Received: 17 June 2022 | Revised: 20 August 2022 | Accepted: 23 August 2022

DOI: 10.1111/jfpp.17112

ORIGINAL ARTICLE

Journal of Food Processing and Preservation | Institute of Food Science + Technology ifst | WILEY

Development and evaluation of hot air-assisted microwave dryer for shrimp (*Metapenaeus dobsoni*)

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Funding information
Indian Council of Agricultural Research

Abstract

The study aimed to develop a hot air-assisted continuous microwave (HAMW) drying system and evaluate the drying of shrimp under microwave radiation. The drying system comprised of a drying chamber with a conveyor belt of dimension 1.5 × 0.5 m, magnetron of 1.45 kW to generate microwaves at frequency of 2450 ± 50 MHz, hot air generation system with air heater of 1 kW and axial fan of 50 W and other controls. Moisture content of shrimp was reduced from 80.55% to 16.5% within 3.5 h of drying. Volumetric heating effect of microwaves resulted in reduction of drying times. Effective moisture diffusivity of microwave-dried shrimp was found to be 6.7×10^{-7} m^2/s. Page model was the suitable fit for the data under study ($R^2 = 0.998454$, RMSE = 0.0.01552 and χ^2 = 0.000134). The drying efficiency and specific energy consumption for hot air-assisted microwave drying of shrimp were calculated to be 35.71% and 1.75 kWh/kg, respectively. Water activity, rehydration ratio and shrinkage of the dried shrimp samples were 0.552%, 2.51% and 14.14%, respectively, with maximum color retention. Proximate and microbiological analysis of fresh and dried shrimp were carried out and were found to be under safe limits. The developed HAMW drying system was found to be suitable for shrimp drying under controlled conditions.

Practical applications

Hot air-assisted microwave (HAMW) drying system was developed to cater drying of shrimp under controlled conditions with lower drying times. Specific energy consumption (1.75 kWh/kg), drying efficiency (35.71%) and effective moisture diffusivity (6.7×10^{-7} m^2/s) during drying was found to be superior to convective drying. Evaluation of quality parameters of dried shrimp such as rehydration ratio (2.51), shrinkage (14.14%), water activity (0.552) and total plate count (2×10^4 CFU/g) was falling under acceptable limits. The study suggests HAMW drying system as a potential means of drying shrimps for large-scale commercial production.

1 | INTRODUCTION

Shrimp is a major commercial seafood in the world and belongs to the phylum arthropod with extended abdomen (Oosterveer, 2006). Owing to the relatively higher water and protein content of shrimps, they are subjected to rapid deterioration soon after harvest. Natural sun drying was practiced as an economic method for drying of fish and shrimps. Since the method has several drawbacks such as longer duration, weather uncertainties, infestation by predators and lack of control, convective drying is adopted commercially for dried shrimp production (Jain & Pathare, 2007). But the existing convective drying systems for shrimp often result in inferior product quality due to longer drying time requirement and non-uniform drying. Drying under microwave (MW) was found to lower drying time and enhance energy efficiency (Soysal et al., 2006). MW drying of shrimp increased drying efficiencies to about 22.54% and reduced specific energy consumption (SEC) to about 28.94%, on increasing MW power from 200 to 500 W (Farhang et al., 2011).

Application of MW radiation for food product drying has been reported in various literatures. Mohd Rozainee and Ng (2010) reported that drying time for catfish slices was reduced to 75% using MW as compared to hot air (HA) drying. Also, there were significant reduction in the SEC and shrinkage of foods under MW convective drying. Darvishi et al. (2013) studied the implication of microwave assisted hot air dryingb (MWHA) on rate of drying, effective moisture diffusivity (EMD) and energy for drying Sardine fish at four varying MW powers of 200, 300, 400 and 500 W and at constant air velocity. Moisture percent of the samples reduced to 0.01 (dry basis) with a reduction in drying time (9.5 to 4.25 min) as power increased. Wu & Mao, 2008, investigated the influence of HA and MW drying on nutritional properties of grass carp (Ctenopharyngodon idellus) fillets. MW drying showed an increase in protein contents since it had less effect on the amino acid composition of grass carp fillets. MW heating of shrimp at 1.3 kW and 2450 MHz was found to retain better color and texture compared to conventional methods (Tsai et al., 2021). Dong et al. (2021) evidenced that MW heating at 1 kW and 2450 MHz showed potential impact on reducing the allergenicity of shrimps. Mounir et al. (2020) published that MW drying of shrimp with intermittent pressure drop removed 90% of moisture within 10 min and exhibited better quality attributes compared to convective dried samples.

Drying involves complex mass, heat and momentum transport followed by intermolecular transformation (Kudra & Mujumdar, 2002). Hence, drying process needs to be effectively designed and optimized. This can be achieved by mathematical modeling using thin layer drying equations that are practical and give adequately fair results on prediction of drying time. Moisture removal during drying can be projected by modeling of drying kinetics (Alfiya et al., 2019). Drying kinetics describe the changes in moisture regime in the product with time. Various models defining the drying rate curve are proposed based on the factors that affects the drying process (Pacheco-Aguirre et al., 2015).

