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Microwave Drying of Sprouted Horse Gram (*Macrotyloma Uniflorum*): Mathematical Modeling of Drying Kinetics

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Abstract

In the present investigation, sprouted horse gram seeds were dried at five different levels (180–900 W) in order to study the effect of microwave power output on certain parameters such as moisture content, moisture ratio, drying rate, drying time and effective moisture diffusivity. As the microwave output power increased, drying time decreased significantly. For studying the drying kinetic parameters, the semi empirical Midilli et al., model was found to be beneficial and it described the drying kinetics very well with $R^2 > 0.999$*. Effective moisture diffusivity and drying rate increased as the microwave power output increased. Effective moisture diffusivity were in the range of* 1.42×10^{-10} m^2/s *to* 5.74×10^{-10} m^2/s*. Modified Arrhenius type equation of exponential type was used to calculate the Activation energy and was found to be 15.3* $W.g^{-1}$*.*

Keywords: Sprouted horse gram, microwave drying, thinly layer models, effective moisture diffusivity, activation energy.

Introduction

Legumes are the essential source of nutrients which are a part of human consumption finding increased benefit as protein and balanced energy[1]. Horse gram (*Macrotyloma uniflorum* L.) which is a member of Fabaceae, is one such legume used as a staple food in different parts of the world. It is adaptable and grown mainly in, dry, hot and tropical regions during the post-rainy seasons and grows mainly on marginal soils[2]. Horse gram is considered as a food with medicinal properties from ancient times in ayurvedic treatments. Although rich in proteins nutrients, due to less acceptable taste and flavor of cooked products, it is consumed only by low-income groups[3-5].Consumption of sprouted seeds is concentrated much in the recent days as it serves as a good source of maintaining people's health, conscious with diet. The seeds and sprouts of various pulses have lots of nutritional values and they lower the risk of many diseases and influences health promoting effects. But sprouts have high moisture content and easily perishable. For longer term usage it needs to be dehydrated and stored.

One amongst the oldest and a very important unit operation process of preservation is drying for food products having high moisture content, involving simultaneous heat and mass transfer [6-9]. Sustainable reduction in the total weight and volume after drying reduces the packing, stocking transportation costs[10]. Along with the alteration in the moisture content, drying brings about changes in physical, chemical and biological and properties of the food such as activity of enzymes, microbial spoilage, viscidness, stiffness, fragrance, flavor and taste[11]. Hot air drying and sun drying are the conventional drying methods which are widely used in the post harvest process of agricultural materials. Slow drying rate during the falling rate period of drying is the main disadvantage for hot air drying[12]. The thermal degradation of the dehydrated products happens due to long drying times and consumes more energy. In case of sun drying, disadvantages are: contamination with dust, insects etc. in drying environment, extremely weather dependent and longer drying time[13]. Microwave drying has many advantages over hot air drying as it is possible to achieve high energy efficiency and drying rates, good product quality, proficient space utilization and better quality dried products. Microwave drying is the result of water molecules present in the food materials. This rapid internal energy generation inside the food material increases the pressure and results in rapid evaporation of water[12,14-17]. Many studies have been carried out by researchers to examine the microwave drying kinetics of agricultural materials. For example, parsley[18], Potato[19],Cabbage[20], Mushroom[21], carrot[22], garlic[23], pumpkin[24], spinach[13], okra[16], Bamboo[25] ,basil[26] ,purslane[27] ,celery leaves[28], white mulberry [29] , mango ginger[30], Elephant foot yam[31].

Mathematical modeling serves to be a most effective way to know the depth of drying in post-harvest processing of agricultural materials. Numerous mathematical equations can be found in literatures that describe drying phenomena of agricultural products. Thin layer drying models has extensive application due to its simplicity of use[32-34].

The objective of this study was to examine the outcome of different microwave power on dying aspects of horse gram sprouts, to choose the best fit amongst various thin layer drying models, to describe the moisture removal behavior in microwave drying and to estimate the effective moisture diffusivity and the activation energy.

Material and Methods

Experimental material: Horse gram seeds were bought from Chikkasandra market, Bangalore, India. The seeds were separated from unwanted materials manually and soaked in distilled water (1:10) for 24 h. After soaking the seeds were rinsed and drained the water. Then the seeds were transferred on to the muslin cloth and tied the cloth in to a bundle. The bundle was placed in a closed container and left for 24 h. Sprouted seeds were put in storage at below 5±1°C in refrigerator until used for further processing. Three 50 g of sprouted horse gram seeds were dried in hot air oven (Neha scientific international, Model no.SI 101A) at 105°C for 24 hr to find out initial moisture content which is written on dry basis (kg H_2O.kg db^{-1}). An average initial moisture content of 1.374 kg H_2O.kg db^{-1} was obtained. Using Vernier calipers the average thickness of the seeds was found to be 0.568 mm.

