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Mathematical modeling for pulsed microwave convective drying of red gram (Brg-2 variety)

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Abstract
The effect of microwave drying experiments on three independent variables *i.e.,* microwave power levels (540, 720 and 900 w), pulsation levels (30, 60 & 90s) and initial moisture contents (14, 16 & 18% w.b) on drying time, drying rate and effective moisture diffusivity of red gram been investigated. By increasing the microwave power (540 to 900w) and Pulsation level (30 to 90s) at a moisture content of 14, 16 & 18% (wet basis), the drying time decreased from 300-690s, 180-360s and 150-330s, respectively. To determine the drying kinetics, the drying data fitted to "n" best thin layer drying various models based on the ratios of the differences between the initial and final moisture contents and equilibrium moisture content versus drying time studied. The Midilli *et al.* model gave a superior prediction than all other models evaluated and described the drying characteristics of red gram more effectively. The relationship between the drying rate was also estimated and gave a linear relationship.

Keywords: Drying rate, moisture diffusivity, modelling, microwave power and pulsation.

Introduction
Pulses are tremendous sources of vegetarian protein, carbohydrates and several other nutrients needed for human being. Majority of the Indians are vegetarians and hence India largely depends on pulses to meet its demand for proteins and prevent malnutrition. Red gram also known as Pigeon pea, is the second important pulse in the country after gram (chana). It contains 54.32% carbohydrates, 21.32% protein, 7.29% fiber and 5.14% ash. It can be consumed as whole, dehulled dhal, canned, boiled, roasted or ground into flour to make a variety of desserts, main dishes, snacks and noodles.

Initial Moisture content of grains is a severe factor that affects the storage life and processing parameters. For safe storage and to obtain good milling output (Sahay *et al*. 1985) [12] the moisture content of pulses should be between 9-10% (d.b). As compared to other conventional drying methods, microwave drying has found better option for commercial drying and dehydration application in many food sectors due to rapid drying capability and less energy consumption with acceptable quality of dried product (Maskan, 2001) [7]. Microwave drying is effective, when the product initial moisture content is below 20%, as used in a number of drying process (Mudgett, 1989) [9] and also reduces energy consumption during drying. It also reduces the drying time and prevents food from decomposing. Thin-layer drying describes the process of drying in a single layer of sample particles. Three types of thin-layer drying models are used to describe the drying phenomenon of agricultural product. The theoretical model considers only the internal resistance to moisture transfer between product and heating air whereas semi-theoretical and empirical models consider only the external resistance (Midilli *et al.,* 2002) [8] and these models derived from simplification of Fick's second law of diffusion. Mathematical modelling and computer simulations be a most effective way to know the depth of drying and these models consider the heat and mass transfer between grain, equilibrium state between grain and the drying air, and variations in the physical properties of air, vapour and grain with variations in temperature and humidity (Brooker D B *et al*., 1982) [1].

The aim of this study was to investigate the effect of initial moisture content, microwave power level combined with pulsation level on drying kinetics of red gram (BRG-2 variety). Followed by comparing the experimental data of microwave drying with the predicted values obtained by using eight mathematical models, and to derive a relationship between drying rate constant.

Materials and Methods
The study was conducted with freshly harvested red gram (Variety-BRG-2), procured from Agricultural Research Station (UASB), Chintamani. The samples were manually cleaned to remove foreign matter, immature grains, dust, dirt, and broken grains.

Drying Equipment and Procedure

The drying treatment was carried out by a domestic microwave oven (Model No: MC3283AMPG). The microwave setup specifications are 230 V, 50 Hz and 900 W, frequency of 2450. The size of the oven is 450 × 520 × 320 mm and its rotating glass plate's diameter is 340 mm. The microwave oven has the capability of operating at five different microwave output powers 180, 360, 540, 720 and 900w. The tuning of microwave output power and processing time was done with the assistance of a digital control facility located on the microwave oven. For drying experiments the independent variables were three microwave power levels (540, 720 &900w), three moisture levels (14, 16 & 18% w.b) and three Pulsation levels (30, 60 & 90s). A sample of 100g red gram was placed at centre in thin layer on the rotating glass plate. Weight losses were periodically measured at every 30 s by taking out the rotating glass through the digital balance with the sensitivity of 1 g and recorded. The tests were conducted in triplicates to a preset microwave output power and time schedule and the data given are average of triplicate results. The Microwave power was applied until the sample reaches safe moisture content level of 8% (w.b).