Post-harvest loss of agricultural and marine products is attributed to be an important factor for the food crisis in the world, where around 10% of the total population does not have enough food to consume (Chauhan & Rathod, 2020). Shrimp, being a highly perishable product, is subjected to immediate spoilage soon after harvest. The drying of commodities reduces the post-harvest loss thereby enhancing shelf life by lowering the moisture content present in the foods (VijayaVenkataRaman et al., 2012). But the existing drying systems for shrimp often results in inferior product quality due to long drying time requirement and non-uniform drying.

The combination of HA and MW is an innovative method to improve the effectiveness of drying with better retention of the quality of products. MW is an electromagnetic wave with a frequency in the range of 0.3–300 GHz and a wavelength in the range of 1 m to 1 mm, respectively. These waves are capable of rotating bipolar molecules, and due to high friction produced by changing polarity of molecules, they produce heat in bipolar materials such as water (Kouchakzadeh & Shafeei, 2010). Application of MWs in drying process causes reduced energy consumption and improves quality of dried products (Andrés et al., 2004). Due to fast mass transferring in this method, removal of emerging moisture from product is difficult, and this result in condensation of steam inside the container (Sharmaa et al., 2009). To overcome this difficulty, combined MW-HA flow drying, pulsed MWs and also combined MW-vacuum drying can be used in drying process (Gunasekaran, 1999). Hybrid drying offers many advantages over conventional drying in terms of reduced drying time, reduced energy usage and improved product quality. Furthermore, most of the existing drying techniques are utilizing high energy or leading to carbon emissions. Hence, it is contemplated to develop technologies which are green, clean and affordable to MSMEs and fisherfolks. Thus, design and development of semi-continuous HAMW dryer for shrimp is planned in this study. However, the MW-based heating systems mentioned in literatures were meant for batch scale production to process very few quantities of products. However, food processing industries are targeting on conveyor type systems that aids in continuous production reducing the material handling and enabling them to meet the consumer demands. Presently, HAMW heating systems are not available for drying fish /fishery products, under continuous/semi-continuous processing method for drying large quantity of products. Hence, the study was aimed to develop a HAMW drying system for marine products. The study was undertaken to develop a HAMW dryer and to carry out performance evaluation of the dryer with shrimp samples. Hence, in this study, an attempt was made to develop a hot air assisted microwave dryer and to evaluate the performance of the dryer with shrimp samples.

2 | MATERIAL AND METHOD

2.1 | Materials

Raw shrimps (*Metapenaeus dobsoni*) were purchased from Chaliyam Fish Harbor of Calicut, Kerala. The shrimps were counting around 350–380 nos./kg and were thoroughly cleaned with potable water. The length, width and thickness of shrimp were determined to be 45 ± 1.5, 24 ± 1.3 and 9 ± 0.6 mm, respectively. Moisture percentage of shrimp was found to be 80.55 ± 1.54 (% w. b.) by gravimetric method (AOAC, 1990).

2.2 | Methods

2.2.1 | Design calculations

HAMW dryer was developed for drying of shrimp with an initial moisture level of around 75–80% w. b. Following assumptions were considered in dryer design (Table 1).

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TABLE 1 Hot air-assisted microwave dryer design assumptions

Factors	Specifications
Capacity	1 kg fresh shrimp/h 0.6 kg/h moisture removal
Product type	Shrimp
Moisture percentage (initial)	75%–80% w. b.
Moisture percentage (final)	10%–15% w. b.
Drying air temperature	60–70°C
Air flow rate	1 m/s
Air temperature (ambient)	30–33°C
Air relative humidity (ambient)	70%–75%
Latent heat of vaporization of water at drying temperature	2260 kJ/kg
Specific heat capacity of air at constant pressure	1 kJ/ kg°C
Air density	1.225 kg/m^3
Specific heat of shrimp	3.65 kJ/kg°C
Specific heat of water	4.2 kJ/kg°C
Drying time	3 h

Thermodynamic equilibrium calculation for energy balance

Energy balance in drying was calculated by the equation (Exell, 1980):

$$M_w L = m_a C_p (T_i - T_f) \quad (1)$$

where M_w: mass of water to be removed, kg; L: LH of vaporization, kJ/kg °C; T_i: Initial temperature of air, °C; T_f: Final temperature of air, °C; m_a: Mass of air, kg; C_p: Specific heat capacity of air at constant pressure, kJ/kg °C.

Amount of water to be removed from product

Amount of water evaporated was calculated as:

$$M_w = \frac{W_i (M_i - M_f)}{100 - M_f} \quad (2)$$

where W_i: Product weight initially, kg; M_i, M_f: Initial and final content of moisture in of the sample, % w. b.

HA requirement for drying

Air requirement for drying was calculated as:

$$M_a = \frac{M_w L}{C_p (T_i - T_f)} \quad (3)$$

Flow rate of air is given as:

$$\text{Mass flow rate of air} \left(\frac{\text{kg}}{s}\right) = \rho \times V_a \quad (4)$$

$$\text{Volumetric flow rate of air } (V_a) \left(\frac{\text{m}^3}{s}\right) = A \times V \times n \quad (5)$$

where V_a: Volumetric flow rate of air, m^3/s; ρ: Air density, kg/m^3; A: Area of air passage duct, m^2; V: Air velocity, m/s and n: Number of air passage ducts.

