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Process optimization for drying of Shrimp (*Metapenaeus dobsoni*) under hot air-assisted microwave drying technology using response surface methodology

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Abstract

The study was carried out to optimize the drying conditions of shrimp in the hot air-assisted microwave drying system using response surface methodology. The drying experiments were performed using a Box–Behnken design with air temperature (50–70°C), air velocity (.5–1.5 m/s), and microwave power level (600–1000 W) as independent variables and drying time, water activity, and rehydration ratio as independent variables. The obtained response variables were fitted into the various regression equations to predict a suitable model. The methodology of desired function was applied to indicate 61.74°C air temperature, 922.61 W microwave power, and 1.0 m/s air velocity which offered a reduced drying time of 2.8 h, the water activity of .424 and improved rehydration ratio of 2.51, respectively with a desirability value of .949. The moisture content, drying efficiency, shrinkage, and total color change were determined for the samples obtained under optimized conditions and were observed as 16.5% (w.b), 35.71%, 14.14%, and 16.95 ± 2.14, respectively. Scanning electron microscopy analysis of dried shrimp showed the formation of pores of diameters ranging from 3.17 to 10.6 μm. The process parameters optimized under the study for hot air-assisted microwave drying can be used for the production of good-quality dried shrimps.

Practical applications

Generally, fish and fish products are dried in the open sun or solar dryers in most developing countries. The traditional methods offer the least process controls with maximum energy and manpower demand to meet the ever-growing industry requirements with increased awareness of the safety and quality of the dried products. The hot air-assisted microwave (HAMW) drying system developed under the study could have complete control over the process parameters without compromising the quality of the dried product. The study suggests the HAMW drying system as a potential means of drying technique for large-scale commercial production of dried shrimps.

KEYWORDS

diffusivity, drying rate, microwave radiation, moisture ratio, rehydration ratio

1 | INTRODUCTION

Shrimp is popular seafood with high protein content belonging to the group of crustaceans (Akonor et al., 2016). Shrimps are perishable in nature due to their higher moisture contents and microbial load (70%–80%), which makes drying an inevitable step in the preservation process. Traditionally, sun drying is practiced as the most convenient and economic method for drying fish and shrimp (Alfiya et al., 2019; Murali et al., 2019). However, due to the inherent drawbacks of open sun drying, the convective hot air drying method is being accepted as commercial practice for drying shrimp and fish (Jain & Pathare, 2007). Convective drying is the most adopted drying method mainly due to its convenience, lack of skilled labor requirement, and less economic inputs (Hiranvarachat et al., 2011). The convective drying technique also comes with the issue of prolonged drying and non-uniform temperature distribution. Also, convective drying has the major disadvantage of decreasing the nutrient contents in foods and increasing the energy consumption for the drying process (Miraei Ashtiani et al., 2022). The demand for dried shrimp in domestic and export markets has led researchers to standardize the drying process for shrimp that would yield products with superior quality at lower energy consumption.

Microwave-based drying systems are found to instantly heat the product and reduce the drying times significantly in the drying process. Microwave drying is one of the novel drying technologies that reduces the drying time by volumetric heating effects of microwaves in the frequency range of 915–2450 MHz. In microwave drying, as heating advances within the material, internal pressure increases causing moisture from cells to reach the surface of the products (Miraei Ashtiani et al., 2022). In order to reduce the intensity of heating by the microwaves and to carry away the moisture from the surface of the products, an external hot air supply at desired air velocities is needed (Miraei Ashtiani et al., 2018). Hence, microwave heating systems are combined with hot air circulation for instant moisture removal from the product and reduce the drying times significantly in the drying process.

Darvishi et al. (2013) studied the effect of microwave and hot air (MWHA) combination on the drying rate, effective moisture diffusivity, and energy demand for drying Sardine fish at MW powers of 200–500 W. The moisture content of the Sardine was reduced to .01 (dry basis) with a reduction of drying time from 9.5 to 4.25 min with the increase in the microwave power. The influence of hot air and MW drying on the nutritional properties of grass carp (*Ctenopharyngodon idellus*) fillets were investigated by Wu and Mao (2008). They reported that microwave drying showed an increase in protein contents since it had less effect on the amino acid composition of grass carp fillets. Microwave drying of shrimp increased drying efficiencies to about 22.54% and reduced specific energy consumption to about 28.94%, by increasing MW power from 200 to 500 W (Farhang et al., 2011). Drying under the microwave (MW) was found to lower drying time and enhance energy efficiency (Soysal et al., 2006).

The response surface methodology (RSM) is used as a tool for the optimization of process conditions that govern the effect of each variable and its interactions. It involves an experimental approach, mathematical procedures, and statistical implication which offer the user to make an efficient empirical exploration of the targeted unit (Murali et al., 2017). Ikrang and Umani (2019) optimized the process conditions for drying catfish using an electrical dryer using RSM. Temperature (50–70°C), the thickness of the sample (10–20 mm), salt concentration (0%–20%), and drying time (480–600 min) were the independent parameters. The moisture content of the dried products under optimized conditions (Temperature: 63.43°C, thickness: 14.81 mm, salt concentration: 9.07%, and drying time: 600 min) was 2.64% (w.b.). Shi et al. (2008) evaluated the horse mackerel (*Trachurus japonicus*) drying under a heat pump dryer using RSM and obtained the optimum conditions of drying air temperature of 30°C, drying air velocity of 1.5 m/s and NaCl content in the osmotic solution of 9.9%.

The sustainability of food processing operations lies in the material handling capacity of the equipment and the types of machinery involved. Most of the microwave-based heating systems mentioned in the literature up to date were meant for batch-scale production to process very few quantities of samples. As the food industry targets more conveyor-type systems with continuous production lines, the optimization of process parameters needs to be evaluated. With this background, the drying of shrimp under a hot air-assisted continuous microwave dryer was studied in this paper. Hence, the study aimed to investigate the effect of drying parameters such as microwave power, air temperature, and air velocity on the quality of dried shrimp and to optimize the drying conditions based on the drying time, water activity, and rehydration ratio of the dried product. The study also aimed to investigate the total color change, rehydration ratio, and microstructure of the optimized product.