Mathematical Modelling of Microwave Drying Kinetics

In order to determine the moisture ratio as a function of drying time, eight different thin-layer drying models as shown in Table 1. The moisture ratio and drying rate of microwave dried red gram were calculated using the equations 1.0 &1.1:

$$\mathrm{MR} = \frac{\mathrm{Mt-Me}}{Mo-Me} \tag{1.0}$$

Where MR is the moisture ratio, M_o is the intial moisture content (%w.b), M_t = mean moisture content (%, w.b) at time t, M_e= equilibrium moisture content, (%, w.b). Equilibrium moisture content assumed to be zero for microwave drying as stated by Maskan.M., 2000.

$$\text{Drying rate} = \frac{\mathrm{Mt}+dt-Mt}{dt} \tag{1.1}$$

Where, M_t = moisture content at t (% w.b.), M_t+dt = moisture content at time t+dt (% w.b.)

Table 1: Mathematical models selected for drying curves

S. No.	Model name	Equation	References
1.	Newton	$MR= \exp^{(-kt)}$	Lewis, 1921 [6]
2.	Page	$MR= \exp^{(-kt^n)}$	Page, 1949 [10]
3.	Modified page	$MR= \exp^{[-(kt)^n]}$	Overhultset *al.*, 1973 [11]
4.	Henderson and Pabis	$MR=a \exp^{(-kt)}$	Henderson and Pabis, 1961 [5]
5.	Logarithmic	$MR=a \exp^{(-kt)} +c$	Chandra and Singh, 1995 [2]
6.	Two term	$MR=a \exp^{(-kt)} + b \exp^{(-gt)}$	Henderson, 1974 [4]
7.	Midilli *et al.*	$MR= \exp^{(-kt^n)} +bt$	Midilli *et al.*, 2002 [8]
8.	Wang and Singh	$MR=1+b t+ a t^2$	Wang and Singh, 1978 [16]

Computational work

The non-linear regression was analyzed using MATLAB 7.12.0.635 R2011a software package. The validation of models can be checked with dissimilar statistical methods. The most widely used method in literature is performing root mean square error (RMSE), reduced chi-square (χ^2) test and coefficient of determination (R^2) analysis, respectively (Togrul and Pehivan, 2002) [14].

The model with lowest values of χ^2 and RMSE and highest R^2 were used to evaluate the goodness of fit (Yaldiz *et al.*, 2001) [15]. The values of χ^2 and RMSE calculations can be done using following equations 1.2 & 1.3:

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(\mathrm{MR_{exp,i}} - \mathrm{MR_{pre,i}}\right)^2}{\mathrm{N-n}} \tag{1.2}$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2\right]^{1/2} \tag{1.3}$$

Where,

$MR_{exp,I}$ = experimental moisture ratio, $MR_{pre,i}$= predicted moisture ratio, N = number of observations, N = number of constants in drying model, MR_{exp}, mean = mean value of experimental moisture ratio

Finally, the effect of the variables on model constants was investigated by performing multiple regression analysis with multiple combinations of different equations such as the simple linear, logarithmic (Guarte, 1996) [2], exponential, power, and the Arrhenius type. After investigating the effect of experimental variables on model constants, the final model was validated by the statistical methods.

Results and Discussion

Drying Kinetics of Microwave Dried Red gram

Red gram having initial moisture contents of 14, 16, & 18% (w.b) were dried up to 8.0% (w.b) at microwave power level of 540,720, and 900 watts with 30, 60 and 90 s pulsation level using a domestic microwave oven.

There was no marked constant rate drying period observed during the drying process and drying of red gram took place in falling rate period.

The result suggests some past studies on drying of various food products and grains like Shepherd and Bhardwaj, (1988) [13] for pigeon pea.

Effect of Initial Moisture Content on Red gram Moisture Reduction

The effect of initial moisture content on drying rate of red gram is observed during initial stages of drying. Initial moisture content of 14%, 16% & 18% (w.b) dried to 8.0% (w.b) at a constant microwave power level of 540 w and pulsation level of 30s. The drying rate in the initial stage was greater than the lower initial moisture content.

The time drying rate decreases and ceases depending on initial grain moisture content. The highest drying time of about 690 secs was seen for drying of 18% (w.b) red gram at 540 w under 90s pulsation, while the lowest drying time of about 150 secs for 14% (w.b) grains dried at 900 w and 30 s pulsation level as shown in Table 2. These observations suggest that the drying rate and drying time was dependent on initial moisture content of grains.