Heat energy required for evaporation

Heat requirement for evaporation is the total of sensible heat required to raise the temperature of sample, sensible heat of water and latent heat of vaporization of water at specific temperature and it can be determined as:

$$Q_{Total} = Q_{sensible,product} + Q_{sensible,water} + Q_{Latent} \quad (6)$$

Sensible heat needed to raise the sample temperature:

$$Q_{sensible,product} = W_d \, C_{pp} \, (T_{fp} - T_{ip}) \quad (7)$$

where $Q_{sensible,product}$: Sensible heat of sample, kJ; W_d: Bone dry weight of product, kg; C_{pp}: Product-specific heat, kJ/kg °C (3.65 kJ/kg °C); T_{ip}: Product temperature (initial), °C; T_{fp}: Temperature of product, (final), °C.

Sensible heat for raising water temperature is estimated as:

$$Q_{sensible,water} = W_w C_{pw} \, (T_{fp} - T_{ip}) \quad (8)$$

where $Q_{sensible,water}$: Sensible heat of water (kJ); W_w: Mass of moisture in product, kg; C_{pw}: Specific heat of water, kJ/kg °C.

Latent heat (LH) needed is represented as:

$$Q_{Latent} = M_w L \quad (9)$$

where Q_{Latent}: LH of water evaporation, kJ; M_w: Mass of water evaporated from sample, kg; L: LH of vaporization of water, kJ/kg.

2.2.2 | Dryer components

Drying chamber

Drying chamber consisted of a single layer of conveyor belt of dimension 1.5 × 0.5 m, being derived from dryer design calculations with respect to the capacity and product bulk density. Samples being fed manually were conveyed along the belt made of heat-resistant Teflon (PTFE) over SS rollers. Magnetron of 1.45 kW rated power, operating at 2450 ± 50 MHz generated the MWs for heating the products in the drying chamber. A solid diagram of the HAMW drying system (Enerzi Microwave Systems, India) is shown in Figure 1 (SOLIDWORKS 3D CAD).

HA generation system

The air heating zone consisted of air inlet duct (0.164 m diameter × 0.175 m length), axial fan (Make: Almonard, 50 W, 1350 rpm), with one air heater of one kilowatt and recirculation system. Ambient air entered into the top of dryer due to the pull of axial fan and is conveyed to the heater assembly by the air deflection valve. The heated air is then uniformly passed through the chamber at determined velocities. The moist air from the chamber is recirculated and blown into inlet by means of blower, and temperature control of heated air was achieved with an automatic thermal cutoff arrangement. Top, front and side views of the HA generation system are depicted in Figure 3.