2 | MATERIALS AND METHODS

2.1 | Materials

Shrimps (*Metapenaeus dobsoni*) required for the study were received from Calicut Fishing Harbor, Kerala. About 350–380 counts of shrimp in a kilogram, were carefully washed with potable water. The length, width, and thickness of shrimp were found to be 45.73 ± 1.4, 23 ± 1.1, and 9.02 ± 0.63 mm, respectively.

2.2 | Hot air-assisted microwave technology

The drying of shrimp was carried out in a continuous hot air-assisted microwave drying unit established at KCAET, Tavanur. A schematic diagram of the drying unit is shown in Figure 1. The drying unit consists of a drying chamber, microwave generator, hot-air provision, exhaust, fan, and control unit. The drying chamber is provided with only a layer of heat-resistant Teflon conveyor belt with dimensions of 1.5 m × 0.5 m. The operation of Magnetron of 1.45 kW power at 2450 MHz generated microwave energy for heating the products spread as a thin layer in the conveyor. The hot air assistance was

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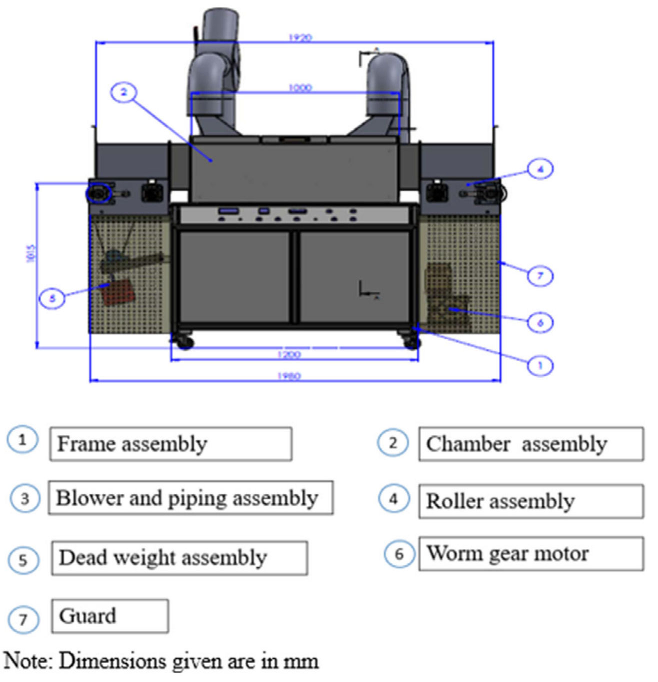

FIGURE 1 Hot air-assisted microwave dryer for shrimp drying.

provided with a 1 kW heating element, an air inlet duct, and an axial fan with a recirculatory section. Fresh inlet air is taken into the top of the dryer with the help of an axial fan and the air deflection valve. The heated air is then uniformly passed over the products at a desired air flow rate. The exit moist air is recirculated into the chamber inlet using a fan and temperature control system for maximum energy savings.

2.3 | Drying experiments using response surface methodology

The drying experiments were performed according to a second-order Box–Behnken design (BBD) with three factors at three levels: microwave power (600, 800, and 1000 W), air temperature (50°C, 60°C, and 70°C), and air velocity (0.5, 1.0, and 1.5 m/s). Drying time, water activity, and rehydration ratio were selected as the response variables. The levels were selected based on literature reviews (Darvishi et al., 2012; Farhang et al., 2011; Lee et al., 2021). A three-factor, three-level BBD experimental design was used in optimizing the drying conditions for shrimp in a hot air-assisted microwave (HAMW) drying system. The quadratic model for predicting the optimum solution was expressed using the following equation:

$$Y=\beta_0+\sum_{j=1}^{k}\beta_jX_j+\sum_{j=1}^{k}\beta_{jj}X_j^2+\sum_i\sum_{<j=2}^{k}\beta_{ij}X_iX_j+e_i \qquad (1)$$

where Y is the response, X_i and X_j are variables (i and j range from 1 to k), 0 is the model intercept coefficient; j, jj, and ij are interaction coefficients of linear, quadratic, and second-order terms, respectively, k is the number of independent parameters ($k = 3$) and e_i is the error. A lack of fit test was used to evaluate the appropriateness of the selected model.

The optimization was performed to optimize the conditions with minimum values of drying time and water activity, and maximum value of rehydration ratio. The design plan consisted of 17 runs with 5 center points. The optimum conditions of process variables were derived using the desirability function. Design Expert Statistical Software package 13.0 version (Stat Ease Inc., Minneapolis, MN) was used to perform statistical analysis. Analysis of variance (ANOVA) was carried out to check the significance of the model and process variables. The experimental runs were carried out as per the design details provided in Table 1. Microwave power levels were adjusted from the control panel of the microwave generator. The air temperature inside the drying chamber was measured using a digital temperature indicator. The air velocity was measured using a vane anemometer. Drying experiments were conducted till the moisture content of 12%–18% (w.b.) is reached. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28 ± 2°C). The weight loss of the shrimp was measured every 30 min of the drying operation.

2.4 | Drying time

It is the time taken for reducing the moisture content of the shrimp to the desired moisture level in the HAMW drying system. It is generally denoted by the number of hours.

2.5 | Water activity

The water activity of dried shrimp was determined using an Aqualab Series 3 L water activity meter, Decagon Devices, Inc., Pullman, Washington, DC at 28°C.

2.6 | Rehydration ratio

To determine the rehydration ratio of dried shrimp, 5 g of the sample was soaked in 200 mL of distilled water at room temperature. Weights of the samples were taken at every 30-min interval until a constant value was obtained (Doymaz & İsmail, 2011).

$$\text{Rehydration ratio}=\frac{\text{Weight of rehydrated sample (g)}}{\text{Weight of dried sample (g)}} \qquad (2)$$

2.7 | Moisture content

The weight of water in the product was represented by moisture content and can be calculated as dry and wet basis values, as given below:

TABLE 1 Drying time and moisture content under various drying conditions.

