An Optimized Design of a PLC-Based Controlled Microwave Vacuum Dryer for Preliminary Drying Studies on Rice Bran

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Abstract—**This study presents an optimized design of a PLC-based microwave vacuum dryer which was used to conduct preliminary investigation of the effects of drying parameters on the drying kinetics of rice bran. The study initially conducted a methodical analysis of the microwave chamber and its auxiliary attachments. Using CST Microwave Studio simulation software, it was seen that the best design for a 30-L MV chamber operating at 2.45 GHz is a cylindrical chamber with a radius of 202 mm, length of 400 mm, and with 2 perpendicular feeders located near the ends of the chamber. To achieve uniform product heating, a rotary drive assembly was incorporated into the system (i.e. mixing the product during the drying process). A PLC-based control box with HMI display was developed to constantly monitor the drying kinetics of rice bran. Subsequently, drying experiments were then carried out. The study successfully used fractional factorial design (FFD) with center points to model the interaction effects on MVD parameters on moisture extracted and color of rice bran. Experimental verification of the model resulted to 1.18% error of the actual versus predicted moisture extracted.**

Index Terms— **fractional factorial design (FFD), microwave vacuum dryer, programmable logic controller (PLC), rice bran**

I. Introduction

Drying is one of the oldest and most common methods of food preservation process [1]. Conceptually, drying inhibits the growth of bacteria and microorganisms through reduction of moisture in food until it is considered safe for storage. Practically, drying is also done to lessen, if not totally eradicate food waste globally. It is quite ironic that a lot of people suffer from hunger yet the world is producing more than enough food. Sad truth is that, almost one third of the foods are actually put into waste [2] in which, actually, the problem largely stems out from poor infrastructure and lack of modern food processing technologies.

There are many known conventional methods of drying food nowadays such as solar drying, hot-air drying, freeze drying, and vacuum drying. These conventional dehydration processes are in fact, already widely used for food industries. However, the shortcomings on these drying methods have been apparent in terms of low energy efficiency, thermal degradation, and nutrient loss of finished products [3] [4]. This consequently leads to the development of microwave-vacuum drying technique which combines the advantages of microwave heating in a vacuum environment. Basically, microwave heating saves drying time and energy while vacuum condition lowers the boiling point temperature [4] [5] [6] which in effect, directly influencing the final product quality. The use of this method could be of interest especially for thermo-labile products such as powdered and granulated foods [7].

Despite the numerous studies supporting the advantages of microwave technology, it is barely explored for drying applications. The difficulty in providing uniformity of the drying material provides the biggest resistance to its widespread use [8] [9]. Thus, in this study, an optimized design of microwave vacuum chamber utilizing rotary drive assembly is proposed to address the predicament. The equipment is then tested to low-moisture food product such as rice bran. Part also of this study is to have a preliminary study on the drying kinetics of rice bran through evaluation of the effects of drying parameters such as microwave power levels, vacuum pressure, capacity, and drying time to the extracted moisture content and finished product's color. Basically, a good understanding of the drying kinetics and the effect of drying parameters are necessary for a design and control of the drying process to achieve the desired quality of products.

II. Development of Microwave Vacuum Dryer

A. Optimization of Microwave Vacuum Chamber

An optimized design of a microwave vacuum (MV) chamber was first studied prior to the development of the whole microwave vacuum dryer. Using CST Microwave Studio simulation software, the optimal design parameters of the chambers were determined. It is seen that the best design for a 30-L MV chamber operating at 2.45 GHz, a frequency which is the same as what is used in a conventional microwave oven, is a cylindrical chamber with a radius of 202 mm, length of 400 mm, and with two perpendicular feeders located near the ends of the chamber. For varying material volumes (50%, 70%, and 90%), the results show that overall, the 50% yielded the highest energy field, energy distribution, and absorption rate. However, all

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the models yield results that are not very far from the other models. This means that the microwave vacuum dryer design performs well at whatever level the material container is filled with. A more detailed discussion of the optimization procedures made by the authors can be seen from [10].