Table 2: Drying Time of Red Gram under Various Experimental Conditions

Code	Drying Time (s)	Code	Drying Time (s)	Code	Drying Time (s)
$M_1P_1T_1$	300	$M_2P_1T_1$	180	$M_3P_1T_1$	150
$M_1P_1T_2$	360	$M_2P_1T_2$	210	$M_3P_1T_2$	180
$M_1P_1T_3$	450	$M_2P_1T_3$	240	$M_3P_1T_3$	210
$M_1P_2T_1$	420	$M_2P_2T_1$	210	$M_3P_2T_1$	240
$M_1P_2T_2$	450	$M_2P_2T_2$	270	$M_3P_2T_2$	270
$M_1P_2T_3$	540	$M_2P_2T_3$	300	$M_3P_2T_3$	300
$M_1P_3T_1$	480	$M_2P_3T_1$	300	$M_3P_3T_1$	270
$M_1P_3T_2$	570	$M_2P_3T_2$	330	$M_3P_3T_2$	300
$M_1P_3T_3$	690	$M_2P_3T_3$	360	$M_3P_3T_3$	330

Note: Moisture content: M_1-18%(wb), M_2-16%(wb), M_3-14%(wb), Power level: P_1-900w, P_2-720w, P_3-540w, $T_{1=}$ pulsation -30s, T_2-60s, T_3-90s

Effect of Microwave Power level on Red gram Moisture Reduction

The effect of different microwave power levels (540w, 720w & 900w) on moisture reduction of red gram with 16% (w.b.) moisture. It was observed that increase in microwave power level increases the drying rate, simultaneously the total drying time was decreased.

The drying rate at the beginning of the drying process was generally lower at 540 w with a marked difference between it and the other microwave power levels. At 540 w the rate of heat transfer was slower compared to 720 and 900w, hence wide gap between the curves was seen for all three microwave power levels investigated. With the increase in microwave power level the drying rate increases and the total drying time decreases.

For an instance during microwave drying (540, 720 and 900 w) of red gram with intial moisture content of 16% (w.b) under constant pulsation level of 60s the total drying time observed was 330, 270 and 210s respectively. The higher drying rate at higher microwave power level was seen because of the nature of grains i.e. the hard nature requires that the grain kernel be heated to a level before the heat transfer will reach the core water and trigger the diffusion process.

Effect of Pulsation level on Red gram Moisture Reduction

A number of previous researchers have neglected the effect of pulsation level during microwave drying. The effect of different pulsation level 30, 60 & 90s on moisture reduction of red gram with constant initial moisture content 14% (w.b) and power level 900w.

It was observed that increase in pulsation level decreases the drying rate, thus total drying time was increased. At 90s pulsation level the rate of heat transfer was slower compared to 60s and 30s, hence a gap between the curves was seen for all three pulsation levels investigated. Moisture content reduced quickly at the intial stage of pulsation level during drying followed by a relatively slow decrease in the removal of moisture that was prominent at higher level. Lower pulsation level resulted in faster drying rate in the intial phase of drying. With the increase in pulsation level the drying rate decreases and total drying time increases.

Modelling of Drying Time (Red gram) as a function of Microwave Drying Conditions

The effect of drying conditions on drying time of red gram was determined by analyzing the 3D response surface plots. These plots were developed by keeping one variable as constant at centre point (Intial Moisture Content = 16% (w.b.), Power level = 720 w, pulsation level = 60 s) to find the simultaneous effects of the remaining two variables as shown in Fig. 1. From Fig. 1. as shown at centre point (16% w.b intial moisture content at "0" level), the drying time gradually decreased with increase in microwave power level, while at centre point of microwave power level (720 w) the drying time decreased with decrease in intial moisture content and pulsation level. Similarly, at centre point of pulsation level (60 s), the drying time decrease with decrease in moisture content and increase in microwave power level.

It is clear that all the three drying variables viz., intial moisture content, microwave power level and pulsation level affect the drying time ($p < 0.0001$) significantly. Intial moisture content appears to be the most significant factor affecting drying time followed by microwave power level and pulsation level to the total sum of square values.