Run	Air temperature (°C), Factor: 1	Microwave power (W), Factor: 2	Air velocity (m/s), Factor: 3	Drying time (h), response: 1	Water activity, response: 2	Rehydration ratio, response:3
1	50 (−1)	600 (−1)	1.00 (0)	6	.579	2.23
2	60 (0)	800 (0)	1.00 (0)	3.5	.531	2.51
3	50 (−1)	800 (0)	0.50 (−1)	4	.56	2.32
4	60 (0)	800 (0)	1.00 (0)	3.5	.54	2.52
5	60 (0)	600 (−1)	0.5 (−1)	5.5	.574	2.2
6	50 (−1)	800 (0)	1.50 (+1)	5	.521	2.49
7	70 (+1)	800 (0)	0.50 (−1)	5	.521	2.29
8	60 (0)	1000 (+1)	1.50 (+1)	3	.572	2.43
9	50 (−1)	1000 (+1)	1.00 (0)	4	.524	2.41
10	60 (0)	1000 (+1)	0.50 (−1)	3	.543	2.41
11	70 (+1)	600 (−1)	1.00 (0)	5	.589	2.24
12	60 (0)	600 (−1)	1.50 (+1)	6	.567	2.35
13	60 (0)	800 (0)	1.00 (0)	3.5	.541	2.52
14	70 (+1)	800 (0)	1.50 (+1)	4.5	.576	2.39
15	70 (+1)	1000 (+1)	1.00 (0)	2.5	.524	2.41
16	60 (+1)	800 (0)	1.00 (0)	3.5	.539	2.54
17	60 (+1)	800 (0)	1.00 (0)	3.5	.541	2.52

Note: Figures in the parenthesis signify the coded values.

$$M_w = \frac{W_I - W_F}{W_I} \quad (3)$$

$$M_d = \frac{W_I - W_F}{W_F} \quad (4)$$

where M_d, M_w are dry and wet basis moisture, respectively; W_I is the sample weight before drying (kg), W_F is the sample weight after drying (kg).

2.8 | Drying efficiency

The efficiency of M_W drying was calculated as the ratio of heat utilized for the vaporization of water to the heat provided by the dryer (Soysal et al., 2006).

$$\eta = \frac{M_w \times L}{P \times t} \quad (5)$$

where η is the HAMW drying efficiency (%); P is the M_W power (W); m_w is the mass of water evaporated (kg), and L is the LH of vaporization of water (2257 kJ/kg), t is the drying time (s).

2.9 | Color

Colorimetric values (L^*, a^*, b^*) were measured to find out the color changes of shrimp and were performed using a colorimeter (Hunterlab, Colorflex: EZ). Conventionally, the Hunter color scale is represented by L^* for lightness or darkness ($L^* = 0$ for darkness and $L^* = 100$ for whiteness), a^* for redness or greenness ($a^* > 0$ for redness and $a^* < 0$ for greenness) and b^* for yellowness or blueness ($b^* > 0$ for yellowness and $b^* < 0$ for blueness). The total variation ΔE, is given as:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (6)$$

where L^*, a^*, b^*, and L_0, a_0, b_0 indicated the color parameters for dried and raw samples, respectively. More variation from control is represented by higher ΔE values.

2.10 | Shrinkage

The volume changes in foods during drying are expressed in terms of shrinkage percentage. The difference in the volume of samples before and after drying was estimated by comparing the dimensions of the sample in three directions using a Vernier caliper (accuracy of ±.05 mm). The percentage of shrinkage was calculated as described by Tirawanichakul et al. (2008),

$$\text{Shrinkage}(\%) = \frac{D_{\text{Initial}} - D_{\text{Final}}}{D_{\text{Initial}}} \times 100 \quad (7)$$

where D_{Initial} and D_{Final} is the geometric mean diameters of shrimp before and after drying, respectively.

TABLE 2 ANOVA and statistical parameters of the model for response variable drying time.

ANOVA for response surface quadratic model					
Analysis of variance table (partial sum of squares)					
Source	Sum of squares	DF	Mean square	F	Prob > F
Model significant	17.22	9	1.91	10.72	0.002
A	.50	1	.50	2.80	.1382
B	12.50	1	12.50	70.00	<.0001
C	.13	1	.13	.70	.4304
A^2	1.33	1	1.33	7.46	.0293
B^2	.41	1	.41	2.30	.1729
C^2	1.33	1	1.33	7.46	.0293
AB	.063	1	.063	.35	.5727
AC	.56	1	.56	3.15	.1192
BC	.063	1	.063	.35	.5727
Residual	1.25	7	.18		
Lack of fit	1.25	3.0	.42		
Pure error	.000	4	.000		
Cor total	18.47	16			
C.V. (%)		3.4			
R^2		.9323			
Adj. R^2		.8453			

2.11 | Microstructure analysis

The texture of a food product is a function of micro and macrostructure properties. The microstructure of dried shrimp was analyzed by using the scanning electron microscopy technique (Model: HITACHI SV6600). The analysis was done at a working distance of 8.5–8.8 mm and an accelerating voltage of 15.0 kV. The samples were mounted on metal stubs with double-sided adhesive tape coated with gold.

3 | RESULTS AND DISCUSSION

3.1 | Model fitting

Response surface methodology was used to optimize the process conditions of shrimp in a hot air-assisted continuous microwave dryer. Drying time varied for shrimp under hot air-assisted microwave conditions varied from 2.5 to 6 h, water activity from 0.521 to 0.589, and rehydration ratio from 2.2 to 2.54 The actual measured values were fitted into various regression models to select the appropriate model. ANOVA was done to test the lack of fit and to determine the significance of the selected model and its coefficients (Tables 2–4). Results showed that the model selected for responses was significant. This means that the selected model is appropriate to represent the relationship between responses and factors. To evaluate the model adequacy, R^2, Adj R^2, and coefficient of variation (CV) values were calculated. The coefficient of variation (%) for drying time, water activity, and rehydration ratio were 3.4, 2.27 and .8 respectively. A very low p-value (<.0001) and higher R^2 value indicate the selected quadratic model is highly significant and sufficient to represent the relationship between the process and response variables. Adequate precision values of all responses are above 4.0 which indicates the existence of adequate model difference. Also, a low PRESS value for responses indicates model suitability. The desirability function was applied to obtain the optimized values for each dependent variable.