Drying methodology: Domestic digital microwave oven (LG, India; Model MC-8087ABR) was used to carry out drying experiments. 5 different microwave power outputs of about 180, 360, 540, 720 and 900 Watts were chosen to carry out the drying experiments. Digital control on the microwave oven was used to regulate the processing time and power levels. 25g of germinated horse gram seeds were arranged in thin layers on petri plates placed on to a rotatable plate delivers equal scattering of radiations which is inbuilt inside the microwave cabin. The drying experiments were carried out at single microwave power output at a time. A digital weighing balance (CAS; Model MW-11-200 series) of accuracy 0.01 g was used to record early and later weight loss at steady intervals of time. The experiment was carried out until the moisture content reduced by 90-92% of the initial value. The whole experiment was conducted in triplicates and average values were reported.

Mathematical modeling of drying kinetics: The experimental data of dimensionless moisture ratio vs drying time were fitted to 8 different thin layer drying models. They are widely used by many researchers and are represented in table-1. The following equations were used to calculate dimensionless moisture ratio and drying rate of germinated horse gram seeds.

$$MR = \frac{X_t - X_e}{X_0 - X_e} \quad (1)$$

$$\text{Rate of drying} = \frac{dX}{dt} = \frac{X_{t+dt} - X_t}{dt} \quad (2)$$

Where X_o is the initial moisture content, X_t is the moisture content at time t and X_e is the equilibrium moisture content[11,35], X_{t+dt} is the moisture content at time t+dt and X_t is the moisture content at time t is the drying time[11].The Equilibrium moisture content (X_e) is assumed to be zero as X_e is relatively small compared to X_o and X_t for long drying time[19,36,37] and equation-1 can be further simplified to MR= X_t/X_o .

Calculation of effective moisture diffusivity: Fick's second law (equation-3) is considered to be a unidirectional diffusion equation and can be used to understand the effective moisture diffusivity for a variety of regularly shaped bodies such as spherical, cylindrical and rectangular products.

$$\frac{\partial X}{\partial t} = D_{eff} \cdot \frac{\partial^2 X}{\partial z^2} \quad (3)$$

Where X is the moisture content (kg.water.kg db^{-1}), t is the time (s), z is the diffusion path (m), D_{eff} is the moisture dependent diffusivity (m^2/s)[24,34,37]. Liquid diffusion is the only physical mechanism which involves the transfer water from the bulk of the material to surface to be evaporated. Drying phenomenon of biological products takes place in the falling rate period after a short heating period[11,38]. Analytical solution to Fick's second law was developed by Crank and following assumptions were made in arriving the solution: uniform distribution of initial moisture throughout the sample, negligible internal resistance to mass transfer, moisture transport/mass transfer by diffusion mechanism, Constant diffusion coefficient, negligible product shrinkage during drying, the sample's surface moisture content instantly reaches equilibrium with the condition of surrounding air[11,39]. Appropriate initial and boundary conditions for solving above equation are given below[33,34].

$t = 0,\ 0 < z < L,\ X = X_o$

$t > 0,\ z = 0,\ dX/dt = 0$

$t > 0,\ z = L,\ X = X_e$

Table-1
Thin layer mathematical drying models selected for drying studies

Models	Equation	References
1. Page Model	$MR=\exp(-kt^n)$	39
2. Lewis model	$MR=\exp(-kt)$	38
3. Midilli et.al model	$MR=a\exp(-kt^n)+bt$	32
4. Handerson and Pabis	$MR=a\exp(-kt)$	35
5. Modified Page-I	$MR=\exp(-kt)^n$	24
6. Logarthamic	$MR=a\exp(-kt)+c$	42
7. Diffusion approximation	$MR=a\exp(-kt)+(1-a)\exp(-bkt)$	35
8. Thompson Model	$t = a\ .\ln MR + b\ .\ (\ln MR)^2$	30

The solution of the equation for infinite slab of thickness of 2L is:

$$MR = \frac{X_t - X_e}{X_o - X_e} = \frac{8}{\pi}\sum_{n=0}^{\infty}\frac{1}{(2n+1)}.\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}}{4L^2}t\right) \quad (4)$$

For long drying period, it can be further simplified to only the first term of the series[40].