Considering the results of the conducted simulations, an optimized design of a microwave vacuum chamber was fabricated as shown in Figure 1. The whole body is made from stainless steel type SS304 which perfectly fit in the design as far as food applications are concerned. Also, it has holes provision for flanges and for other major components with proper sealing ensuring no significant leakage occurs.

Fig. 1. Fabricated microwave vacuum chamber as the result of the simulations

B. Incorporation of Rotary Drive Assembly

Non-uniform product heating has been a problem so far with the microwave vacuum dryers [8] [9] especially if the raw materials to be dried are in powdered form. However, with careful control of microwave power, especially during the final stages of drying, high quality product has been reported to be obtainable [3] [11]. For this study though, the problem with non-uniform heating was resolved in a more direct manner by just incorporating a mechanism for mixing the product during the drying process. Figure 2 shows the attachment of a motor drive assembly to the fabricated MV chamber.

Figure 3 shows the designed sample holder fit for MV chamber. The holder was made using a food-grade transparent material compatible for microwave application. The positioning of the mixing plights was also carefully considered in the design of the sample holder. The plights on the top and bottom part of the container were angled to

Fig. 2. Attachment of rotary drive assembly to the microwave vacuum chamber

Fig. 3. Design of sample holders with plights

direct the bran to the center during rotation. Mixing experiments were even done to determine the effectiveness of product mixing.

C. Control System Development

The whole system was controlled by a Panasonic FP0-C16T Programmable Logic Controller (PLC). It was incorporated with a 10-inch Human-Machine Interface (HMI) so operators could achieve the desired output with minimal input. Every process was activated accordingly as set in the programming of the controller. Figure 4 shows the block diagram of the control system for an MVD.

In consideration of the drying technology requirement of dried materials in the MVD, the drying parameters could be set optionally in the HMI including the microwave power, motor angular speed, and drying time as depicted in Figure 5. As design optimization is not a straight forward process, there was an iterative characterizations and re-testing in order to meet the control parameters for rice bran.