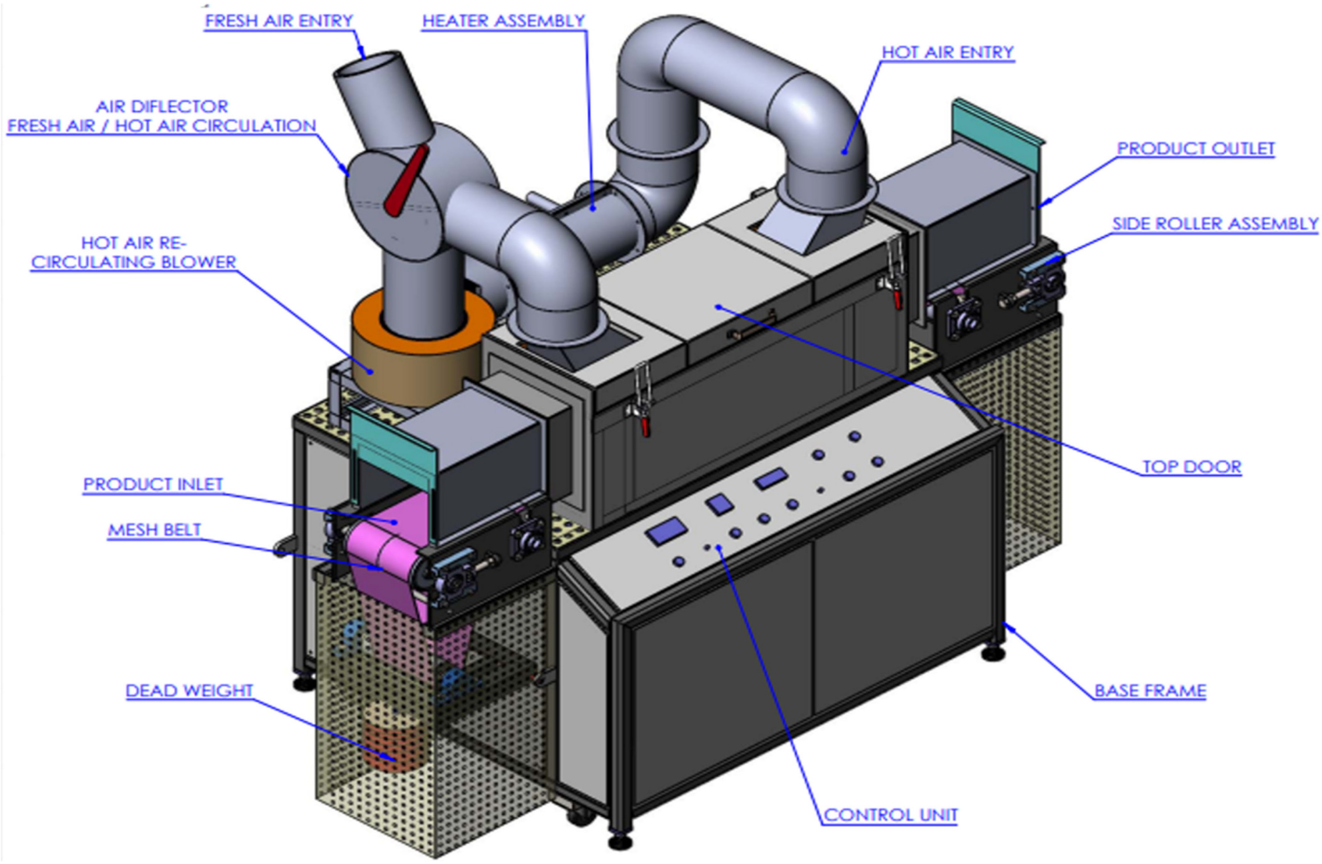

FIGURE 1 Hot air-assisted microwave dryer—Solid diagram (courtesy: Enerzi microwave systems Pvt. Ltd., Belgaum, India).

2.2.3 | Drying procedure

Performance evaluation of HAMW drying system was carried out using shrimp under MW power of 1000W and HA temperature of 60–65°C. Drying was continued up to 12%–18% w.b. moisture content. Drying studies were conducted in triplicates. For each drying experiment, 1000g of cleaned samples was taken and fed to the conveyor. A handheld infrared thermometer (METRAVI, Kolkata, India) was used to measure chamber and shrimp temperature during drying. Relative humidity of air ranged from 67±1% to 36±1% during drying. Based on the preliminary experiments, MW power levels were optimized for the desired temperature range for drying of shrimps. Dried products were packed in laminated polyethylene polyester packaging material and stored at ambient temperature (28±2°C). Weight loss of the shrimp was measured in every 30min of drying operation. The experimental setup of HAMW dryer and graphical abstract of shrimp during HAMW drying is shown in Figures 2 and 3, respectively.

Moisture content

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

$$M_w = \frac{W_I - W_F}{W_I} \quad (10)$$

$$M_d = \frac{W_I - W_F}{W_F} \quad (11)$$

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).

Drying rate

Amount of moisture removed in terms of time is described by drying rate and is determined as follows (Sodha et al., 1987):

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (12)$$

where DR, the drying rate, is obtained as kg of water per kg dry mass per h, M_t is moisture content at time t (kg water/kg dry mass), M_{t+dt} is moisture content at time, $t+dt$ (kg water/kg dry mass and dt is the difference in time, h.

Moisture ratio

Moisture ratio was determined as below:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (13)$$

where MR stands for moisture ratio, M_0, M_e and M_t are the percent moisture contents initial, equilibrium and at time, t (in % db),