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

Equation-5 can be simplified to a straight line equation as shown below:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{eff}.\pi^2}{4L^2}t\right) \quad (6)$$

Effective moisture diffusivity was found from the slope ($\pi^2 D_{eff}/4L^2$) of the graph showing experimental drying data in terms of ln(MR) vs drying time.

Statistical analysis: The regression analysis of the models were done using Nonlinear Least square method using the SOLVER tool based on the Generalized Reduced Gradient (GRG) method of iteration available in Microsoft Excel (Microsoft Office 2010, USA). For evaluating the goodness of fit, four statistical parameters such as residual sum square (RSS), root mean square error (RMSE), chi square (χ^2), were used as primary criterion in addition to coefficient of determination (R2)". Statistical parameters can be calculated using following mathematical equations.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N}(\overline{MR}_{pre,i} - MR_{exp,i})^2} \quad (7)$$

$$RSS = \sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2 \quad (8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N}} \quad (9)$$

$$\chi^2 = \frac{1}{N-p}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2 \quad (10)$$

Where N is the total number of observations, p is number of factors in the mathematical model, $MR_{exp,I}$ and $MR_{pre,i}$are the experimental and predicted moisture ratio at any observation[5].

Results and Discussion

Effect of Microwave Power on Drying Kinetics: The effect of microwave power output on moisture content, drying rate, drying time, effective moisture diffusivity during the microwave drying of sprouted horse gram were studied by using five different microwave powers (180-900 W). Drying curves illustrating the variation of moisture content with drying time is given in figure-1.

As the microwave power increases the drying time also decreases significantly and reduces the initial moisture content by 90%. The microwave drying process takes 20 to 55 min depends upon the microwave power output. Initially drying rate was very high and the moisture content reduced by 50% by consuming 25-30% of the total drying time. Drying rate vs drying time at various microwave power is illustrated in Figure-2.

