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Research Article

Microwave-vacuum drying of green peas: drying kinetics and influence of system parameters on physical properties

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Abstract

The drying kinetics of green peas was studied during microwave-vacuum drying (MVD) at different microwave powers (100W, 200W, 300W) and vacuum levels (50 mm Hg, 225 mm Hg, 400 mm Hg). The dynamic equilibrium was reached in the longest period of 490 min at microwave power of 100W and vacuum of 50 mm Hg, whereas, it took a shortest period of 95 min at microwave power of 300W and vacuum of 400 mm Hg. Seven drying models were fitted to experimental data and it was found that coefficient of determination varied between 0.9993 and 0.9687 and Chi square values ranged between 0.0040 and 0.0001. The study was also carried out to characterize the physical properties of dried green peas in respect of volumetric shrinkage ratio (VSR), bulk density ratio (BDR), burnt and damaged (B&D) grain percentage and hardness of rehydrated samples. VSR data fitted well to a microwave power dependent linear model, whereas, BDR, B&D grain percent and hardness data to second order polynomial models.

Keywords: drying kinetics, microwave-vacuum drying, dried green-peas, India.

Introduction

Conventional air drying is one of the most widely used methods of food dehydration. Final products are characterized by low porosity, high apparent density [1], frequently, low sorption capacity [2] and a significant change in colour during air drying. In fruit and vegetables, water loss is usually accompanied with a sufficient shrinking, leading to product deformation and an undesired texture [3]. Another drawback of air drying is that it takes comparatively longer time in accomplishing drying up to the desired low-moisture which allows substantial damage to the product quality to take place.

In recent years microwave-vacuum drying (MVD) has emerged as an important alternative to convective drying. MVD has advantages of both microwave heating and vacuum drying and can be used for obtaining dehydrated food products with superior quality [4, 5]. In MVD, the electromagnetic microwave energy penetrates into the interior of the food, where it is converted to thermal energy, providing a rapid heating mechanism. Vacuum reduces the boiling point of water keeping the product temperature low, as well as creating a pressure gradient that enhances the drying rate [6]. The amount of heat generated depends on the strength of the electromagnetic field and the dielectric properties of the material being heated [7].

A number of studies have reported positive effects of MVD on quality of dehydrated fruit and vegetables. The puffing effect due to the internal expansion of the microstructure during drying improves rehydration [8, 9] and textural properties [3]. MVD has been reported to result in more colour retention in green peas [10] and strawberries [11]. The retention of nutrients in products dried by MVD, as compared to those by air drying techniques, have been reported as better in several studies, such as in Saskatoon berries [12] and wild cabbage [13].

India stands second in the world in green pea (*Pisum sativum* L.) production [14]. Green peas are legume crops and, therefore, rich in protein and fibre content. Being seasonal and perishable, it is necessary to preserve the green peas using suitable preservation techniques such as freezing, canning, or drying. The canned peas and frozen peas are available throughout the year, but they are expensive and, also, cannot be used in several preparations such as in vegetable soup powder and in traditional Indian snacks (*namkeens)*. Consequently, the dehydrated peas are gaining popularity because they offer the advantage of greater shelf-life, palatability, convenience during transport and handling and good culinary quality, in addition to considerable scope for export. Commercially available dehydrated green peas dried by conventional methods are not of prime quality in terms of sensory appeal [10] and time involved in drying is also considerably high. The present work was aimed to study the drying kinetics of green peas during MVD vis-à-vis the effect of microwave power and vacuum on physical properties of dried product.

Materials and Methods

Raw material

Good quality fresh peas were procured from the local market. The damaged, immature and dried pods were removed manually by visual inspection. The pea pods were shelled manually and then graded using a metallic sieve with 8 mm diameter openings. The fraction retained over the screen was used for drying experiments and for determination of various selected properties. The graded peas were blanched in distilled water at 98ºC for 3 min and cooled, followed by spreading over absorbing paper to remove the moisture adhering to the surface.

Microwave-vacuum drying

The experimental setup comprised of a domestic microwave oven of power rating 800W (Model MO-9760A, Kitchen Appliances India Ltd., Kenstar, Aurangabad, India) with a hole made on upper face, through which the hose pipe was passed. One end of the hose pipe was connected to the lid of a polycarbonate vacuum desiccator (Tarsons Products Pvt. Ltd., Kolkata, India) kept inside the oven cavity, while the other, to a vacuum pump via a combined unit of vacuum gauge and pressure regulator and a surface-cooled condenser. The microwave oven was connected to an AC electric supply (220 V, 50 Hz) via a wattmeter, a variable voltage transformer and a servo type voltage corrector. For each experiment, approximately 100 g accurately weighed sample was evenly spread in

thin layer over a perforated desiccator-plate and kept in the desiccator. The desiccator was then kept inside the microwave oven and covered with a lid. The vacuum pump was switched on and desired vacuum was maintained inside the vacuum desiccators by adjusting pressure regulator. Then the microwave oven was switched on and desired microwave power was maintained by adjusting variable voltage transformer. The sample was periodically weighed to note down the weight loss by switching off the microwave; quickly releasing the vacuum and weighing the desiccators-base containing the sample, on an electronic balance and were subjected to further drying until the weight of sample remained unchanged in two consecutive observations. The dried sample was then kept inside glass desiccator, containing silica gel, for cooling. When the temperature of the sample lowered to normal, it was packed in the LDPE pouches (100 gauge) and heat sealed. The moisture content obtained at this stage was marked as equilibrium moisture content (EMC). The dry-matter content of product in each experiment was determined by drying samples in a hot air oven at 100±2^{o}C for 16 h [15] the moisture contents at any stage of drying was calculated by applying mass balance.