The values of R^2, Adj R^2, and coefficient of variation (CV) values were determined to evaluate the adequacy of the selected model. The R^2 is the measure of the degree of fit and was obtained as .9323, .9122 and .9864 for drying time, water activity and rehydration ratio, respectively and the corresponding adjusted R^2 values were .8453, .8354, and .9690, respectively. A very low value of the coefficient of variation (3.7, 2.17, and 0.8) indicated greater reliability of the experimental data. Therefore, a very low p-value (<.0001) and higher R^2 value indicate the selected quadratic model is highly significant and sufficient to represent the relationship between the process and response variables. Adequacy precision values of all responses are above 4.0 which indicates the existence of adequate model difference. The model suitability is also indicated by a low PRESS value for response.

3.2 | Effect of process parameters on drying time

The RSM plots showing the interactions between air temperature, microwave power, and air velocity on drying time are shown in Figure 2a–c. It is evident from the figure that drying time decreased

TABLE 3 ANOVA and statistical parameters of the model for water activity.

ANOVA for response surface quadratic model					
Analysis of variance table (partial sum of squares)					
Source	**Sum of squares**	***DF***	**Mean square**	***F***	**Prob > *F***
Model significant	7.126E−003	9	7.917E−004	4.68	0.0271
A	8.450E−005	1	8.450E−005	.50	0.5027
B	2.664E−003	1	2.664E−003	15.74	0.0054
C	1.805E−004	1	1.805E−004	1.07	0.3361
A^2	1.601E−005	1	1.601E−005	.095	0.7674
B^2	1.297E−003	1	1.297E−003	7.66	0.0278
C^2	2.729E−004	1	2.729E−004	1.61	0.2448
AB	2.500E−005	1	2.500E−005	.15	0.7121
AC	2.209E−003	1	2.209E−003	13.05	0.0086
BC	3.240E−004	1	3.240E−004	1.91	0.2090
Residual	1.185E−003	7	1.692E−004		
Lack of fit	1.113E−003	3	3.712E−004	20.85	0.0066
Pure error	7.120E−005	4	1.780E−005		
Cor total	8.310E−003	16			
C.V. (%)		2.27			
R^2		0.9122			
Adj. R^2		0.8354			

TABLE 4 ANOVA and statistical parameters of the model for rehydration ratio.

ANOVA for response surface quadratic model						
Analysis of variance table (partial sum of squares)						
Source		**Sum of squares**	***DF***	**Mean square**	***F***	**Prob > *F***
Model significant		.20	9	.022	32.78	<0.00
A	1.800E−003	1	1.800E−003	2.72	.1430	
B	.051	1	.051	77.41	<.0001	
C	.024	1	.024	36.59	.0005	
A^2	.032	1	.032	48.46	.0002	
B^2	.053	1	.053	80.21	<.0001	
C^2	.016	1	.016	24.67	.0016	
AB	2.500E−005	1	2.500E−005	0.038	.8514	
AC	1.225E−003	1	1.225E−003	1.85	.2157	
BC	4.225E−003	1	4.225E−003	6.39	.0394	
Residual	4.630E−003	7	6.614E−004			
Lack of fit	4.150E−003	3	1.383E−003	11.53	.0194	
C.V. (%)		.8				
R^2		.9864				
Adj. R^2		.9690				

with an increase in air temperature (50–70°C) and microwave power (600–1000 W). Synergistic effects of air temperature and microwave power led to a reduction in drying times due to the volumetric heating effects of microwaves supplemented by increased temperature gradient created by hot air. However, the increase in air velocity and temperature reduced the drying times to a certain limit, beyond which air velocity increased the drying times at all temperatures (50–70°C) due to the lesser temperature gradient on the product. Moreover, at the highest microwave power (1000 W) with the intermediate air velocity (1 m/s) lowest drying time of shrimp can be obtained. Similar