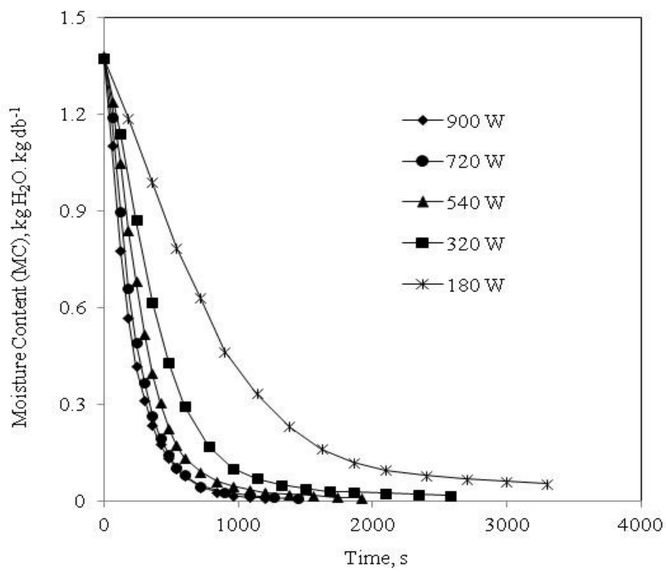

Figure-1
Moisture ratio vs. drying time at various microwave powers

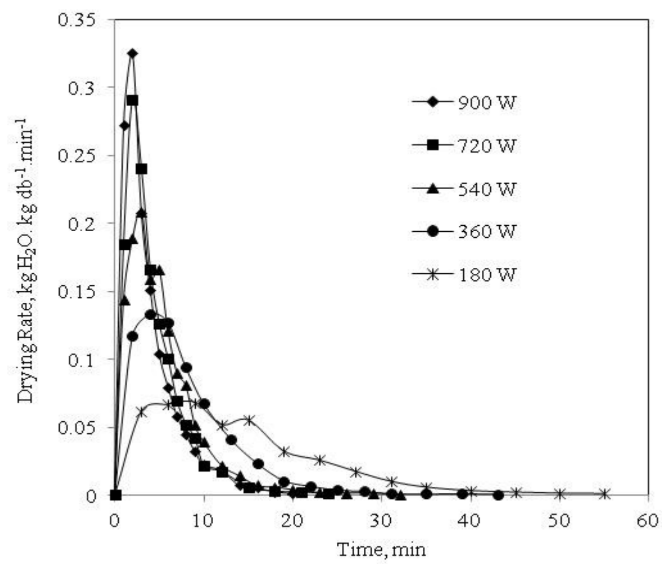

Figure-2
Drying rate vs. Time

There is sudden increase in dehydration rate initially and there is no constant rate period observed in the present studies but a short accelerating period at the start. Similar results were found for different food materials such as banana[41], Parsley[18], Carrot[22], Lactose[42], elephant foot yam[43], apple pomace[24], bamboo[25], using microwave drying as reported by the authors. In the present study, drying rate is directly proportional and drying time is inversely proportional to the microwave power output. Increase in microwave power level increased the drying. Drying rate is illustrated in figure-3 as a function of moisture content during the course of microwave drying. Drying rates reduced rapidly with the decrease in moisture content after a short period in which high drying rates prevailed, and took more time to remove the remaining moisture. Average Drying rates were in the range of 4.49×10^{-4} to 1.39×10^{-3} kg water.kg $db^{-1}.s^{-1}$ at microwave power levels from 180 W to 900 W. The kinetic rate constant (k) in Midilli *et al.*, model increased with increase in microwave power output.

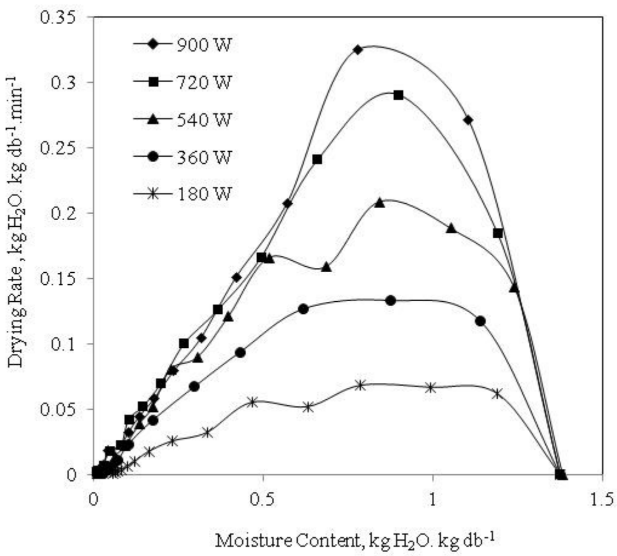

Figure-3
Drying rate vs. moisture content at different microwave power levels

Evaluation of Thin Layer Drying Models: The most suitable model to predict the microwave drying behavior of sprouted horse gram was selected by regressing dimensionless moisture ratio against drying time according to the thin layer drying models presented in table-1. The good fitting model was selected on the basis of the coefficient of determination (R^2) reduced chi square, residual sum squares and RMSE calculated from equations-7, 8, 9 and 10 respectively. Among these models examined the semi empirical Midilli *et.al* gave best fitting with drying data with higher values of R^2 and lower values of RMSE, Chi square and RSS. The estimated value of statistical parameters and constants of Midilli et al. model were presented in table-2.

Effect of Microwave Power Output on Effective Moisture Diffusivity: The method of slope was used to calculate the effective moisture diffusivities of sprouted horse gram. According to Equation-6, a plot of ln (MR) vs drying time gives a straight line (Figure-4) with the slope ($\pi^2 D_{eff}/4L^2$). The effective moisture diffusivities and corresponding coefficient of determination (R^2) values are presented in Table-3. During microwave drying, the effective moisture diffusivities of sprouted horse gram varied from 1.42×10^{-10} m^2/s to 5.74×10^{-10} m^2/s as the microwave power output increased from 180 W to 900 W indicating an increase of 404 % in effective moisture diffusivities. The values of effective diffusivities estimated in the present work lie within the general range of 10^{-11}–$10^{-9} m^2/s$ for food materials[38].

Table-2
Estimated coefficients and statistical analysis of Midilli et.al model at various microwave output powers.

	Statistical values				Model Constants			
	R2	**RSS**	**RMSE**	**χ^2**	**k (min^{-1})**	**n**	**a**	**b**
180	0.9998	3.091E-04	4.539E-03	2.810E-05	0.0343	1.2772	0.9984	7.500E-04
360	0.9996	6.492E-04	6.370E-03	5.410E-05	0.0809	1.2800	1.0035	5.113E-04
540	0.9994	1.168E-03	7.643E-03	7.302E-05	0.1182	1.3139	1.0054	5.607E-04
720	0.9991	1.440E-03	9.487E-03	1.200E-04	0.1873	1.2232	1.0121	6.053E-04
900	0.9989	1.525E-03	9.763E-03	1.271E-04	0.2663	1.0721	1.0092	5.234E-04

Table-3
Effective moisture diffusivities of sprouted horse gram at various microwave power output.

Power (W)	**900**	**720**	**540**	**360**	**180**
$D_{eff} \times 10^{10}$ ($m^2.s^{-1}$)	5.7409	5.0448	3.7198	2.4253	1.4201
R^2	0.9920	0.9772	0.9631	0.9362	0.9659

D_{eff} Effective diffusivity; R^2 coefficient of determination.