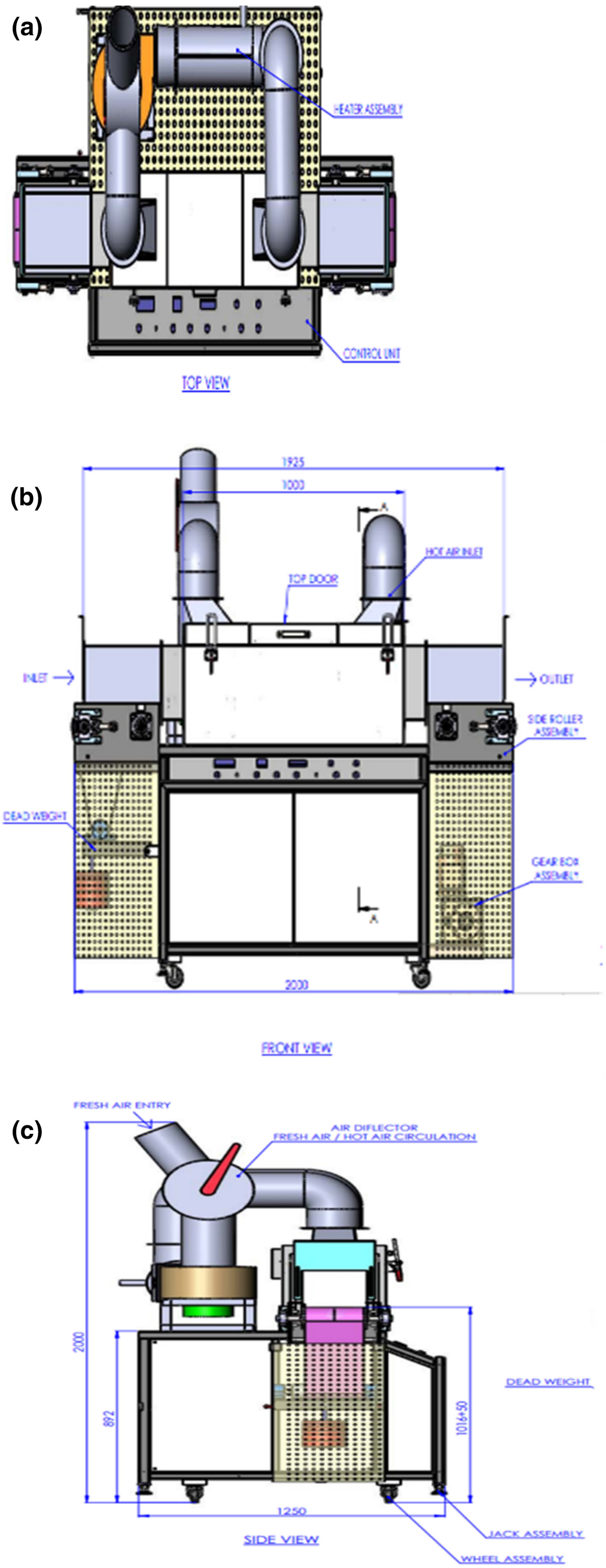

FIGURE 2 Hot air generation system (a) top view, (b) front view and (c) side view (courtesy: Enerzi microwave systems Pvt. Ltd., Bangalore, India).

FIGURE 3 Hot air-assisted microwave dryer.

respectively. Above equation takes the form as equation (16) by omitting the term M_e, as it is very small comparable with M_0 and M_t values (Sacilik et al., 2006).

$$\mathrm{MR} = \frac{M_t}{M_0} \tag{14}$$

EMD

Diffusion, which is the major driving force for moisture removal in drying, is expressed by EMD that determine the overall mass transfer process. It is the rate of movement of moisture and gives insight to the migration of water during drying and hence needed for optimization process. Movement of water inside hygroscopic material during falling rate drying is given by Fick's law as:

$$\frac{\delta M}{\delta t} = \nabla.\left(D_{\mathrm{eff}}\,\nabla M\right) \tag{15}$$

where M denotes moisture content of the sample in kg water/kg dry matter, t stands for drying time in s, and D_{eff} represents the EMD in m^2/s.

It was assumed that shrimp for drying were cylindrical in shape for the diffusivity calculation. For an infinite cylinder (where the moisture diffusion takes place in radially outward direction only), the assumptions considered for calculating diffusivity were (Crank, 1975):

- Uniform distribution of moisture initially in the ample
- Symmetric mass transfer with reference to cylindrical center
- Surface mass transfer resistance is very less compared with internal resistance to mass transfer
- Shrinkage of product is negligible with constant diffusion coefficient

For cylindrical material, Crank's solution for equation (17) is given by:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{4}{b_n^2} \exp\left(- \frac{D_{eff} b_n^2 t}{r^2} \right) \quad (16)$$

Taking the initial term, diffusivity is calculated as (Zogzas & Maroulis, 1996):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \sum_{n=1}^{\infty} \frac{4}{b_n^2} \exp\left(- \frac{D_{eff} b_n^2 t}{r^2} \right) \quad (17)$$

In the above equation, r represents mean radius of sample in meters, n denotes positive integer, and b_n are the root of Bessel's function (2.405, 5.52, 8.654 ……). For $n > 1$, solution is obtained as (Lopez et al., 2000):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{4}{b_1^2} \exp\left(- \frac{D_{eff} b_1^2 t}{r^2} \right) \quad (18)$$

where b_1 is 2.405.

The simplified form of equation (20) in logarithmic form is written as:

$$\ln(MR) = A - B \times t \quad (19)$$

Here, B represents the slope of line and is related to moisture diffusivity as:

$$B = \frac{b_1^2 D_{eff}}{r^2} \quad (20)$$

Thus, moisture diffusivity is determined from the slope obtained from plot of linear regression of ln (MR) with time (Equation 23)

$$D_{eff} = - \frac{B\,r^2}{b_1^2} \quad (21)$$

Mathematical modeling of drying behavior

Drying data were substituted in thin layer drying equations (Table 2) to predict behavior, control parameters and improve efficiency. The solutions to the values of model constants and non-linear regression analysis were executed by MATLAB (R2021b) software (Alfiya et al., 2018). The prediction on the model of best fit was done with respect to higher coefficient of determination (R^2) and lower percentage root mean square (RMSE) and reduced chi-square (χ^2).

Drying efficiency

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

$$\eta = \frac{Mw \times L}{P \times t} \quad (22)$$

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

SEC

SEC is determined using the following equation and is expressed as kWh/kg of water evaporated (Wang & Sheng, 2006).

$$SEC = \frac{E_T}{M_W} \quad (23)$$

where E_T is the total energy (kWh) and M_W is mass of water evaporated (kg).

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:

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (24)$$

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.