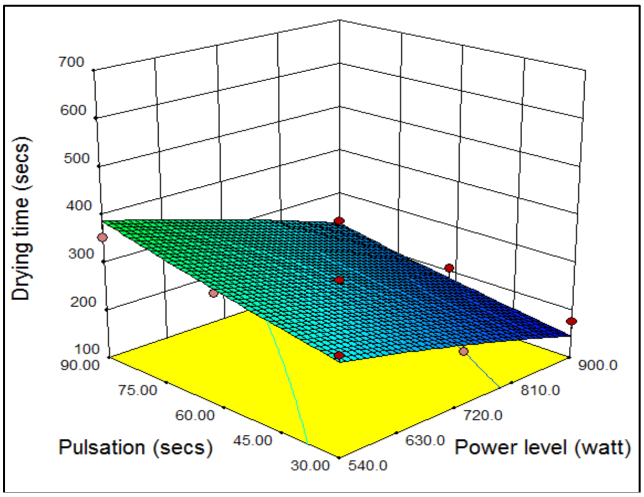
Intial Moisture Content alone accounted for 48.81% of the total sum of squares values, followed by Microwave power level and pulsation level which contributed 22.04 and 9.14% respectively.

These figures indicate the magnitude of the effect of these variables on drying time. The interactions of these variables were also significant except the interaction between microwave power level and pulsation level ($p > 0.05$). The interaction effect between IMC and Microwave power level, Intial moisture content and pulsation level were more significant ($p < 0.001$).

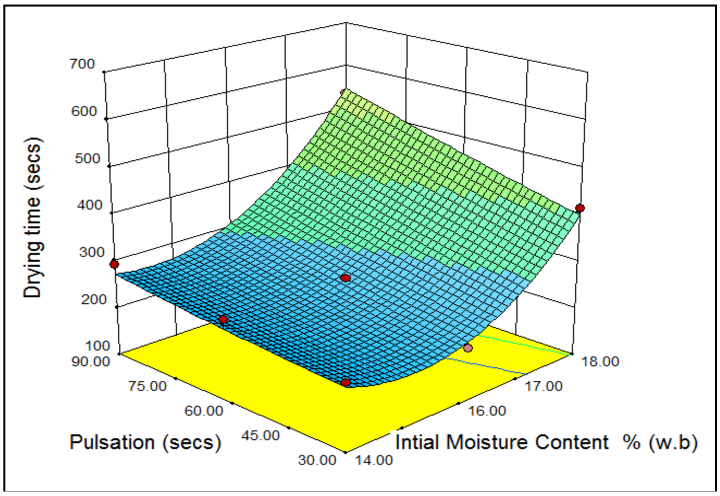
Drying time was modeled as a function of intial moisture content, Microwave power level and Pulsation level by response surface methodology. Among various models evaluated, the relationship between these three variables was predicted by using a second order polynomial model as shown in Eq. 1.7

$$T_d = 268.55+111.67*A-75*B+48.33*C-22.50*AB+25.00*AC-5.00*BC+94.19*A^2-5.81*B^2+4.19*C^2 \quad (1.7)$$

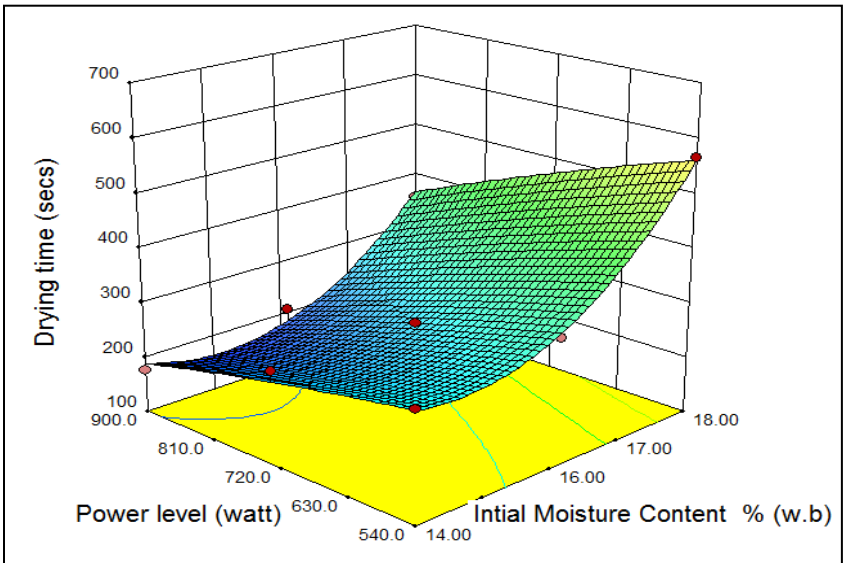
Where T_d = Drying time, A = Initial Moisture content, (% w.b), B = Microwave power level, (watts), C = Pulsation level (secs).



