln(t)$	Logarithmic	Chandra and Singh (1995)

Moisture diffusivity:

In drying, diffusivity is used to indicate the rapidness of flow of moisture or moisture out of material. In falling rate period of drying, moisture is transferred mainly by molecular diffusion. Diffusivity is influenced by shrinkage, case hardening during drying, moisture content and temperature of material (Karim and Hawaldar, 2005).

The falling rate period in drying of biological materials is best described by simplified mathematical Fick's second law diffusion as given below.

$$\frac{\delta M}{\delta t} = D\frac{\delta^2 M}{\delta X^2} \quad (4)$$

where, D=Diffusion coefficient, M=Moisture content, g water per g dry matter, X=Characteristic dimension *i.e.* distance of surface from the centre line of product and t=Time elapsed during the drying.

The solution of Fick's model as proposed by Crank (1975) is

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[\frac{-(2n+1)^2\pi^2 D_{eff} t}{L^2}\right] \quad (5)$$

where, D_{eff} = Effective diffusivity in m^2/s, L = Characteristic dimension *i.e.* thickness of slab and t = Time elapsed during the drying (s).

The equation can be simplified by neglecting second and other terms. So equation reduced to

$$MR = \left(\frac{M - M_e}{M_0 - M_e}\right) = \frac{8}{\pi^2}\exp\left(-\pi^2\frac{D_{eff}\, t}{L^2}\right) \quad (6)$$

Taking logarithm and rearranging the equation (6) as

$$\ln[MR] = \ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \ln\frac{8}{\pi^2} - \left(\frac{\pi^2 D_{eff} t}{L^2}\right) \quad (7)$$

$$\ln[MR] = -0.21 - \left(\frac{\pi^2 D_{eff} t}{L^2}\right) \quad (8)$$

A general form of above eq^n could be written in semi-logarithmic form, as follows

$$\ln(MR) = A - Bt \quad (9)$$

where, A is constant and B is slope. Experimental values of the effective diffusivity are calculated by plotting experimental drying data in terms of ln(*MR*) versus drying time *t*. It gives a straight line and the slope of the line would be used to measure the moisture diffusivity.

EXPERIMENTAL FINDINGS AND ANALYSIS

The results of the present study as well as relevant discussions have been presented under following sub heads:

Mathematical modelling under study:

To determine the most suitable drying equation, the moisture ratio data of osmosed mushroom sample dried at various air temperatures and velocity of air were fitted into the six thin-layer drying models (Exponential, Henderson and Pabis, Page, Modified page, Logarithmic and Power law) in their linearized form using regression technique. Among all these models, the best model suitable to fit the data were selected on basis of highest values of R^2 and the lowest value of reduced mean square of the deviation (χ^2) and root mean square error (E_{RMS}) which were calculated by using Eqn. (2) and Eqn.(3).

The overall statistical parameters for different models used for osmo-convective dried mushroom samples have been presented in Table 2. It was observed that in all models the values of R^2 were greater than 0.95 indicating a good fit except for power law model. The values of coefficient of determination (R^2) for Page model at all levels of temperatures and velocity of air were greater than 0.994 *i.e.* in the range of 0.995 to 0.997 and the values of root mean square error (E_{RMS}) and reduced mean square of the deviation (χ^2) were in range 0.016 to 0.020 and 0.0004 to 0.0005, respectively which were lower than the rest of other five models (Exponential, Logarithmic, Page, Modified page and Power law). The details are presented in Table 2. Hence, Page model was found to be the most satisfactory than the other models to represent the thin-layer drying of mushroom samples. This was another confirmation of the suitability of Page model to thin layer drying, which has been reported by Kar and Gupta (2001) and Giri and Prasad (2007) for air drying of mushroom.

The selected Page model for osmo-convective drying studies was validated by comparing the predicted and observed values of moisture ratio in all drying experiment. The predicted and observed values of moisture ratio were plotted as shown in Fig. 1 (Erketin, *et al*., 2004) for all drying air velocities.

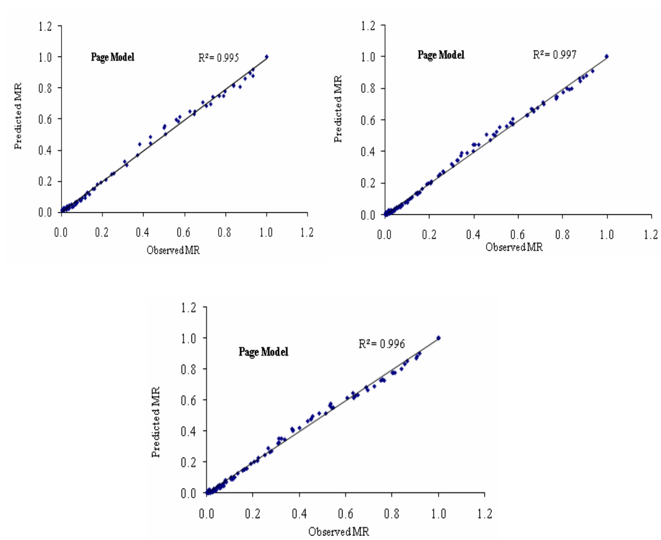

Fig.1 : Experimental and predicted values of moisture ratio by Page model for 1.0, 1.5 and 2.0m/s air velocity and at various temperatures, respectively

Moisture diffusivity during convective drying of osmotically dehydrated sample:

The experimental D_{eff} values during convective drying of

Table 1 : Overall values for model constants and statistical parameters used in convective drying of osmotically dehydrated mushroom sample