Shrinkage

The volume changes in foods during drying are expressed in terms of shrinkage. Difference in volume of samples before and after drying was estimated by comparing the dimensions of sample in three directions using Vernier caliper (accuracy of ±0 0.05 mm) before and after drying. Equation to calculate shrinkage is given as (Tirawanichakul et al., 2008):

$$\text{Shrinkage}\,(\%) = \frac{D_{Initial} - D_{Final}}{D_{Initial}} \times 100 \quad (25)$$

where $D_{Initial}$ and D_{Final} are geometric mean diameter of shrimp before and after drying, respectively.

Rehydration ratio

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

$$\text{Rehydration ratio} = \frac{\text{Weight of rehydrated sample}\,(g)}{\text{Weight of dried sample}\,(g)} \quad (26)$$

Microbial analysis

Microbiological quality of the dried shrimp was tested for total plate count (TPC) as per the standard procedures of Food and Drug Administration (FDA), Bacteriological Analytical Manual (US Food and Drug Administration, 2020). Ten grams of the shrimp sample

TABLE 2 Modeling of drying data

S. No.	Model name	Equation	R^2	RMSE	Reduced χ^2	Constants
1	Logarithmic (Moradi et al., 2020)	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + c$	0.9954	0.02853	0.000466	$a = 1.086$ $b = 0.7624$ $c = 0.0688$
2	Henderson and Pabis (Arslan et al., 2010)	$MR = \frac{M - Me}{M0 - Me} = ae^{-kt}$	0.9979	0.01698	0.000405	$a = 1.01$ $b = 0.9793$
3	Modified page (Karacabey & Buzrul, 2017)	$MR = \frac{M - Me}{Mo - Me} = e^{(-kt)^n}$	0.9979	0.01698	0.000367	$a = 1.01$ $b = 0.9698$
4	Two-term exponential (Toğrul & Pehlivan, 2004)	$MR = \frac{M - Me}{Mo - Me} = \mathrm{a} * \exp(-\mathrm{k1} * \mathrm{t}) + \mathrm{b} * \exp(-\mathrm{k2} * \mathrm{t})$	0.9972	0.02973	0.001144 0.000362	$a = 14.32$ $b = 13.32$ $k1 = 0.7225$ $k2 = 0.7075$
5	Wang and Singh (Wang et al., 2005)	$MR = \frac{M - Me}{Mo - Me} = 1 + at + bt^2$	0.9887	0.04396	0.000324	$a = 0.6979$ $b = 0.1253$
6	Verma et al. (Yaldýz & Ertekýn, 2001)	$MR = \frac{M - Me}{Mo - Me} = ae^{-kt} + (1 - a)e^{-gt}$	0.9977	0.01919	0.000378	$a = 0.1973$ $b = 0.9468$ $g = 0.9664$
7	**Page (Roy et al., 2022)**	$MR = \frac{M - Me}{Mo - Me} = e^{-kt^n}$	**0.9984**	**0.01552**	**0.000134**	$\mathbf{a = 0.9592}$ $\mathbf{b = 1.052}$
8	Newton (Benseddik et al., 2018)	$MR = \frac{M - Me}{Mo - Me} = e^{-kt}$	0.9977	0.01622	0.000412	$a = 0.9704$

Bold values indicates the best fit moodel for drying under study.

was aseptically cut into a sterile Petri dish and blended with 90 ml of sterile normal saline (NS) in a stomacher and made two-fold serial dilution up to 10^{-6}. For TPC on Total Plate Count Agar, one ml of the appropriate dilutions was pipetted and pour plated with the corresponding medium in duplicate plates. These plates were allowed to set, inverted and incubated at 37°C for 18–24 h. The diluted plates contained colonies ranging from 25–250 numbers. The experiments were done in triplicates, and the average value was recorded.

Water activity

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

Proximate analysis

Fresh shrimp and shrimp dried under were examined for its proximate composition like moisture, crude protein, crude fat and ash (AOAC, 1990).

Sensory evaluation

Dried shrimp samples were evaluated for sensory parameters like appearance, texture, color, odor and overall acceptability (Chavan et al., 2008). Sensory analysis was carried out using 9-point hedonic scale with 9 – like extremely, 8 – like very much, 7 – like moderately, 6 – like slightly, 5 – neither like nor dislike, 4 – dislike slightly, 3 – dislike moderately, 2 – dislike very much and 1 – dislike extremely. The evaluation was done by 25 semi-trained panel members. The members were the staff and researchers of ICAR-CIFT who were general fish consumers and were able communicate and report variations in the sample (Figure 4).