Experimental design

The independent variables of MVD experiments were microwave power and vacuum levels. The levels of these independent variables were selected by applying Face Centered Central Composite Design. A vacuum range of 50-400 mm Hg (negative gauge pressure) was selected in combination with the microwave power range of 100-300 W on the basis of preliminary experiments. The factorial points and axial points were replicated three times and center point was replicated five times. Response surface methodology (RSM) was applied to various responses using Design Expert 7.1.1 software. Response surfaces were represented by first order or second order, linear/polynomial regression models. The second order model is given by following general equation.

$$Y = \beta_0 + \sum_{i=1}^{2}\beta_i X_i + \sum_{i=1}^{2}\beta_{ii} X_{ii}^2 + \sum_{i\neq j=1}^{2}\beta_{ij} X_i X_j \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Where, 'Y' is any response variables and β_0, β_i, β_{ii} and β_{ij} are linear, quadratic and cross product regression coefficients, respectively.

In the present study adequacy of any regression model for fitting experimental results for any response was examined by adding interaction term (X_1 X_2 term) to the first order model followed by adding second order terms, until the added terms showed a non-significant improvement in adequacy of model. Regression analysis and analysis of variance (ANOVA) were conducted for fitting the models represented by Eq. (1) to the experimental data and to examine the statistical significance of the model terms. The adequacy of the models was determined by lack-of-fit test and coefficient of determination (R^2) analysis as suggested by Lee et al. [16]. The lack-of-fit is a measure of the failure of a model to represent data in the experimental domain. If there is a significant lack-of-fit as indicated by a low probability value, the model is discarded. The coefficient of determination is a measure of degree of fit and defined as the ratio of the explained variations to the total variation [17].

Modelling of drying

Semi-theoretical models which are commonly applied for fruit and vegetable drying were adopted from the literature [18, 19] as shown in Table 1. In the proposed drying models, the moisture ratio (MR) is a nonlinear function of time. MR is a dimensionless term given by $(X_n - X_e)/(X_o - X_e)$, where X_n and X_o, are moisture contents in fraction dry basis (g of moisture per g of dry matter) at time t_n and at the beginning of drying, respectively and X_e is EMC in consistent unit. Nonlinear regression modeling of experimental data was carried out to obtain the values of constants of these models. Besides the coefficient of determination (R^2), the goodness of fit of drying models to experimental

data was evaluated on the basis of statistical parameters; namely, Chi-square (χ^2), root mean square error (RMSE) and mean relative deviation modulus (P_0, %) defined by Eq. (2)-(4). The first three parameters, though, describe the comparative adequacy of a model among the chosen ones, P_0 provides basic criterion of adequacy. A P_0 value ≤ 10 % for a model is considered as satisfactory [19] and lesser the value, the better the model, fitting to experimental data.

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

$$RMSE = \frac{\sum_{i=1}^{N}(MR_{exp\,i} - MR_{pre\,i})^2}{N} \quad \ldots\ldots\ldots\ldots (3)$$

$$P_0(\%) = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{(MR_{exp\,i} - MR_{pre\,i})}{MR_{exp\,i}}\right| \quad \ldots\ldots\ldots\ldots (4)$$

Where, $MR_{exp\,i}$ is experimental value of moisture ratio for *i* th observation, $MR_{pre\,i}$ is predicted value of moisture ratio for *i* th observation, *N* is number of observations and *n* is number constants in drying model. It is worth mentioning here that for the calculation of above mentioned statistical parameters, MR for Nth observation, being zero, was omitted for the reason that it yielded nondeterministic *N* th term in Eq. (4).

Table 1. Selected drying models for describing drying behaviour of green peas during microwave vacuum drying.

Names of Models	Model equations[#]
Newton	$MR = \exp(-kt)$
Henderson and Pabis	$MR = a * \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Approximate diffusion	$MR = a * \exp(-kt) + (1-a) * \exp(-kbt)$
Logarithmic	$MR = a * \exp(-kt) + c$
Wang and Singh	$MR = 1 + at + bt^2$
Two term	$MR = a * \exp(-k_0 t) + b * \exp(-k_1 t)$

a, b, c, k, k_0, k_1 are model constants and t is time (min).

Determination of properties

Volumetric shrinkage ratio (VSR)

A weighed quantity of randomly selected pea-grains was submerged into the toluene for measurement of apparent volume as has been reported by Chauhan and Srivastava [10]. The apparent volume was divided by the number of grains to calculate mean apparent volume per grain. Following formula was applied for volumetric shrinkage ratio.

$$VSR\ (\%) = \frac{Mean\ \ apparent\ \ volume\ per\ grain\ after\ \ drying}{Mean\ \ apparent\ \ volume\ per\ grain\ of\ \ fresh\ \ sample} \times 100 \quad \ldots\ldots\ldots\ldots (5)$$

Bulk density ratio (BDR)

The bulk density of sample was measured using the standard method of mass and volume [20] and was calculated as the ratio of weighed amount of peas and the volume occupied by the peas in a measuring cylinder [11].

$$\text{BDR}\ (\%) = \frac{\text{Bulk density after drying}}{\text{Bulk density of fresh sample}} \times 100 \qquad \ldots\ldots\ldots\ldots\ (6)$$

*Burnt and damaged (B&D) grain percent*age

The ratio of weight of grains having brown patches and/or the seed coat having apparent breakages to the sample-weight, in percent has been reported as burnt and damaged grain percent.