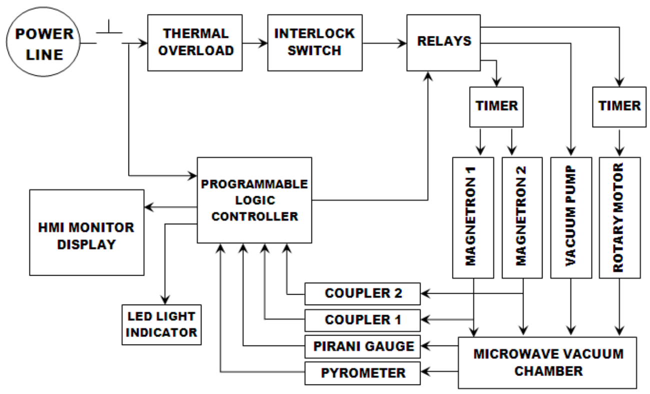

Fig. 4. System block diagram of an MVD

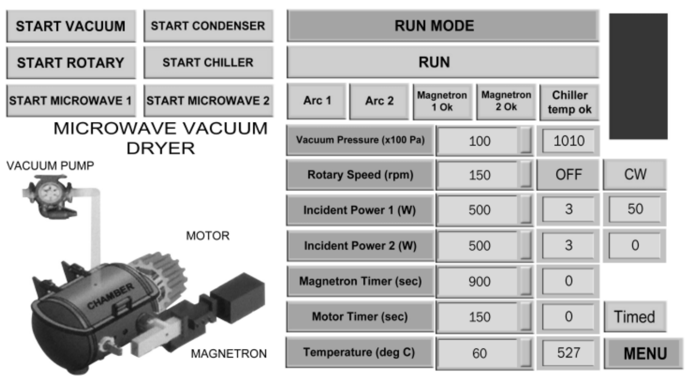

Fig. 5. Setting of drying parameters in the HMI of the control panel box

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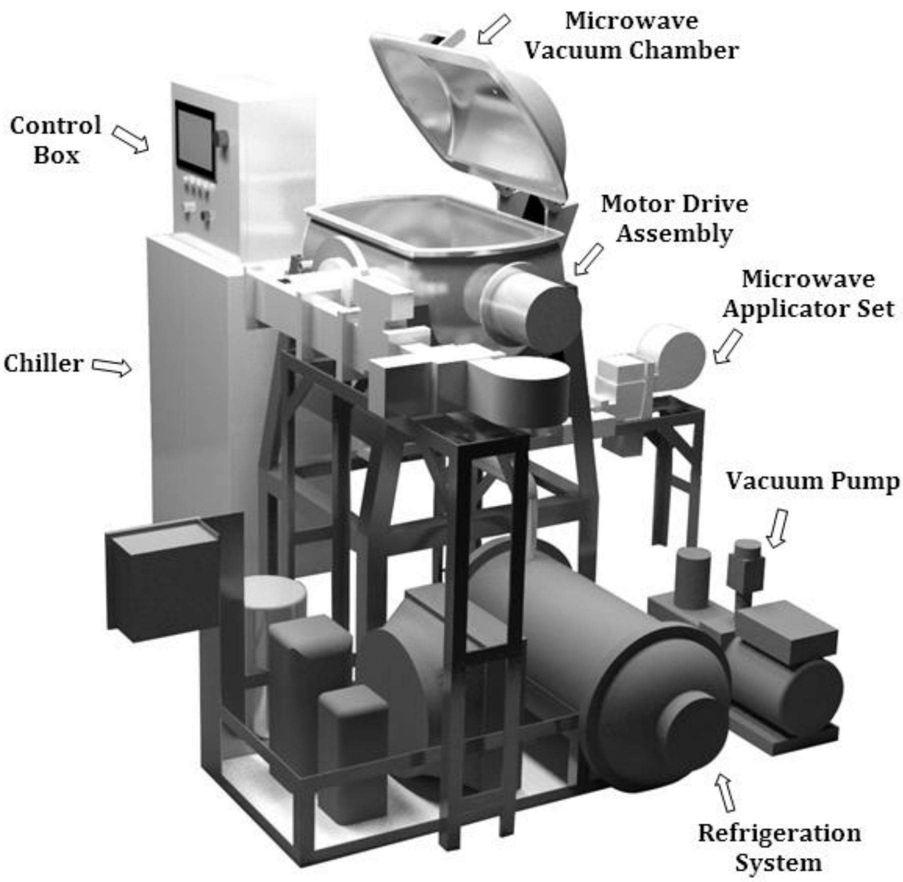

Fig. 6. Complete overview of a microwave vacuum dryer

D. Complete Microwave Vacuum Dryer

A complete system diagram of a microwave vacuum dryer is depicted in Figure 6. The main components of the microwave vacuum dryer consists of 1) microwave vacuum chamber, 2) rotary drive assembly, 3) microwave applicator set, 4) refrigeration system, 5) rotary pump, 6) control box, and 7) chiller.

Two microwave applicator sets were utilized in the design generating a variable power of 0 to 1kW at a single frequency of 2.45 GHz. The magnetrons were attached perpendicularly in accordance to the simulation made to achieve a uniform energy distribution inside the chamber as much as possible. Alongside with the generators, a recirculating chiller was installed to serve as a parallel cooling system for the two microwave generators.

A one-phase-motor vacuum pump capable of lowering the pressure to at least 10kPa was used to create a vacuum inside an MV chamber. Working pressure must be thoroughly selected in accordance to Paschen's Law, not too low to avoid breakdown voltage necessary to start electric arc inside the chamber. Since drying is primarily extracting moisture from the food, it is therefore inevitable for water to accumulate in the vacuum pump in the long run. A refrigeration system must then be installed in between the MV chamber and vacuum pump to ice the moisture before it even reaches the vacuum pump.

A pirani gauge and an optical pyrometer were installed to respectively measure real-time pressure and temperature inside the MV chamber. Arc detector was also incorporated shutting the microwave generator down whenever extremely high electric field strength builds up inside the chamber.

Design materials needs to be considered especially for the attachments in the chamber that any protruded metal inside the chamber may be transformed into an antenna which may produce undesired plasma during drying process.