3 | RESULTS AND DISCUSSION

3.1 | Drying rate and moisture content during drying

Figure 5 shows the variation in moisture content and drying rate with respect to drying time for shrimp under HAMW drying conditions. It is evident from the graph that moisture content of shrimp decreased from an initial value of 80.55% to a final value of 16.5% within 3.5 h of drying. Volumetric heating effect of MWs can be attributed for the reduction in drying time. MW heating falls under dielectric heating method wherein the moisture content of the product directly influences the heating rate. Mohd Rozainee and Ng (2010) made laboratory studies on MW heating and published that moisture content of sardine fish was reduced from 2.76 to 0.01 (dry basis) within 4.25 min under MW 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 MW-assisted vacuum dryer, which is only 25% of the time required for HA drying of the same. Darvishi et al. (2012) also reported that at MW powers of 200, 300, 400 and 500 W, time taken to dry shrimp from moisture levels of 3.103% (d.b.) to 0.01% (d.b.) was 11.75, 7, 4.75 and 4 min, respectively. Lower drying times are also related to higher drying rates of shrimp under HAMW treatment. Drying rate exhibited maximum value of 2.74 during the initial stages in drying that can be due to the higher moisture content of sample that created more friction and heat generation due to dipole rotation. Dipole rotation arises owing to the presence of water molecules in the sample that tends to change the polarity depending on the rapidly changing electromagnetic field induced by the magnetron. As the moisture content reduces, the magnitude of dipole rotation also

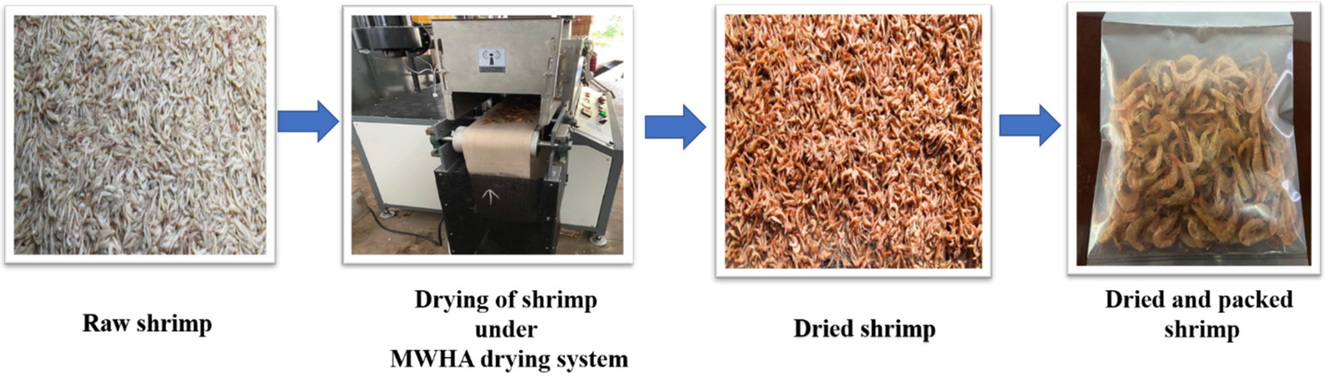

FIGURE 4 Graphical abstract of shrimp drying under HAMW drying system.

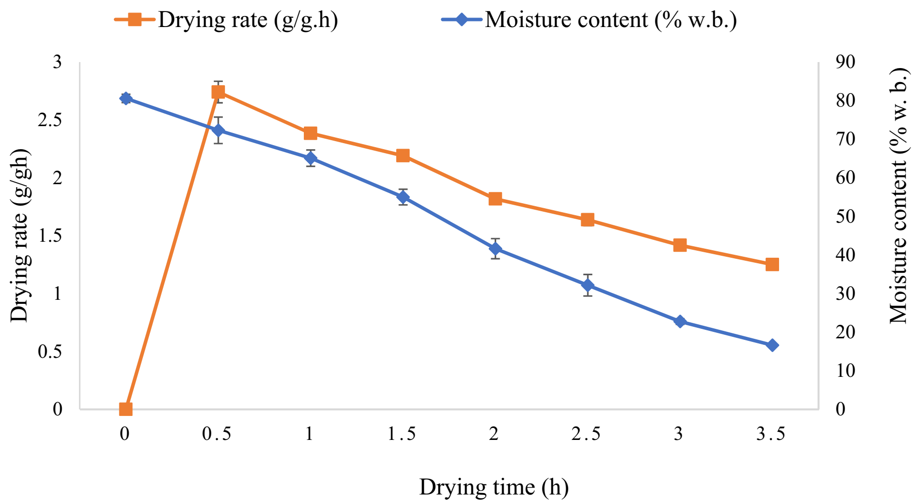

FIGURE 5 Variation in drying rate and moisture content during HAMW drying of shrimp.

reduces and thereby lowering the drying rate. As moisture removal rate is less towards the end, drying occurred under falling rate period. Olatunde et al. (2017) concluded that higher core temperature of materials together with the consistent direction of heat transfer and moisture diffusion enhanced the drying rate in MW drying.

3.2 | EMD

Sum of liquid and vapor diffusion during drying is represented by EMD of foods. Precise prediction of the same can optimize the drying process. The plot of ln (MR) against time gave the slope value to determine the diffusivity (Figure 6). EMD during drying of HAMW of shrimp was determined to be 6.7 $\times 10^{-7}$ m^2/s. EMD was estimated from the experimental data based on Fick's law of diffusion. This parameter represented the intrinsic mechanism by which moisture transport was facilitated by means of liquid diffusion, vapor diffusion, hydrodynamic flow and other means. The volumetric heating effect of MWs resulted in higher drying rates and decreased drying times due to higher moisture diffusivity. Thus, moisture diffusivity served as the quantitative parameter at molecular level for explaining drying kinetics. Kaveh et al. (2021) opined that MW drying exhibited higher values of diffusivity compared to convective drying based on his study on drying of pomegranate arils. Darvishi et al. (2014) studied MW drying effects on mulberry and reported diffusivities in range of 1.06×10^{-8} to 3.45×10^{-8} m^2/s as the MW power was varied from 100 to 500 W. MW drying of persimmon exhibited a moisture diffusivity value of 2.97×10^{-8} m^2/s and 4.63×10^{-6} m^2/s under varying operating conditions (Çelen, 2019).