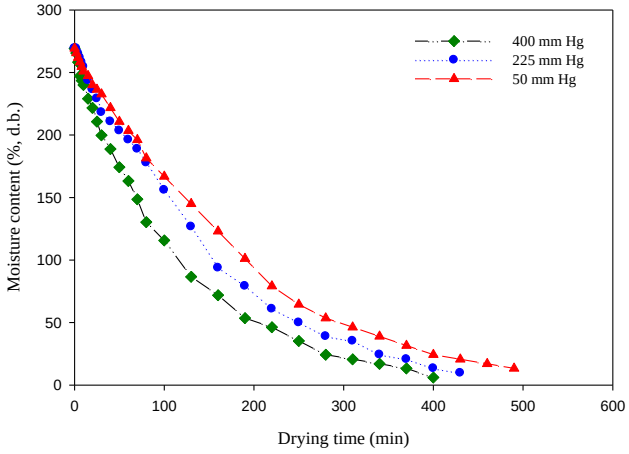
Hardness of rehydrated peas (H)

The probe "P/100" compression platen (100 mm) was used for textural analysis on Texture Analyzer (Model: TAHD, Stable Micro Systems, England). The settings of the instrument were as follows: pre-test speed-2 mm/s; test speed-1 mm/s; post-test speed-2 mm/s and distance (strain) 50%. The peak force in compression was taken as the hardness of rehydrated pea samples. Data presented are mean values of peak compression forces of 5 randomly selected grains.

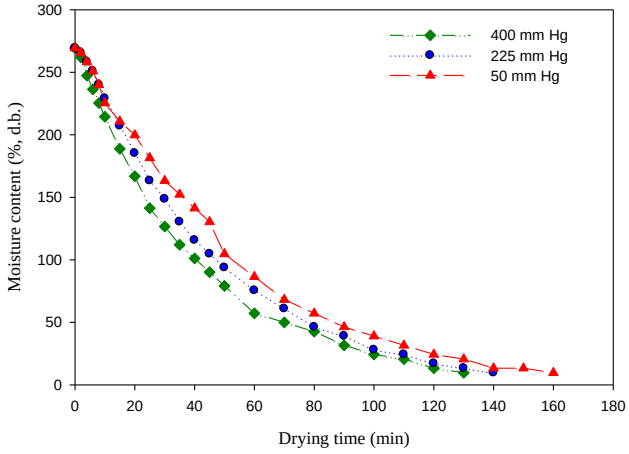
Results and Discussion

Drying kinetics

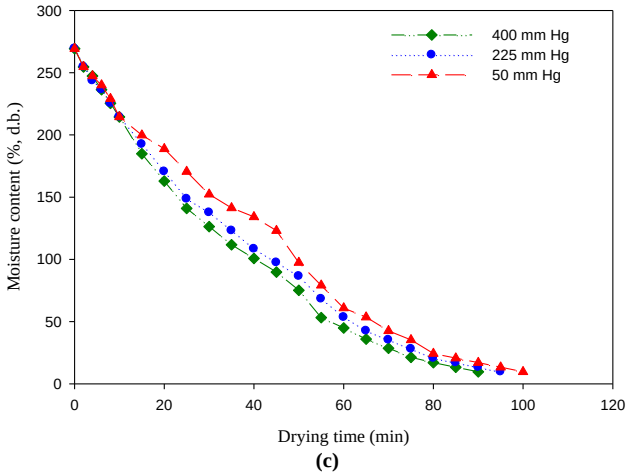
The drying curves at various microwave power levels are shown in Figs. 1(a) to (c). At any combination of microwave power and vacuum levels, the constant-rate drying period was not observed and drying apparently occurred entirely in falling-rate period. The moisture contents of



(a)



(b)



(c)

Figure 1. Effect of vacuum on drying behaviour at various microwave powers (a) 100 W, (b) 200 W and (c) 300 W

samples decreased with the increase in drying time until they reached a constant value. Average initial moisture contents of blanched samples was 269.25% (d.b.) which reduced faster during initial stage of drying as is evident by steeper slope of drying curves, however, as the drying proceeded it became slower evidenced by flatter drying curves. At a given microwave power level, the drying occurred relatively faster under higher vacuum. For example, at 100 W microwave power level, say after 30 min of drying, the moisture contents of the samples dried at 50, 225 and 400 mm Hg vacuum were 163.23, 148.60 and 126.67 % (d.b.), respectively. This was due to the fact that the water vapor has a lower saturation temperature at a lower absolute pressure (or higher vacuum) which results in a faster vaporization of moisture at a lower temperature. Interestingly, it was observed that at 200 and 300 W microwave power levels, the final moisture contents of all the samples did not alter with the change in vacuum levels and they were 6.02% and 9.68% (d.b.), respectively. However, vacuum levels did affect drying times required to reach equilibrium (dynamic) moisture conditions and it was shorter for samples dried under higher vacuum. At 300 W microwave power and under the vacuum of 50, 225 and 400 mm Hg, the drying times for the samples were 110, 100 and 95 min, respectively. But the same trend was not observed for the samples dried at 100 W microwave power. Probably, the application of vacuum for comparatively much longer period at 100 W microwave power as compared to those at 200 W and 300 W resulted in vacuum being a dominant factor in influencing the final moisture content.