III. EXPERIMENTAL PROCEDURES

A. Test for Mixing Effectiveness

Mixing experiments were made to determine the effectiveness of mixing raw materials inside the developed sample holder. Only 50% equivalent to 900 g of the container volume was utilized. A combination of colored (green) and uncolored rice bran (natural) was used with a ratio of 1:9 (colored to uncolored). A 90 g of green colored bran was placed at the bottom part of the container and topped with 810 g of the natural-colored sample. The bran was mixed for 5 minutes at different rotary speed starting from 50 to 150 rpm with an increment of 25 rpm. Samples from the top, middle, and bottom portions of the sample holder were collected using a polyvinyl chloride (PVC) pipe. The L*, a*, and b* measurements of mixed samples and of the control (natural-colored bran) were collected using a HunterLab Spectrocolorimeter. The color difference between the mixed samples compared to the natural-colored rice bran ΔE^*_{ab} was calculated using

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where ΔL^* is the numerical lightness difference ($L^*=0$ yields black and $L^*=100$ indicates diffuse white), Δa^* is the numerical difference in the red-green coordinate in the color space ($+a^*$ indicates redness and $-a^*$ indicates greenness), and Δb^* is the numerical difference in yellow-blue coordinate in the color space ($+b^*$ indicates yellowness and $-a^*$ indicates blueness).

B. Statistical Analyses

Fractional factorial design (FFD) is a collection of mathematical and statistical techniques to screen the influence of several independent variables to a response variable [12]. A fit data for response variables used multiple linear regression analysis with equation

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i z_i + \sum_{ij=1,i<j}^{n} \beta_{ij} z_i z_j + \cdots + \beta_{1,2\ldots,L.} z_1 z_2 \ldots z_L + \varepsilon \quad (2)$$

where Y is the predicted response, $\beta^t = \{\beta_1, \beta_2, \ldots, \beta_{1,2,\ldots,L}\}$ are the effect coefficients (t represents transpose), $z = (z_1, z_2, \ldots, z_L)$ are the independent variables, and ε is the error term. In this study, a fractional factorial design with 4 center points and 2 replicates was generated and analyzed using Design-Expert 7.0 software.

C. *Microwave Vacuum Drying Setup*

Sacks of rice bran were purchased directly from a local rice mill in Nueva Ecija, Philippines and were sieved afterwards removing any dirt or contaminations mixed with it (e.g. stones and rice husk) to amass just fine-grade bran. The independent parameters that were considered are the microwave power (Watt), vacuum pressure (kPa), and process time (minutes). The moisture (M %) and color difference (ΔE^*_{ab}) are the response variables of the independent MVD parameters. The initial moisture content of the rice bran varies for different samples therefore only the changes measured after MVD were considered using:

$$\Delta\%Moisture = FMC\% - IMC\% \quad (3)$$

where $\Delta\%Moisture$ is the difference in moisture content in percentage, $FMC\%\ and\ IMC\%$, are the final moisture and initial moisture content in percentage. The color difference of rice bran can be determined using equation (1).

D. Verification Procedure

Based on the model, a setup of MVD parameters with the objective of minimizing the microwave power and process time and maximizing the rice bran weight and vacuum pressure was generated as shown in Table 1. The importance of the goals for the MVD parameters was to set to minimum while the importance for maximum extracted moisture was set to maximum. The moisture extracted generated by the model was verified experimentally.

TABLE I. SPECIFICATIONS OF CRITERIA FOR THE VERIFICATION OF THE INDEPENDENT AND RESPONSE VARIABLES

Factors	Optimization Criteria		
A. Independent Variables	Goal	Limits	Importance
Microwave Power	Minimize	200-1200	+
Weight	Maximize	150-1440	+
Process Time	Minimize	10-30	+
Pressure	Maximize	4.4-20	+
B. Dependent Variable			
Extracted moisture	Maximize	5-8	+++++

IV. RESULTS AND DISCUSSIONS

A. Effect of Rotary Speed to Mixing Homogeneity

Table II shows the behavior of the rice bran when mixed with different rotaring speed for five minutes. It is expected to have a low delta E from brown and a high delta E from green since 90% of the mixture composed of natural-colored rice bran. Data shows that the rice bran mixed at 100, 125, and 150 rpm have $\Delta E*$ values that are almost the same from the top, middle, and bottom portion of the mixture. Therefore, mixing should be set at greater than or equal to 100 rpm to ensure proper mixing.