Name of Model	Drying constant					Statistical parameters		
	Air velocity, m/s	k	n	a	b	R^2	χ^2	E_{RMS}
Exponential	1.0	0.018	-	-	-	0.987	0.0012	0.031
$MR = \exp(-kt)$	1.5	0.022	-	-	-	0.988	0.0011	0.030
	2.0	0.025	-	-	-	0.990	0.0011	0.028
Page	1.0	0.030	0.853	-	-	0.996	0.0004	0.018
$MR = \exp(-kt^n)$	1.5	0.038	0.844	-	-	0.997	0.0003	0.016
	2.0	0.038	0.876	-	-	0.995	0.0004	0.020
Modified page	1.0	0.017	0.853	-	-	0.996	0.0004	0.018
$MR = \exp(-kt)^n$	1.5	0.022	0.844	-	-	0.997	0.0005	0.020
	2.0	0.025	0.876	-	-	0.995	0.0005	0.020
Henderson and Pebis	1.0	0.017	-	0.948	-	0.990	0.0009	0.028
$MR = a\exp(-kt)$	1.5	0.020	-	0.941	-	0.992	0.0008	0.029
	2.0	0.024	-	0.963	-	0.992	0.0010	0.027
Power law	1.0	-	-	2.682	-0.537	0.885	0.0576	0.226
$MR = At^B$	1.5	-	-	2.689	-0.567	0.897	0.0588	0.231
	2.0	-	-	2.738	-0.591	0.902	0.0626	0.235
Logarithmic	1.0	-	-	1.191	-0.199	0.958	0.0050	0.067
$MR = a + b\ln(t)$	1.5	-	-	1.221	-0.211	0.966	0.0052	0.070
	2.0	-	-	1.201	-0.212	0.956	0.0060	0.074

osmotically dehydrated mushroom samples were obtained by the modified method of slopes. The average effective moisture diffusivity $(D_{eff})_{avg}$ values of osmo-convectively dried mushroom samples varied considerably with moisture content and air drying temperature from 1.392 x 10^{-9} to 4.671 x 10^{-9}, 1.435 x 10^{-9} to 4.814 x 10^{-9} and 1.570 x 10^{-9} to 4.919 x 10^{-9} m^2/s for air velocity of 1.0, 1.5 and 2.0 m/s, respectively (Table2). These values are within the general range of 10^{-8} to 10^{-12} m^2/s for drying of food materials (Mcminn and Magee, 1999). These values are in fact consistent with those existing in literature e.g. 2.32 x 10^{-10} to 2.76 x 10^{-9} for hot air drying mulberry (Maskan and Gogus, 1998); 1.104 x 10^{-9} to 5.045x$10^{-9}$$m^2/s$ for fluid bed drying of osmotically dehydrated button mushroom slices (Murumkar *et al.*, 2006) etc.

Based on the diffusivity values presented in Table 2, the data were statistically analysed to develop a semi empirical equation demonstrating the relationship between moisture diffusivity and other related process parameters using the regression technique. The proposed mathematical relationship is as follows:

$$(D_{eff})_{avg} = 6.0394 \times 10^{-13} \times T^{2.006} \times V^{0.191}$$

$R^2 = 0.96$

where, $(D_{eff})_{avg}$ =average effective moisture diffusivity, m^2/s,T= temperature, K and V=drying air velocity, m/s

The diffusivity values calculated by the Eqn (10) are also shown in Table 2 as predicted values. The above expression shows that the drying air temperature has a pronounced influence on the moisture diffusivity, whereas, the effect of air velocity was very limited as indicated by its predicted values Table (2). The average effective diffusivity during the convective drying of osmotically dehydrated mushroom samples at various air temperatures and velocities as determined experimentally (Table 2) and predicted by Eqn. (10) are shown

Table 2 : Moisture diffusivity in air drying of osmotically dehydrated samples

Sr. No.	Temperature of drying (^{0}C)	Air velocity, m/s	Diffusivity coefficient, $(D_{eff})_{avg}$ x 10^{-9}, m^2/s	Predicted diffusivity coefficient x 10^{-9}, m^2/s
1.	45	1.0	1.392	1.251
2.	45	1.5	1.435	1.352
3.	45	2.0	1.570	1.428
4.	55	1.0	1.613	1.871
5.	55	1.5	1.682	2.022
6.	55	2.0	1.837	2.136
7.	65	1.0	2.793	2.616
8.	65	1.5	2.870	2.827
9.	65	2.0	3.161	2.986
10.	75	1.0	3.391	3.486
11.	75	1.5	3.966	3.767
12.	75	2.0	4.339	3.979
13.	85	1.0	4.671	4.481
14.	85	1.5	4.814	4.842
15.	85	2.0	4.919	5.115

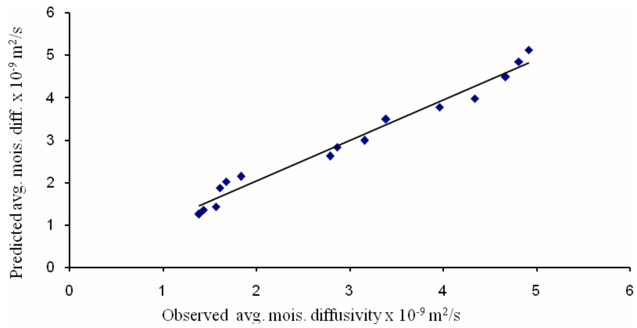

Fig. 2 : Experimental and predicted values of moisture diffusivities

in Fig. 2. It can be seen from the figure that there is a good co-relation between the observed and the predicted values of water diffusivities with $R^2 = 0.98$.

Conclusion:

Convective drying of mushroom slices occurred in the falling rate period and no constant rate period of drying was observed. Page model was found to be the most suitable for describing drying of mushroom slices with R^2 of 0.996, χ^2 of 0.0004 and E_{RMS} of 0.018. The effective moisture diffusivities values increased with both parameters *i.e.* drying air temperature and air velocity.

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