Table 2. Statistical parameters estimated from regression analysis of drying models.

Model Name	Parameter	Microwave Power(W)								
		100			200			300		
					Vacuum (mm Hg)					
		50	225	400	50	225	400	50	225	400
Newton	R^2	0.9937	0.9856	0.9980	0.9895	0.9916	0.9978	0.9688	0.9823	0.9828
	χ^2	0.0009	0.0020	0.0003	0.0013	0.0011	0.0003	0.0037	0.0021	0.0020
	RMSE	0.0287	0.0438	0.0157	0.0359	0.0320	0.0159	0.0595	0.0445	0.0442
	P_0 (%)	27.155	32.634	4.5181	43.039	29.368	14.621	66.458	67.782	56.084
Page	R^2	0.9949	0.9962	0.9983	0.9980	0.9992	0.9990	0.9854	0.9920	0.9933
	χ^2	0.0007	0.0005	0.0002	0.0003	0.0001	0.0001	0.0018	0.0010	0.0008
	RMSE	0.0258	0.0223	0.0142	0.0158	0.0101	0.0104	0.0408	0.0300	0.0277
	P_0 (%)	19.384	9.9011	6.3966	12.998	8.7078	8.7893	32.959	38.672	30.264
Henderson & Pabis	R^2	0.9937	0.9872	0.9986	0.9928	0.9962	0.9986	0.9712	0.9841	0.9857
	χ^2	0.0009	0.0018	0.0002	0.0010	0.0005	0.0002	0.0036	0.0019	0.0018
	RMSE	0.0285	0.0412	0.0129	0.0297	0.0215	0.0124	0.0572	0.0422	0.0404
	P_0 (%)	26.408	29.708	5.2085	35.597	21.946	12.445	62.078	63.093	50.889
Logarithmic	R^2	0.9978	0.9953	0.9988	0.9976	0.9989	0.9993	0.9936	0.9984	0.9984
	χ^2	0.0003	0.0007	0.0002	0.0003	0.0002	0.0001	0.0008	0.0002	0.0002
	RMSE	0.0169	0.0249	0.0119	0.0172	0.0117	0.0092	0.0270	0.0134	0.0135
	P_0 (%)	5.0389	10.563	2.9163	9.3191	3.6334	5.9010	16.940	11.755	9.0855
Approxim-ate Diffusion	R^2	0.9937	0.9957	0.9989	0.9972	0.9976	0.9989	0.9937	0.9687	0.9730
	χ^2	0.0009	0.0006	0.0002	0.0004	0.0003	0.0002	0.0008	0.0040	0.0036
	RMSE	0.0287	0.0238	0.0115	0.0185	0.0173	0.0112	0.0268	0.0592	0.0556
	P_0 (%)	27.178	10.126	5.5806	9.8395	19.888	5.7818	15.497	98.234	77.336
Two term	R^2	0.9937	0.9872	0.9986	0.9928	0.9962	0.9986	0.9712	0.9841	0.9857
	χ^2	0.0009	0.0020	0.0002	0.0011	0.0006	0.0002	0.0039	0.0021	0.0020
	RMSE	0.0285	0.0412	0.0129	0.0297	0.0215	0.0124	0.0572	0.0422	0.0404
	P_0 (%)	26.394	29.683	5.2084	35.560	21.940	12.444	62.097	63.101	50.857
Wang & Singh	R^2	0.9934	0.9972	0.9768	0.9963	0.9943	0.9854	0.9950	0.9977	0.9978
	χ^2	0.0009	0.0004	0.0030	0.0005	0.0008	0.0018	0.0006	0.0003	0.0003
	RMSE	0.0293	0.0192	0.0530	0.0213	0.0263	0.0407	0.0239	0.0162	0.0160
	P_0 (%)	11.607	7.4794	22.606	13.107	16.330	26.131	10.045	6.1850	4.1661

Modeling of drying curves

For all combinations of microwave power and vacuum levels, the experimental data were fitted to seven semi-theoretical and empirical models as given in Table 1. The values of these statistical parameters for selected models have been shown in Table 2. The R^2 values ranged between 0.9993 and 0.9687, the χ^2 values ranged between 0.0040 and 0.0001, whereas, RMSE ranged between 0.0595 and 0.0092. For all combinations of microwave power and vacuum, one or more models passed the criterion of having P_0 value $\leq$ 10 %, except in case of drying at 300W microwave power and 50 mm Hg vacuum, wherein the least P_0 value was found to be marginally higher than 10% (i.e. 10.045 %) for Wang & Singh Model.

Effect of microwave power and vacuum on physical properties

Table 3 presents experimental data on physical properties of dehydrated peas obtained in MVD at various levels of microwave power and vacuum. The results of linear/polynomial modeling of these physical properties have been summarized in Table 4.