B. Regression Models

The corresponding regression coefficients of MVD parameters in the linear model is shown in Table III. The p-values of the models generated for the effects of MVD parameters on ΔMoisture% and (ΔE^*_{ab}) are less than 0.05 which indicates that the models are significant. Also, the coefficients with superscript '*a*' show significant p-value ($p<0.05$). Therefore, the generated model shows significant effects of microwave power, capacity, and process time on Δ%Moisture. Only the capacity shows significant effect on (ΔE^*_{ab}). The vacuum pressure did not have any significant effect on dependent variables. However, the interaction of pressure to other independent variables indicates significant effects on the response variable. Every generated model has high desirable adequate precision. This means that the models can adequately predict the response variable as a function of microwave power, capacity, process time, and vacuum pressure.

C. Effects on Moisture Content

The contour plot in Figure 7 presents the interaction effects of microwave power and process time on the square root of moisture extracted (Δ%Moisture). An increase in microwave power and process time also increases the moisture extracted in rice bran. Given an initial moisture

TABLE III. CORRESPONDING COEFFICIENTS OF MVD PARAMETERS IN THE QUADRATIC PREDICTIVE MODELS AND MEASURES OF MODE FIT

	Corresponding coefficients	
	Δ %Moisture	ΔE^*_{ab}
Model		
Constant	+0.9116	-0.1279
A-Microwave Power	+6.6481E-004[a]	0.0002
B-Capacity	-1.27454E-004[a]	0.000338 [a]
C-Process Time	+0.031361 [a]	-0.00738
D-Pressure	-0.014126	0.0313
AB	-6.96637E-007[a]	-1.6E-07
AC	+2.00188E-005[a]	2.01E-05 [a]
AD	+2.54445E-005 [a]	-3.4E-05[a]
R^2	0.9945	0.6974
R^2adj	0.9656	0.546051
Adeq Precision	30.346 [b]	8.5940 [b]
Curvature	< 0.0001[a]	0.0059[a]
Lack of Fit	0.4803	------
F-value	85.15[a]	4.61[a]
P-Value	< 0.0001[a]	0.0073[a]
Transformation	$\sqrt{Y}$	None

R^2, R^2adj and Lack of fit are measures of fit of the model.
a Coefficients significant (95% confidence level).
b "Adeq Precision" measures the signal to noise ration. A ratio greater than 4 is des

TABLE II. COLOR DIFFERENCE ANALYSIS FOR MIXING RICE BRAN USING DIFFERENT ROTATING SPEED

Experiment Parameters	Sampling pints	Color			Change in color	
		L	*a*	*b*	*delta E (ΔE*) from Brown*	*delta E(ΔE*) from Green*
Control, green		56.00	-12.47	28.83		
Control, brown		74.41	2.21	19.50		
Time: 5 minutes Rotation: 150 rpm	Top	70.21	0.46	21.07	4.82	20.72
	Middle	69.86	0.31	21.69	5.40	20.16
	Bottom	70.38	0.25	21.55	4.93	20.54
Time: 5 minutes Rotation: 125 rpm	Top	67.33	0.75	22.45	3.45	15.00
	Middle	67.28	0.81	22.61	3.48	14.97
	Bottom	67.03	0.61	22.46	3.77	14.73
Time: 5 minutes Rotation: 100 rpm	Top	70.63	0.62	21.41	4.53	20.99
	Middle	70.48	0.33	21.52	4.80	20.66
	Bottom	70.45	0.22	21.40	4.82	20.71
Time: 5 minutes Rotation: 75 rpm	Top	67.66	1.79	22.62	2.70	15.95
	Middle	67.43	0.89	22.58	3.30	15.12
	Bottom	67.74	0.22	22.62	3.50	14.74
Time: 5 minutes Rotation: 50 rpm	Top	72.79	1.10	20.24	2.10	23.24
	Middle	72.20	0.30	20.52	3.10	22.24
	Bottom	71.40	-0.73	20.82	4.42	20.15

content of 10-13%, the plot highlights the possible combinations of microwave power and process time which can lead to the desired final moisture of 5-8%. The minimum value of ΔM% for these combinations would be 5% or $\sqrt{\Delta\%\text{Moisture}} = 2.25$.