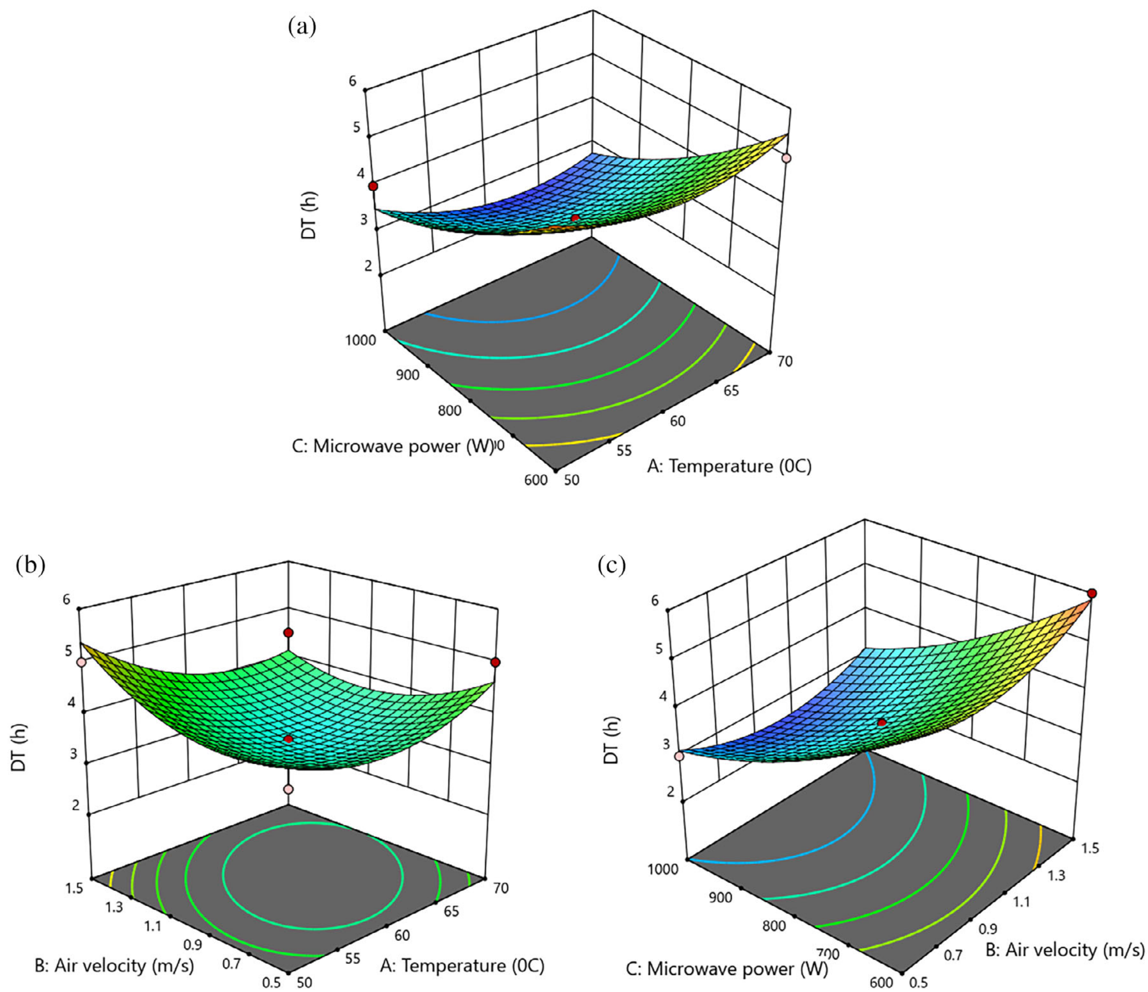

FIGURE 2 Effect of process parameterson drying time (DT).

trends were seen in the interaction reported by Han et al. (2010) for microwave drying of apple slices.

The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box–Behnken design.

$$\text{Drying time} = +3.50 - 0.25*A - 1.25*B + 0.12*C + 0.56*A^2 + 0.31*B^2 + 0.56*C^2 - 0.12*A*B - 0.38*A*C - 0.13*B*C \quad (8)$$

where *A*, *B*, and *C* denotes air temperature, microwave power, and air velocity, respectively.

3.3 | Effect of process parameters on water activity

The effect of air temperature, microwave power, and air velocity on the water activity of the dried product is shown in Figure 3a–c as air velocity increased (0.5–1.5 m/s), water activity decreased to a certain limit, further which it increased. As the water activity of the product is directly related to its moisture content, an increase in moisture content has enhanced the water activity of the products. An increase in microwave power and air temperature reduced the water activity due to increased drying rates. The water activity of the samples decreased significantly with increased temperature, probably due to the lower moisture content of samples at higher temperatures. At higher temperatures, food structure becomes more porous which accelerates the loss of water. Also, proteins become denatured due to higher temperature thereby losing their water binding capacity leading to more removal of water and reducing the water activity (Azizpour et al., 2016). However, with both thicknesses, aw dramatically decreased with an increase in temperature. Most enzymes and bacteria will be inactive when the food system has water activity below .80. To some extent increase in air velocity, enhances the drying rate, and further reduces the drying rate due to evaporative cooling on the surface of the product (Kilic, 2009). The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results based on the Box–Behnken design