Volumetric shrinkage ratio

As the drying proceeds, the water present in the tissue gets evaporated, which results in the evacuation of the space inside the tissues. As a result of this, the tissue structure of wet biological material, being dried, collapses and causes volumetric shrinkage. From Table 3 it can be observed that the mean VSR at 100 W microwave power was lowest for the samples dried under 225 mm Hg vacuum followed by that at 400 mm Hg vacuum, whereas, for other two microwave power levels the values were highest for those samples which were dried under 225 mm Hg vacuum. From ANOVA (Table 4), it is evident that the linear model for VSR was significant ($p<0.01$) with a low value of coefficient of determination (0.68). Only linear term of microwave power had a significant effect on VSR at $p<0.01$ and vacuum did not show a significant effect on VSR. Since lack-of-fit was not significant, the model was found to be acceptable despite low coefficient of determination. The following regression equation, in coded factors, is obtained for VSR:

$$Y_{VSR} = 41.09 + 10.49 * X_1 - 1.99 * X_2 \quad \ldots\ldots\ldots\ldots\ldots (7)$$

The microwave power showed a positive correlation with VSR as is evident from Eq. (7) and Fig.2, depicting the influence of microwave power and vacuum on the predicted VSR. The reason for the higher VSR in samples dried at higher applied microwave power was the rapid drying which would have introduced a permanent tension that prevented the original dimensions to some extent and cracks and voids developed internally [3].

Bulk density ratio

The change in the bulk density is correlated to the moisture content, linear shrinkage and volumetric shrinkage. The product that has higher ratio of linear and volumetric shrinkages will have lower value of the BDR, if moisture content remains the same. The BDR of dehydrated pea samples in MVD ranged between 63.75 and 91.45%. The values were highest for samples dried at 200 W and lowest for those dried at 300W, which might be due to a complex interplay of certain properties as have been mentioned above. The quadratic model showed a good significance (at $p<0.01$) as can be seen from Table 4, with a moderate value of R^2 (0.89). The linear term of microwave power showed significance at $p<0.01$ and that of vacuum at $p<0.05$. Also, interaction and quadratic terms of both the factors were significant at $p<0.01$. The regression model in terms of coded factors, obtained is as follows.

$$Y_{BDR} = 84.93 - 2.76 * X_1 - 1.95 * X_2 - 3.92 * X_1 * X_2 - 17.24 * X_1^2 + 4.49 * X_2^2 \quad \ldots\ldots\ldots\ldots\ldots (8)$$

Coded variables		Actual variables		Responses			
X_1	X_2	x_1	x_2	VSR (%)[a] (Y_{VSR})	BDR (%)[b] (Y_{BDR})	B&D (%) ($Y_{B\&D}$)	Hardness (N)[c] (Y_H)
-1	0	100	225	28.50	68.42	0.00	7.81
0	-1	200	50	33.33	93.20	2.40	6.32
1	0	300	225	44.33	66.07	6.55	2.94
1	1	300	400	44.33	63.00	14.60	2.53
-1	1	100	400	28.00	77.69	0.00	6.41
-1	-1	100	50	33.33	74.81	0.00	8.34
1	-1	300	50	44.33	76.27	10.96	4.48
-1	0	100	225	32.14	69.45	0.00	7.31
-1	-1	100	50	31.13	72.86	0.00	8.05
0	0	200	225	33.33	84.60	2.25	5.41
0	1	200	400	38.00	96.73	4.48	4.32
1	1	300	400	45.01	65.81	16.60	2.05
0	0	200	225	38.08	83.54	2.90	5.59
-1	1	100	400	32.14	79.06	0.00	6.52
1	0	300	225	64.86	64.75	10.76	3.53
-1	0	100	225	32.59	68.25	0.00	7.81
0	0	200	225	48.31	86.57	3.22	5.41
1	1	300	400	46.80	62.43	15.00	2.56
1	-1	300	50	59.02	73.80	8.27	4.16
0	1	200	400	35.03	80.74	2.12	4.30
0	-1	200	50	42.86	91.02	2.00	6.08
0	0	200	225	38.91	80.56	2.45	5.59
0	0	200	225	48.68	93.52	2.10	5.59
0	1	200	400	37.41	80.60	3.10	4.16
1	0	300	225	65.41	65.08	7.24	3.53
-1	1	100	400	33.56	77.78	0.00	6.32
0	-1	200	50	40.14	90.12	2.10	6.03
1	-1	300	50	59.02	74.11	9.10	4.06
-1	-1	100	50	32.99	72.71	0.00	8.26

X_1 is microwave power (W) and X_2 is vacuum (mm Hg)