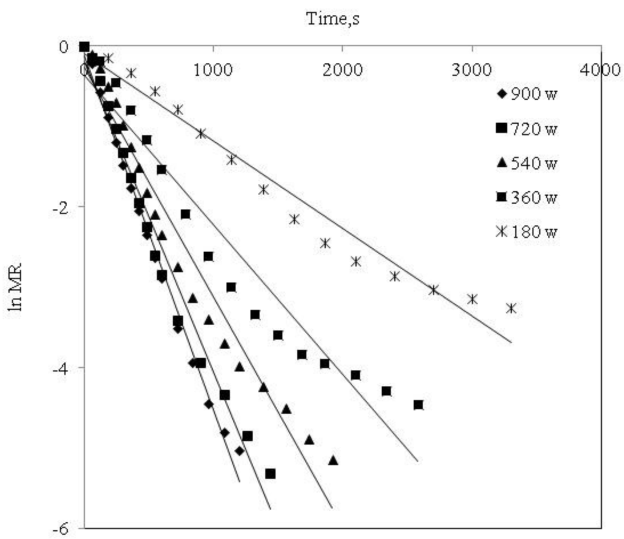

Figure-4
Logarithm of moisture ratio versus time at various microwave power

Estimation of Activation Energy: In the present research work, temperature used in the microwave oven for drying experiments is not considered as a directly measurable quantity. The modified form of Arrhenius equation as derived by Dadali *et al*. (2007a)[16,44] illustrates the relationship between the effective diffusivity and the ratio of the microwave power output to sample weight instead of temperature tor the computation of activation energy and the equation is as shown below:

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

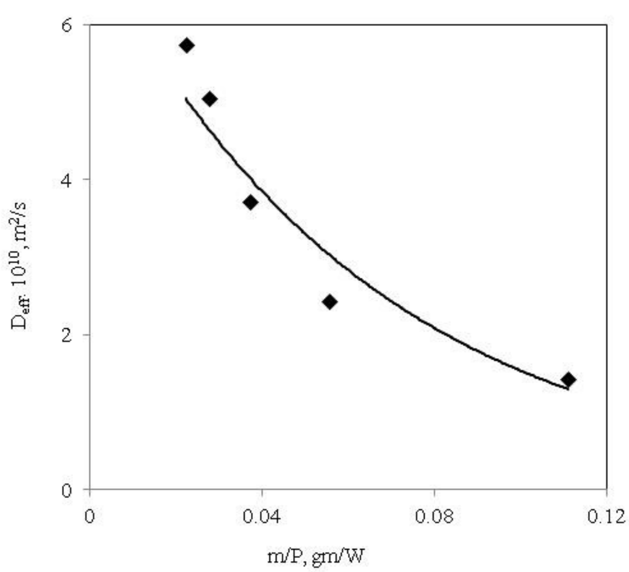

Figure-5
Relationship between effective moisture diffusivity and m/P

Where D_o (m^2s^{-1}) is the pre-exponential factor, E_a is the activation energy ($W.kg^{-1}$), P is the microwave power output (W), m is the mass of the sample (g).

The effective diffusivity D_{eff} values regress well with ratio of sample mass to microwave power (m/P) value based on Equation-11 with coefficient of determination (R^2) 0.933 for the model and illustrated in Figure-5. The estimated values of D_o and E_a from modified Arrhenius type exponential equation are 7.1 x $10^{-10} m^2s^{-1}$ and 15.3 $W.g^{-1}$ respectively.

Conclusion

Microwave drying of sprouted horse gram legumes was studied in domestic microwave oven at different microwave power outputs 180-900 W. Increase in Microwave power decreased the drying time but increased the rate of drying. There was on constant drying rate period, entire drying took place in falling rate period. Average drying rates were in the range of $4.49x10^{-4}$ to $1.39x10^{-3}$ kg water.kg $db^{-1}.s^{-1}$ at microwave power levels from 180 W to 900 W. Semi-empirical Midilli et al., model was found to be the best model for predicting microwave drying behavior of sprouted horse gram, which regressed well with the experimental data. Effective moisture diffusivity was calculated using Fick's second law to understand the mass transfer mechanism, and the calculated values ranged from 1.42×10^{-10} m^2/s to 5.74×10^{-10} m^2/s ate the microwave power 180 W to 900 W. Activation energy which describes the effect of microwave power on moisture diffusivity was estimated using modified Arrhenius equation and found to be 15.3 W/g.

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