A



B



C

Fig 1: Response surface plots for red gram drying time (min) as a function of IMC (% w.b.), Microwave power level (w) and Pulsation level (s) keeping the third variable fixed at "0" level viz., a) Intial moisture content - 16% (w.b), Microwave power level – 720 w c) Pulsation level – 60s.

Mathematical Modelling of Red gram Drying Curves

The variation of moisture content with drying time is obtained for each set of variables; from these results, drying rates were calculated and then plotted against moisture content red gram for different values of Intial moisture content, Microwave power level and Pulsation level. The moisture content data of each variable combination were converted to the more useful moisture ratio expression and plotted against drying time. Eight commonly used and simple thin layer models (Table.1) were fitted using the non-linear regression procedure in MATLAB version 7.12.0.635 (R2011a). The regression analysis was performed with the selected models to find out the constant values that supply the best appropriateness of models.

Goodness of Fit

The goodness of fit for each model was evaluated by the most widely used statistical method in literature, by finding coefficient of determination (R^2), chi-square (χ^2) test and root mean square error (RMSE) analysis, respectively. The predicted moisture ratio and experimental moisture ratios were compared using root mean square error and chi square as shown in (Eq. 1.2 & 1.3). The model constants and coefficients for all eight models for each experimental condition are presented in Table 4.5, 4.6 & 4.7.

Acceptable R^2values of above 0.99 were obtained for all eight models evaluated to all drying runs.

It was evident that the highest R^2 and lowest RMSE and lowest χ 2 values were obtained for Midilli model. Hence, the Midilli model gave a superior prediction than other models and described the drying characteristics of red gram with 14, 16 and 18% (w.b) with a R^2 values above 0.99 for all the drying conditions.

Table 3: Statistical analysis of the models at various microwave output powers at 18% M.C (w.b)

Model	18-900-30	18-900-60	18-900-90	18-720-30	18-720-60	18-720-90	18-540-30	18-540-60	18-540-90
Newton									
R^2	0.9853	0.9839	0.971	0.9803	0.9785	0.9737	0.9737	0.9803	0.9781
RMSE	0.0378	0.04039	0.05311	0.04465	0.04652	0.05356	0.05356	0.04447	0.04722
Chi-square	0.0014	0.001631	0.002821	0.001993	0.002164	0.002868	0.00229	0.00197	0.00223
Page									
R^2	0.9892	0.9839	0.9846	0.9948	0.9959	0.9984	0.9984	0.9957	0.9969
RMSE	0.03391	0.04218	0.04013	0.02389	0.02102	0.01362	0.01362	0.02138	0.01825
Chi-square	0.0011	0.004934	0.001611	0.000571	0.000442	0.000186	0.00066	0.000457	0.00035
Modified Page									
R2	0.9853	0.9839	0.971	0.9803	0.9785	0.9737	0.9737	0.9803	0.9781
RMSE	0.03964	0.04218	0.05497	0.04633	0.04815	0.05511	0.05511	0.04569	0.04828
Chi-square	0.0016	0.001779	0.003022	0.002147	0.002319	0.003037	0.00244	0.002088	0.24362
Logarithmic									
R2	0.9976	0.998	0.9984	0.9998	0.9993	0.9977	0.9977	0.9986	0.9989
RMSE	0.01673	0.005474	0.01323	0.005003	0.009209	0.01661	0.01661	0.01246	0.01095
Chi-square	0.003	3.00E-05	0.0001752	2.50E-05	8.48E-05	2.76E-04	3.00E-04	1.55E-04	1.20E-04
Henderson & Pabis									
R2	0.03919	0.9862	0.9733	0.9838	0.9836	0.9833	0.9833	0.9859	0.9852
RMSE	0.9856	0.03909	0.05281	0.04205	0.04199	0.04383	0.04383	0.03862	0.03976
Chi-square	0.0015	0.001528	0.0027886	0.001768	0.001763	0.001921	0.00206	0.001657	1.58E-03
Midilli *et al.*									
R2	0.9997	0.9997	0.9995	0.9998	0.9995	0.9996	0.9996	0.9988	0.9995
RMSE	0.006533	0.005981	0.007823	0.004807	0.00803	0.006985	0.006985	0.01174	0.007794
Chi-square	4.27E-05	3.58E-05	6.12E-05	2.31E-05	6.45E-05	4.88E-05	3.82E-04	1.38E-04	4.40E-04
Two therm									
R2	0.9907	0.9949	0.9859	0.9998	0.9959	0.9981	0.9978	0.9955	0.9965
RMSE	0.03529	0.02616	0.04141	0.005012	0.02276	0.01582	0.0169	0.02307	0.02013
Chi-square	0.0012	0.000684	0.001719	2.54E-05	0.000518	0.00025	0.00081	1.961974	4.10E-04
Wang & Singh									
R2	0.9912	0.998	0.9956	0.9989	0.9987	0.9979	0.9979	0.9968	0.9988
RMSE	0.03064	0.01495	0.02136	0.01089	0.01172	0.01572	0.01572	0.01848	0.01154
Chi-square	0.0009	0.000223	0.000456	0.000119	0.000137	0.000247	0.00014	0.000663	0.06218