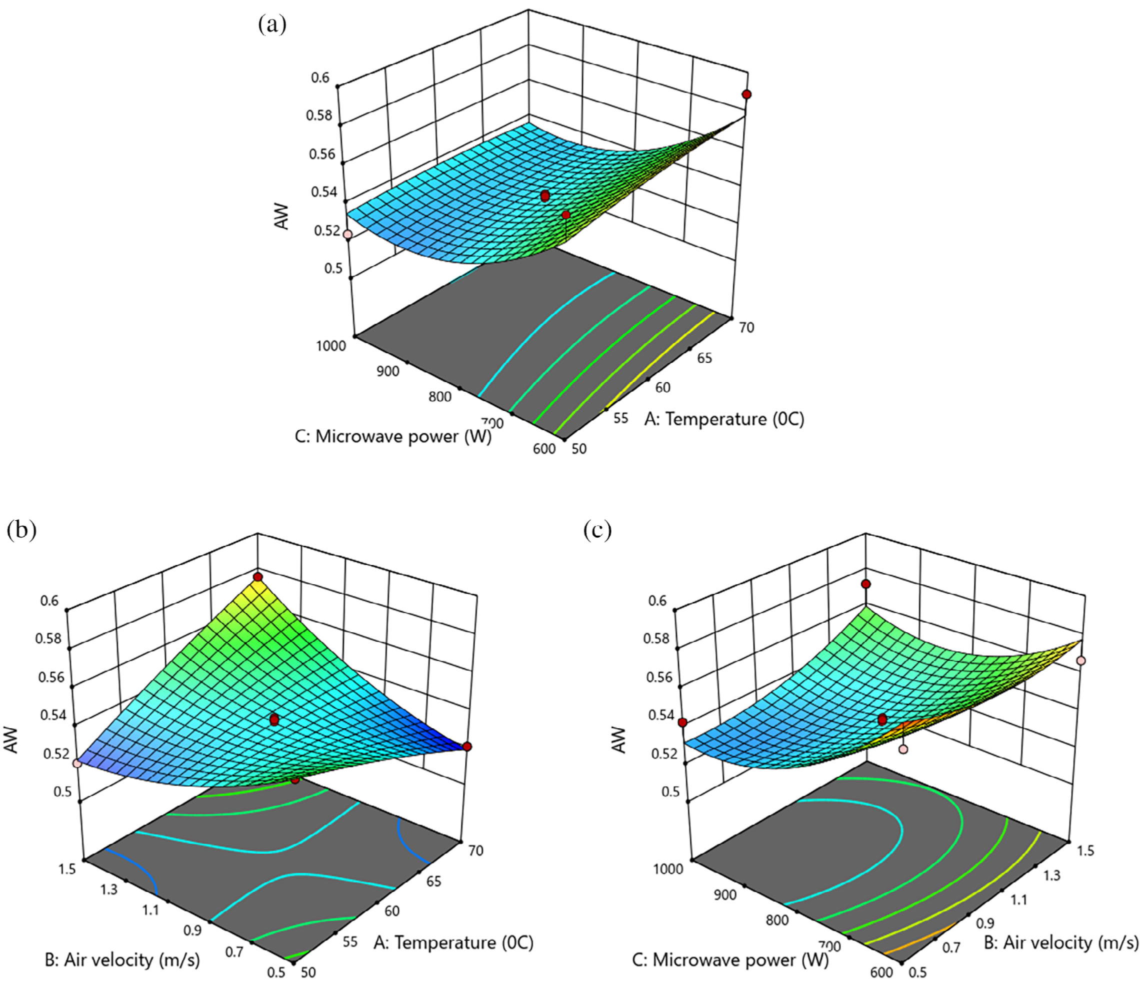

FIGURE 3 Effect of process parameters on water activity (AW)

$$\text{Water activity} = +.54 + 3.250E-003*A - .018*B + 4.750E-003*C - 1.950E-003*A^2 + 0.015*B^2 + 8.050E-003*C^2 - 2.500E-003*A*B + .024*A*C + 9.000E-003*B*C \quad (9)$$

where *A*, *B*, and *C* denote air temperature, microwave power, and air velocity, respectively.

3.4 | Effect of process parameters on rehydration ratio

The rehydration ratio is an important factor indicating the efficiency of the drying process as the rate of rehydration is will be less when the cells and tissues are collapsed or irreversibly damaged (Bozkir et al., 2019). Air temperature, microwave power, and air velocity had a significant effect on the rehydration ratio ($p \leq .01$) (Figure 4a–c). The regression coefficient is positive and maximum for microwave power levels, which indicates better rehydration properties of dried shrimp dried at high microwave power levels. This can be attributed to the high internal pressure development at higher microwave power levels. Higher microwave power causes more internal heating that creates a flux of rapidly escaping water vapor, which opens up the pores. This in turn prevents shrinkage and gives better rehydration properties (Giri & Prasad, 2007). Duan et al. (2011) reported that the rehydration ratio increased with increasing the duration of microwave drying at constant microwave power and also that the rehydration ratio increased with an increase in microwave power at constant time. Qin et al. (2020) observed that microwave combined with hot-air drying could reduce the irreversible structural damage in drying grass carp fillets and further, the rehydration rate increased along with microwave drying time.

The following second-order polynomial equation in terms of coded units was generated to obtain the empirical relationship between the experimental results,

$$\text{Rehydration ratio} = +2.52 - .01*A + .080*B + .055*C - .087*A^2 - .1*B^2 - .062*C^2 - 2.500E-003 * - .018*A*C - .033*B*C \quad (10)$$

where *A*, *B*, and *C* denotes air temperature, microwave power, and air velocity, respectively.

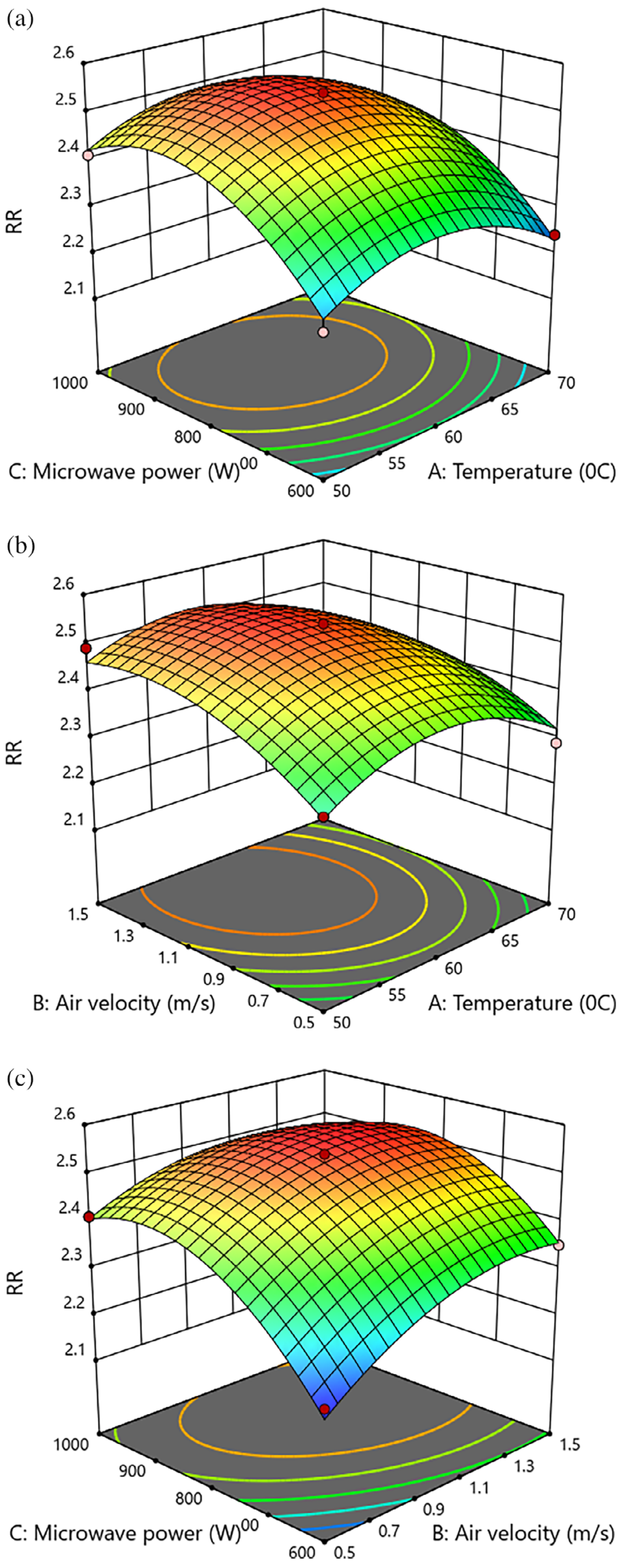

FIGURE 4 Effect of process parameterson rehydration ratio (RR).