Figure 8(a) shows the interaction of microwave power and rice bran quality and their effects on moisture extracted in rice bran. Increase in microwave power and capacity decreases the moisture extracted in rice bran. Given an initial moisture content of 10-13%, the plot highlights the possible combinations of microwave power and capacity which can lead to desired final moisture content of 5-8%. The interaction effects of pressure and microwave power is shown in Figure 8(b). At low microwave power, the moisture extracted increase slightly with the increase in pressure. The effect is opposite for high microwave power where the moisture extracted decreases with increasing pressure. There is no significant effect of pressure to extracted moisture using 450-700 Watts microwave power.

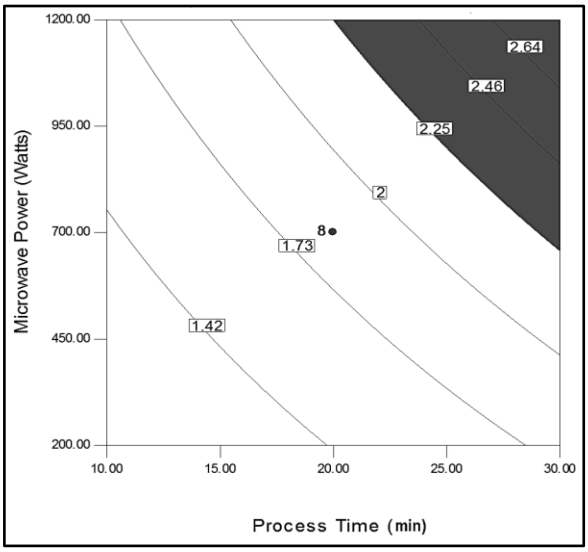

Fig. 7. The effects of microwave power (Watts) and process time (min) on the moisture extracted (ΔM%) in rice bran.

D. Effects on Color

Figures 9(a) presents the contour plot of the effects of microwave power over time on the color of rice bran. A value of ΔE^*_{ab} less than 1 means no visible color changes in rice bran. Therefore, no visible color changes are observed when using the 200-1200 Watts microwave power for 10-30 min. However, it was observed that increasing the microwave power beyond 450 Watts increases the value of ΔE^*_{ab} which could still increase for microwave power greater than 1200Watts.

In Figure 9(b), the combined effects of microwave power and pressure on the color (ΔE^*_{ab}) of rice bran are shown. With the presence of vacuum pressure, the ΔE^*_{ab} still increases but the ΔE^*_{ab} values saturates at around 700 Watts. The pressure somewhat controls the color changes in rice bran.

V. CONCLUSION

The study presents an optimized design of a microwave vacuum dryer which were used to conduct preliminary drying studies on rice bran. The problem with non-uniform product heating leading to scorching was resolved by incorporating a mechanism for mixing the product during the drying process. As per the control system, a PLC-based control panel with HMI display was developed to monitor the real-time drying kinetics of rice bran and to consequently establish a set of MVD parameters maximizing the drying process. Subsequently, the developed equipment was successfully used for drying kinetics study on rice bran. The study used FFD with center points to model the interaction effects of MVD parameters on moisture extracted ($\Delta\%Moisture$) and color (ΔE^*_{ab}) of rice bran. The generated model indicates significant effects of microwave power, capacity, and process time on the moisture extracted and color in rice bran. The vacuum pressure has no significant effect on moisture extracted but effectively regulates the color of rice bran having ΔE^*_{ab} greater than 1. Experimental verification of the model results to 1.18% error of the actual versus predicted moisture extracted.