Table 4: Statistical analysis of the models at various microwave output powers at 16% M.C (wb)

Model	16-900-30	16-900-60	16-900-90	16-720-30	16-720-60	16-720-90	16-540-30	16-540-60	16-540-90
Newton									
R^2	0.985	0.9791	0.9787	0.9713	0.982	0.9838	0.9802	0.977	0.9767
RMSE	0.04382	0.05029	0.05023	0.05949	0.0455	0.04229	0.04604	0.05014	0.04966
Chi-square	0.00072	0.002529	0.002523	0.003539	0.00207	0.00179	0.00212	0.00251	0.00247
Page									
R^2	0.9951	0.9932	0.9951	0.9935	0.9967	0.996	0.9922	0.9943	0.9939
RMSE	0.02741	0.03106	0.02588	0.03062	0.02059	0.02205	0.03042	0.02617	0.02649
Chi-square	0.00075	0.000965	0.00067	0.000937	0.00042	0.000486	0.00093	0.00068	0.0007
Modified Page									
R2	0.985	0.9791	0.9787	0.9713	0.982	0.9838	0.9802	0.977	0.9767
RMSE	0.04801	0.05432	0.0537	0.06426	0.04826	0.04458	0.04853	0.05258	0.05187
Chi-square	0.0023	0.002951	0.002884	0.004129	0.00233	0.001987	0.00236	0.00277	0.00269
Logarithmic									
R2	0.9994	0.9999	0.9997	0.9998	0.9993	0.9999	0.9996	0.9998	0.9999
RMSE	0.01102	0.003063	0.006374	0.005822	0.01004	0.00445	0.007553	0.005419	0.003948
Chi-square	0.00012	9.38E-06	4.08E-04	3.40E-05	1.00E-04	2.00E-05	5.71E-05	2.97E-05	1.57E-05
Henderson & Pabis									
R2	0.9863	0.9811	0.9814	0.9749	0.9849	0.9863	0.9823	0.9806	0.9804
RMSE	0.04594	0.05172	0.0502	0.06013	0.04427	0.041	0.04591	0.04826	0.04753
Chi-square	0.00211	0.002675	0.00252	0.003616	0.00196	0.001681	0.00211	0.00233	0.00226
Midilli *et al.*									
R2	0.9995	0.9999	0.9998	0.9999	0.9997	0.9999	0.9997	0.9998	0.9999
RMSE	0.01181	0.002607	0.005516	0.004769	0.006746	0.00294	0.006936	0.004951	0.004009
Chi-square	1.40E-04	6.80E-06	3.04E-05	2.28E-05	4.55E-05	1.21E-05	4.82E-05	2.45E-05	1.61E-05
Two therm									
R2	0.9943	0.9811	0.9814	0.9925	0.9969	0.9871	0.9926	0.9976	0.9805
RMSE	0.03809	0.06334	0.05939	0.04012	0.02313	0.04515	0.03368	0.01907	0.05244
Chi-square	0.00146	0.004012	0.003527	0.00161	0.00054	0.002043	0.00113	0.00037	0.00275
Wang & Singh									
R2	0.997	0.9988	0.9995	0.9997	0.9989	0.9985	0.9977	0.007684	0.9994
RMSE	0.02146	0.01325	0.008278	0.006812	0.01201	0.01377	0.01669	0.9995	0.008006
Chi-square	0.00046	0.000176	6.83E-05	4.64E-05	0.00014	0.000194	0.00028	5.91E-05	6.41E-05