[a] Mean volume of fresh pea grains = 0.574 cm^3

[b] Mean bulk density of fresh peas = 0.429 g/cm^3

[c] Mean hardness of fresh pea samples = 23.75 N

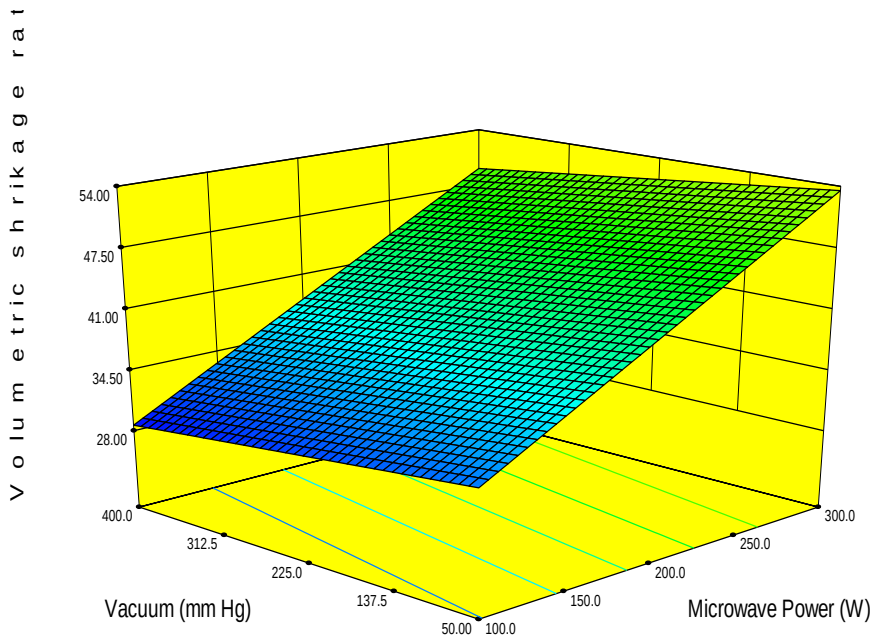


Figure 2. Effect of microwave power and vacuum on the volumetric shrinkage ratio of dried green peas.

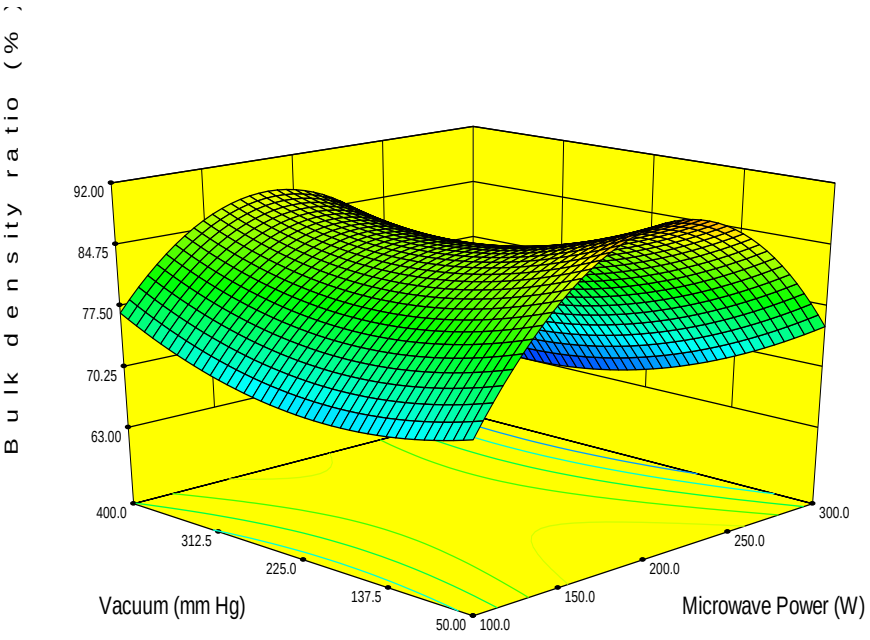


Figure 3. Effect of microwave power and vacuum on the bulk density ratio of dried green peas.

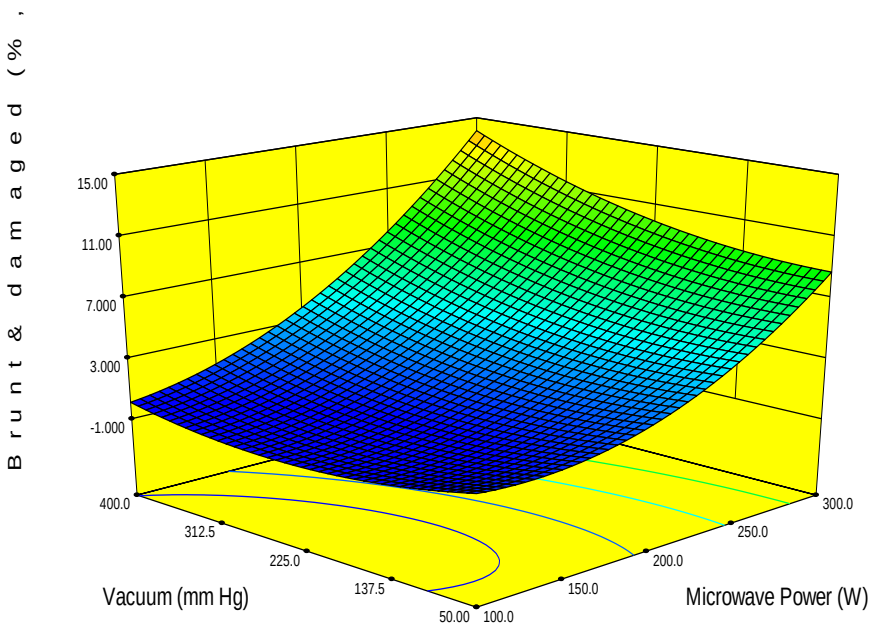


Figure 4. Effect of microwave power and vacuum on the burnt and damaged grains percentage of dried green peas.