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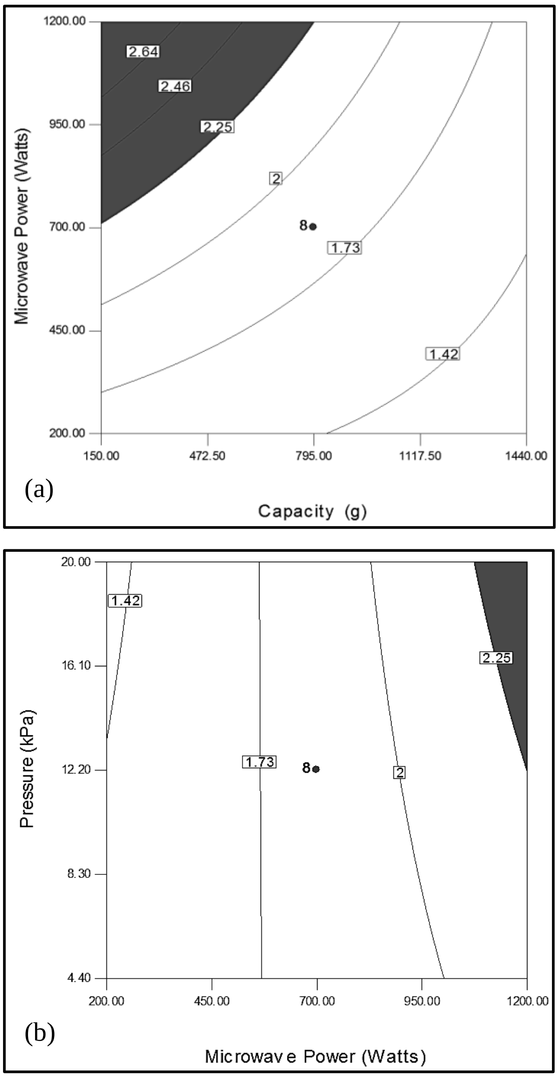

Fig. 8. The effects of (a) microwave power (Watts) and rice bran capacity (grams) and (b) pressure and microwave power (Watts) on the moisture extracted (ΔM%) in rice bran.

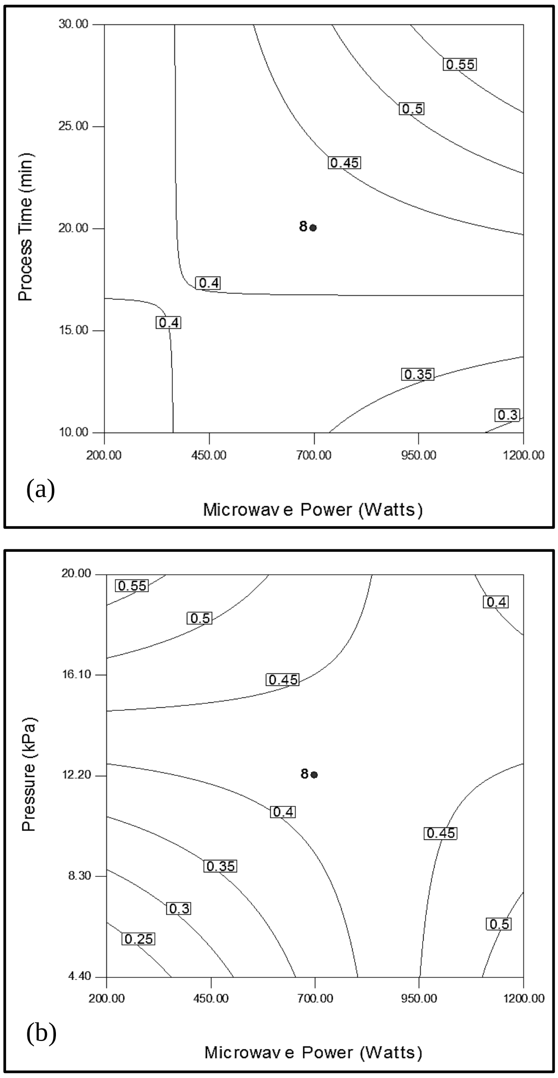

Fig. 9. The effects of (a) process time (min) and microwave power (Watts) and (b) pressure (kPa) and microwave power (Watts) on the color (ΔE^*_{ab}) of rice bran.

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