Table 5: Statistical analysis of the models at various microwave output powers at 14% M.C (wb)

Model	14-900-30	14-900-60	14-900-90	14-720-30	14-720-60	14-720-90	14-540-30	14-540-60	14-540-90
Newton									
R^2	0.9809	0.9882	0.9865	0.9816	0.9768	0.9784	0.9753	0.9775	0.9763
RMSE	0.05234	0.03926	0.04049	0.04589	0.05151	0.04877	0.05388	0.04922	0.05138
Chi-square	0.00274	0.001607	0.00166	0.49895	0.382262	0.30169	0.50425	0.470809	0.49037
Page									
R^2	0.9959	0.9973	0.9952	0.9928	0.9949	0.9967	0.9954	0.9927	0.9964
RMSE	0.0272	0.02043	0.02595	0.03078	0.02561	0.02018	0.02474	0.02965	0.0211
Chi-square	0.000767	0.000418	0.00068	0.45587	0.341042	0.26407	0.59567	0.54564	0.56596
Modified Page									
R2	0.9809	0.9882	0.9865	0.9816	0.9768	0.9784	0.9753	0.9775	0.9763
RMSE	0.05852	0.04301	0.04373	0.04905	0.05463	0.05141	0.05715	0.05188	0.05388
Chi-square	0.0079	0.001928	0.00194	0.43853	0.326561	0.25346	0.5673	0.523135	0.56112
Logarithmic									
R2	0.9999	0.9995	0.9997	0.9998	0.9998	0.9984	0.3999	0.9998	0.9993
RMSE	0.005598	0.01003	0.006571	0.006122	0.005673	0.01478	0.3012	0.004982	0.009656
Chi-square	3.15E-05	9.08E-05	1.79E-05	5.10E-01	3.85E-01	3.04E-01	5.28E-02	5.92E-01	6.34E-01
Henderson & Pabis									
R2	0.9823	0.9893	0.9877	0.9832	0.9803	0.9832	0.979	0.9804	0.9814
RMSE	0.0563	0.04094	0.04171	0.04694	0.05029	0.04537	0.05267	0.04839	0.04771
Chi-square	0.00317	0.001744	0.001744	0.47763	0.375484	0.30088	0.6423	0.58458	0.62634
Midilli *et al.*									
R2	0.9999	0.9997	0.9998	0.9999	0.9999	0.9991	0.9997	0.9999	0.9999
RMSE	0.000249	0.009216	0.006232	0.005088	0.003722	0.01187	0.006741	0.004586	0.004478
Chi-square	6.46E-08	6.71E-05	1..15E-05	6.15E-01	4.44E-01	3.40E-01	7.75E-01	6.81E-01	7.02E-01
Two therm									
R2	0.9996	0.9972	0.995	0.9832	0.9803	0.9832	0.979	0.9804	0.9814
RMSE	0.01124	0.02704	0.03255	0.05554	0.05808	0.05146	0.06082	0.05489	0.05337
Chi-square	0.000126	0.00074	0.0011	0.66796	0.501924	0.38638	0.85763	0.757183	0.79095
Wang & Singh									
R2	0.9995	0.9973	0.9969	0.9978	0.9995	0.998	0.9999	0.9986	0.9995
RMSE	0.009756	0.02066	0.02103	0.01683	0.008055	0.01585	0.003904	0.01297	0.007863
Chi-square	9.52E-05	0.000391	0.0004	0.44641	0.3307	0.25688	0.57833	0.532784	0.54973

Conclusion

The total microwave drying of red gram (BRG-2) occurred in falling rate period followed by a constant rate period after short period heating. The drying rate increases with increasing the microwave power and drying coefficient generating high pressure inside the samples due to sudden and volumetric heating. The drying curves obtained for red gram (BRG-2) under various drying conditions, from the results it was observed that the Midilli model were found to have highest coefficient of determination (more than 0.99), lowest root mean square error (RMSE), and lowest chi square values for red gram. The effective moisture diffusivity was dependent on microwave power level and to some extent on pulsation level.

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