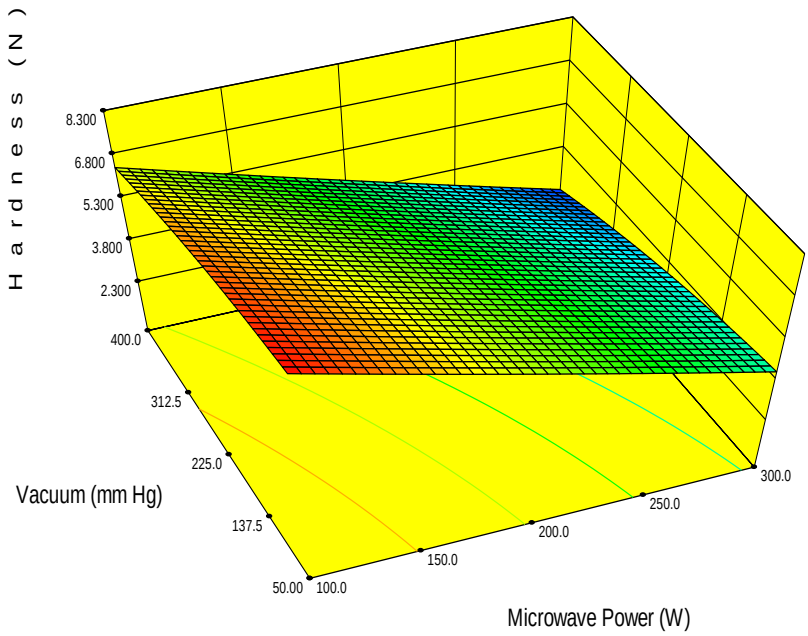


Figure 5. Effect of microwave power and vacuum on hardness of dried green peas after rehydration.

Table 4. ANOVA for models of different physical properties[#]

Variables/ factors	VSR	BDR	B&D	Hardness
		F values		
Model	27.20(2)**	35.73(5)**	63.46(5)**	785.65(3)**
Microwave power (X_1)	52.48(1)**	10.09(1)**	260.66(1)**	1954.83(1) **
Vacuum (X_2)	1.89(1)	5.02(1)*	11.79(1)**	393.09(1)**
X_{12}	--	13.58(1)**	12.72(1)**	--
X_1^2	--	147.04(1)**	23.42(1)**	--
X_2^2	--	9.98(1)**	5.49(1)*	9.03(1)**
Residual	--(26)	--(23)	--(25)	--(25)
Lack of Fit	1.33(6)	0.60(3)	8.5(5)**	0.72 (5)
Pure error	(20)	(20)	(20)	(20)

Significance: ** ($p<0.01$); * ($p<0.05$)

[#]Values given in parentheses are degree of freedom (df) of respective variables/ factors

Fig. 3 shows response surface plot for BDR. The linear term of microwave power and quadratic term of vacuum showed a positive correlation with BDR while the linear term of vacuum vis-à-vis quadratic term of microwave power and interaction term showed a negative correlation.

Burnt and damaged (B & D) grains percentage

The regression model (Eq. (9)) for the burnt and damaged dehydrated peas was significant at $p<0.01$ (Table 4). Linear terms and two factor interaction term of both the factors significantly affected the phenomenon at $p<0.01$. However, quadratic term of only microwave power was found to be significant (at $p<0.01$). Although, 'lack-of-fit' was found to be significant, the model may be accepted since the model was significant with a high value of coefficient of determination (0.93). Fig.4 shows the response surface plot depicting the effect of microwave power and vacuum on the predicted response variable. B&D grains percentage was found to be noticeably higher when drying was carried out at 300 W, whereas, at 200 W microwave power level it had acceptably low mean values, in the range of 2.17% and 3.23%. At 100 W, there were no B&D grains observed. Microwave drying is often implicated for having uneven energy distribution over the products which results in uneven drying [21]. This nature of microwave energy was apparent when the drying was carried out at 300 W. A high microwave power causes higher heat generation leading to more rise in temperature and resulting in higher risk of burning and damage to kernels at the final stage of drying. Also, since microwave has good penetration power, its higher level would have developed greater pressure due to the generation of efflux of water-vapor inside the grains, resulting in their bursting. This phenomenon might be more apparent in peas because they were dicotyledonous grains, protected by a weak seed-coat. A higher vacuum further aggravates bursting due to higher pressure difference between pea surface and core. The quadratic model obtained for B &D grains is as given below:

$$Y_{B\&D} = 1.93 + 5.50 * X_1 + 1.17 * X_2 + 1.49 * X_1 * X_2 + 2.70 * X_1^2 + 1.31 * X_2^2 \quad \text{.....(9)}$$

Hardness (H) of rehydrated peas

The hardness of rehydrated samples dried at a higher level of vacuum and at a given microwave power was found to lower. Similarly, the values also decreased for the samples dried at higher microwave power level with a given level of vacuum. Table 3 indicates hardness of rehydrated samples dried in MVD experiments.

Table 4 shows that the regression model for the hardness for rehydrated peas was significant at $p<0.01$. Linear terms of both the factors and quadratic term of vacuum significantly affected the hardness (at $p<0.01$) and had negative correlation with it. The interaction term and quadratic term of microwave power did not show significance. The coefficient of determination was found to be high (0.99) and lack of fit was not significant which indicates that experimental data fitted well to the model.

Fig.5 shows the response surface plot, depicting the effect of microwave power and vacuum on the predicted hardness of rehydrated samples. The quadratic model obtained for hardness of rehydrated peas is as follows.

$$Y_H = 5.50 - 2.06 * X_1 - 0.92 * X_2 - 0.23 * X_2^2 \quad \ldots\ldots\ldots\ldots\ldots (10)$$

Reduced hardness in rehydrated samples is attributed to higher moisture on rehydration, which in turn, was due to more puffing (as is evidenced by higher VSR) during MVD at a higher level of vacuum as well as microwave power.