3.5 | Determination of optimized conditions

The optimization of drying process parameters was done based on Derringer's desirability function. Microwave power (600–900 W), air temperature (50–70°C) and air velocity (0.5–1.5 m/s) were set within the range with minimization of drying time and water activity and maximization of rehydration ratio. Based on the value of maximum desirability (0–1), optimum conditions were selected. The methodology of desired function was applied to indicate 61.74°C air temperature, 922.61 W microwave power and 1.0 m/s air velocity which indicated the drying time, water activity, and rehydration ratio of 2.8 h and .424 and 2.51, respectively with a desirability value of .949 (Figure 5).

3.6 | Moisture content during drying

The experiments were conducted in the HAMW drying unit at the optimized condition. The moisture content of shrimp decreased from an initial value of 80.55% to a final value of 16.5% (w.b.) within 3.5 h of drying. The volumetric heating effect of microwaves can be attributed to the reduction in drying time. Microwave heating falls under the dielectric heating method wherein the moisture content of the product directly influences the heating rate. Mohd Rozainee and Ng (2010) made laboratory studies on microwave heating and published that the moisture content of sardine fish was reduced from 2.76 to .01 (dry basis) within 4.25 min under microwave power of 500 W. Lin et al. (1999) reported that drying of shrimps from a moisture level of 83% to 20% was achieved within 60 min in a microwave-assisted vacuum dryer, which is only 25% of the time required for hot-air drying of the same. As the moisture removal rate is less toward the end, drying occurred under the falling rate period. Olatunde et al. (2017) concluded that the higher core temperature of materials together with the consistent direction of heat transfer and moisture diffusion enhanced the drying rate in microwave drying.

3.7 | Drying efficiency

The drying efficiency of the HAMW unit was determined for the experiments conducted on the optimized values and was observed to be 35.71%. This was a result of the volumetric hearing effect of microwave radiation combined with the convective effect of hot air. Hassan (2016) reported that microwaves act only on polar molecules, microwave drying efficiency decreased with time and increased with the moisture content of date samples during microwave drying. Maximum drying efficiency of 32% was recorded with a specific energy consumption of 7.15 MJ/kgH_2O. Zarein et al. (2015) observed efficiencies of 54.34% and 17.42% at MW powers of 600 and 200 W, respectively during the drying of apple slices in a laboratory-scale MW dryer.

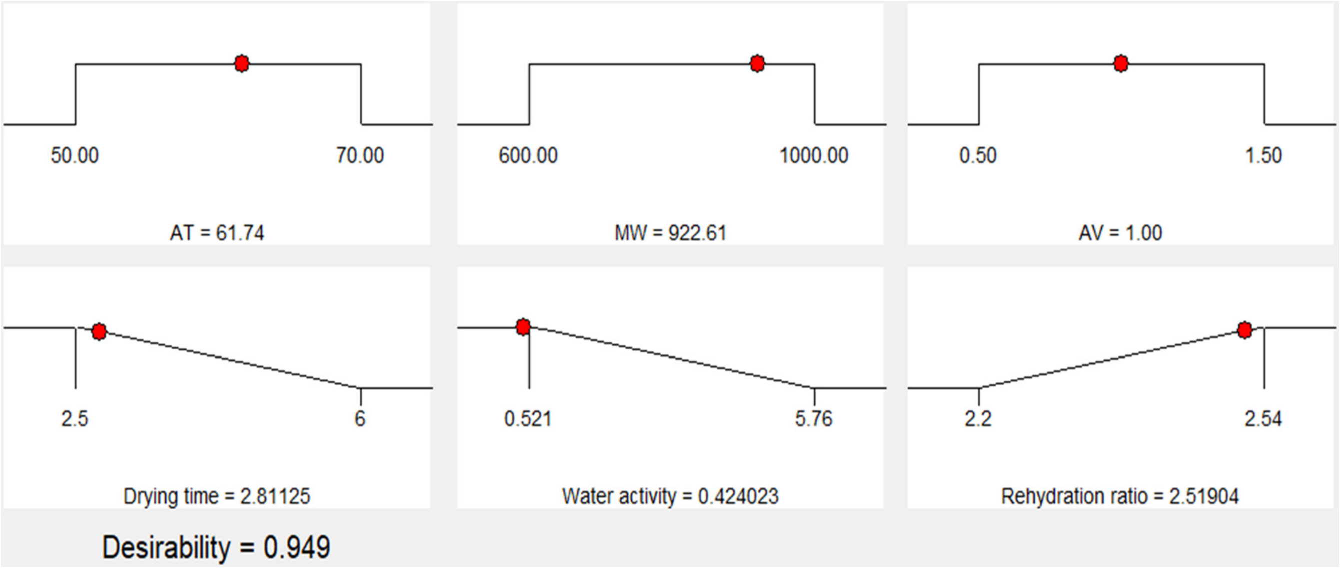

FIGURE 5 Desirability ramps for the optimized conditions of shrimp drying under a hot air-assisted microwave drying system.

FIGURE 6 Color variation in hot air-assisted microwave drying of shrimp.

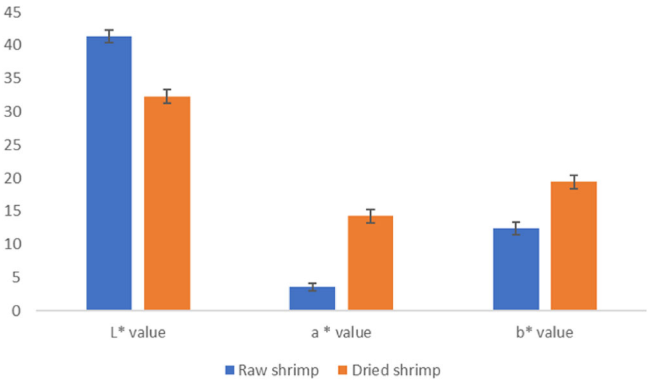

FIGURE 7 Photograph of shrimp before (a) and after drying (b) under a hot air-assisted microwave drying system.