Conclusion

The experimental study has indicated that microwave power has a dominant effect on drying kinetics of green peas. A higher level of microwave power definitely reduces drying time and yields a low-moisture product, whereas a higher vacuum does it marginally. Both microwave power and vacuum have positive influence over physical properties included in this study, except over burnt and damaged grains percentage. However, if the microwave power is limited to around 200 W, the burnt and damaged grain percentage may be kept reasonably low. In our earlier article [10], the optimum level of microwave power and vacuum were statistically predicted as 237.31 W and 360.22 mm Hg, respectively which may yield dehydrated peas with a low percentage of burnt and damaged grains.

References

1. Zogzas, N.P., Maroulis, Z.B. and Marinos-Kouris, D. (1994). Densities, shrinkage and porosity of some vegetables during air drying. ***Drying Technology,*** 12:1653-1666.

2. Maroulis, Z.B., Tsami, E., Marinos-Kouris, D. and Saravacos, G.D. (1998). Application of the GAB model to the sorption isotherms of dried fruits. ***Journal of Food Engineering,*** 7(1): 63-78.

3. Raghavan, G.S.V. and Silveira, A.M. (2001). Shrinkage characteristics of strawberries osmotically dehydrated in combination with microwave drying. ***Drying Technology,*** 19 (2): 405-414.

4. Clary, C.D., Mejia-Meza, E., Wang, S. and Petrucci, V.E. (2007). Improving grape quality using microwave vacuum drying associated with temperature control. ***Journal of Food Science,*** 72 (1): E023-E028.

5. Fathima, A., Begum, K. and Rajalakshimi, D. (2001). Microwave drying of selected greens and their sensory characteristics. ***Plant Foods for Human Nutrition***, 56**:** 303–311.

6. Scaman, C.H. and Durance, T.D. (2005). Combined microwave vacuum-drying. In: Sun, Da-Wen (Ed.) Emerging Technologies for Food Processing (pp 505-531). Elsevier Academic Press.

7. Gracia, A., Iglesias, O. and Roques, M. (1992.) Microwave drying of agar gels. In: Mujumdar A.S.(Ed.) Drying '92 (pp 595–606). Elsevier Academic Press.

8. Yongsawatdigul, J. and Gunasekaran, S. (1996). Microwave-vacuum drying of cranberries: part I, energy use and efficiency. ***Journal of Food Processing and Preservation***, 20(2):121-143.

9. Liu, C., Zheng, X., Jia, S., Ding, N., Gao, X. (2009). Comparative Experiment on hot-air and microwave-vacuum drying and puffing of blue honeysuckle snack. ***International Journal of Food Engineering***, 5(4): Art.4 (doi: 10.2202/1556-3758.1683).

10. Chauhan, A.K.S. and Srivastava, A.K. (2009). Optimizing drying conditions for vacuum-assisted microwave drying of green peas (*Pisum sativum* L.). ***Drying Technology***, 27(6): 761-769.

11. Krulis, M., K¨uhnert, S,, Leiker, M. and Rohm, H. (2005). Influence of energy input and initial moisture on physical properties of microwave-vacuum dried strawberries. ***European Food Research and Technology***, 221: 803-808.

12. Kwok, B.H.L., Hu, C., Durance, T. and Kitts, D.D. (2004). Dehydration techniques affect phytochemical contents and free radical scavenging activities of Saskatoon berries (*Amelanchier alnifolia* Nutt.). ***Journal of Food Science***, 69(3):SNQ122-126.

13. Yanyang, X., Min, Z., Mujumdar A.S., Le-qun, Z. and Jin-cai, S. (2004). Studies on hot air and microwave vacuum drying of wild cabbage. ***Drying Technology***, 22(9): 2201-2209.

14. http://faostat.fao.org/site/339/default.aspx. (accessed 09/03/2012).

15. Ranganna, S. (1986). Handbook of analysis and quality control for fruits and vegetables products. Tata McGraw Hill, New Delhi. p:4

16. Lee, J., Ye, L., William, O.L.J. and Eitenmiller, R.R. (2000). Optimization of extraction procedure for the quantification of vitamin E in tomato and broccoli using response surface methodology. ***Journal of Food Composition and Analysis***, 13(1):45–57.

17. Montgomery, D.C. (1984). Design and analysis of experiments. John Wiley & Sons, New York.

18. Ong, S.P. and Law, C.L. (2009). Mathematical modeling of thin layer drying of salak. ***Journal of Applied Sciences***, 9(17): 3048-3054.

19. Pardeshi, I.L., Arora, S. and Borker, P.A. (2009). Thin-layer drying of green peas and selection of a suitable thin-layer drying model. ***Drying Technology***, 27(2):288-295.

20. Alves-Filho, O., Garcı´a-Pascua,l P., Eikevik, M.T. and Strømmen, I, (2004), Dehydration of green peas under atmospheric freeze-drying conditions. In: Proceedings of the 14th International Drying Symposium (Drying-2004), Vol. C, 1521–1528, São Paulo, Brazil, August 22–25, 2004.

21. Wang, R., Li, Z., Su, W., Ye, J. (2010). Comparison of microwave drying of soybean in static and rotary conditions. ***International Journal of Food Engineering***, 6(2): Art.2 (doi: 10.2202/1556-3758.1836).