3.8 | Color change

The total value of color change (Δ*E*) determined for dried shrimp was 16.95 ± 2.14. The "*L*" value of the dried shrimp (41.31 ± 1.63) decreased during drying whereas the "*a*" and "*b*" values increased from 3.56 ± 1.54 to 14.23 ± 2.36 and 12.42 ± 0.65 to 19.42 ± 1.61 during the drying process (Figure 6). The darker color of shrimps can be due to the Maillard reaction. Photographs of shrimp before and after drying is shown in Figure 7. Celen (2019) evaluated the color of persimmon dried using microwave radiation and obtained values of 13.25 and 24.320 for Δ*L* and Δ*E*, respectively at a microwave power of 600 W. It was also observed that higher microwave powers may cause unstable microwave fields that may affect the color quality of

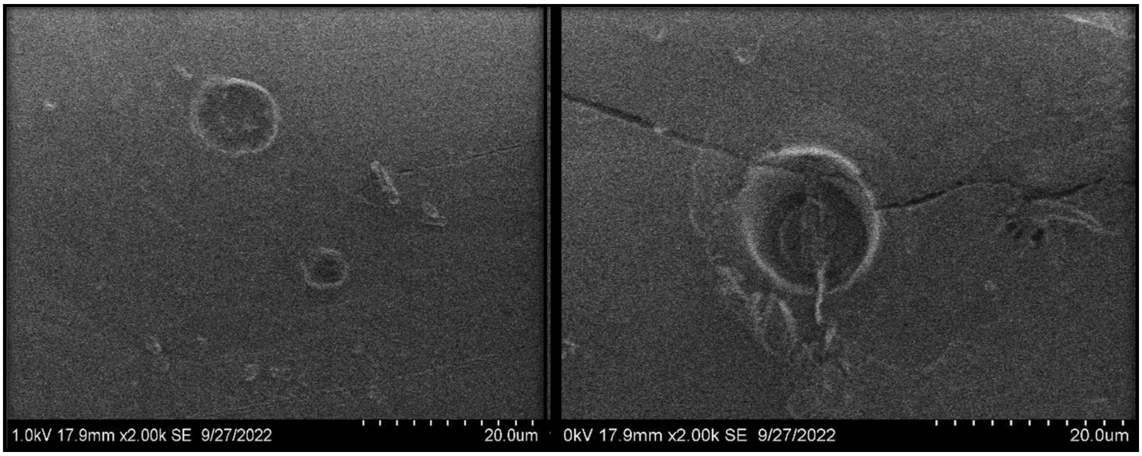

FIGURE 8 Microstructural observations in hot air assisted microwave dried shrimp.

products. Taib and Ng (2011) also showed that in microwave drying of catfish slices, hot air treatment imparted brighter color to dried products shifting toward red and yellow.

3.9 | Shrinkage

During the drying of food, moisture is removed from the product which results in a change in the volume of the product. This volume change is reflected as shrinkage (%) in the dried products. Under the study, the shrinkage percentage of dried shrimp was found to be 14.14%. The lesser shrinkage observed in the samples could be due to shorter drying time with the controlled drying conditions as reported by Murali et al. (2019, 2021). Reduction in shrinkage (%) was also due to the quick evaporation of moisture from the product by microwave heating that created a vapor flux preventing case hardening issue. MW vacuum drying of mushrooms resulted in dried products with very less shrinkage compared to hot air-dried samples (Giri & Prasad, 2007). Similarly, Kathirvel et al. (2006) observed that MW-dried herbs exhibit lesser shrinkage and higher retention of biochemical constituents.

3.10 | Microstructure analysis

The optimized sample was analyzed for microstructure to study the pore size distribution in the dried product. Scanning electron microscopy analysis of dried shrimp showed the formation of pores of diameters ranging from 3.17 to 10.6 μm (Figure 8). The reason for the higher rehydration ratio of hot air-assisted microwave-dried shrimp can be the presence of these pores. The volumetric heating effects of a microwave cause abrupt removal of water molecules which left the internal lattice vacant thereby creating pores of varying diameters. Mounir et al. (2020) studied the porosity and microstructure of shrimp snacks and concluded that higher porosity improved the functional behavior and drying process and quality attributes of the products.

4 | CONCLUSIONS

Process optimization for drying Shrimps (*M. dobsoni*) under hot air-assisted microwave drying technology using a BBD of RSM was employed in this study. The drying experiments were performed using air temperature (50–70°C), air velocity (0.5–1.5 m/s), and microwave power level (600–1000 W) as independent variables and drying time, water activity, and rehydration ratio as independent variables. The methodology of desired function was applied to indicate 61.74°C air temperature, 922.61 W microwave power, and 1.0 m/s air velocity which offered a reduced drying time of 2.8 h, the water activity of .424 and improved rehydration of 2.51, respectively with a desirability value of .949. At the optimized conditions. The moisture content, drying efficiency, shrinkage, and total color change were determined for the samples obtained under optimized conditions and were observed as 16.5%, 35.71%, 14.14%, and 16.95 ± 2.14, respectively. It can be concluded from the study that process parameters optimized under the study for hot air-assisted microwave drying can be used for the production of good quality dried products at the commercial scale.

AUTHOR CONTRIBUTIONS

P. V. Alfiya: Conceptualization, Investigation, Data curation, Formal analysis, Writing - original draft. **G. K. Rajesh**: Resources, Methodology, Supervision, Project administration, Review and editing. **S. Murali:** Methodology, Review and editing. **D. S. Aniesrani Delfiya:** Methodology, Review and editing. **Manoj P. Samuel:** Supervision, Project administration. **M. V. Prince**: Supervision, Project administration. **K. P. Sudheer:** Supervision, Project administration.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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