3.3 | Evaluation of drying models

HAMW of shrimp was represented by reduction in moisture percent as a function of drying time. Moisture ratio obtained during drying was fitted into thin layer drying models by non-linear regression analysis (Table 2). Page model was identified as the best fit model with higher R^2 value of 0.9984, lower χ^2 value of 0.000134 and RMSE value of 0.01552 (Table 2). To verify the acceptability of the selected page model, observed moisture ratio values were plotted against predicted values. It was observed that actual and predicted moisture ratio values were close to each other with the R^2 value of 0.9984 which implies that the selected model satisfactorily described the drying behavior of shrimp under the HAMW dryer

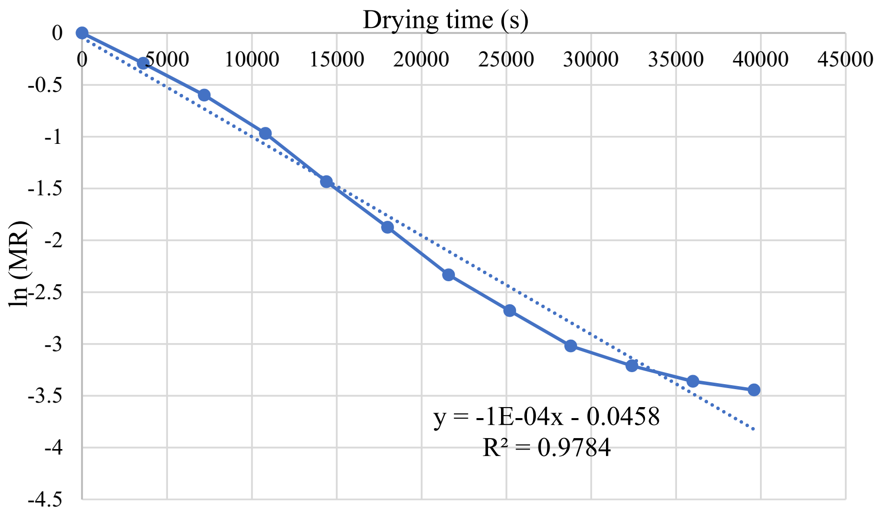

FIGURE 6 Plot of ln (MR) against time for HAMW drying of shrimp.

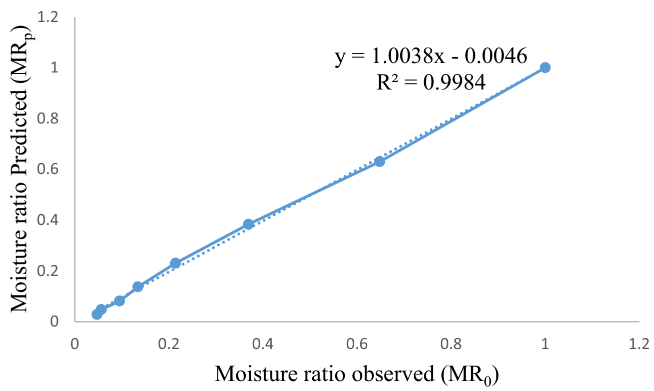

FIGURE 7 Best fit page model.

(Figure 7). Similar study was published by Murali et al. (2021) for drying of shrimp in solar-LPG hybrid dryer.

3.4 | Drying efficiency

Drying efficiency of the dryer under HAMW mode was observed to be 35.71%. This was a result of volumetric hearing effect of MW radiation combined with convective effect of HA. Hassan (2016) published that since MWs act only on polar molecules, MW drying efficiency decreased with time and increased with moisture content of sample during studies on MW drying of date. Maximum drying efficiency of 32% was recorded with a SEC 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 drying of apple slices in laboratory scale MW dryer.

3.5 | SEC

The SEC value for HAMW of shrimp was found to be 1.75 kWh/kg. Sharma and Prasad (2006) reported SEC of 26.32 MJ/kg for drying of garlic under MW power of 40 W and HA temperature of 70°C. MW and convective drying of pomegranate arils were calculated to have SEC of 35.42 and 145.12 kWh/kg (Kaveh et al., 2021). It is understood that as moisture content decreases, the energy requirement and SEC increases due to difficulties in removing water other than free and unbound moisture in the product. But the volumetric heating effect of MWs in the study tended to fasten the drying process leading to higher drying rates and subsequently lower SEC as compared with convective drying. As moisture content of product decreased, the MW energy absorbed by the shrimp also reduced leading to higher SEC during later stages of drying. SEC in MW drying was observed to have 70% more energy savings as compared to convective drying (Sadi & Meziane, 2015).

3.6 | Color change

The total value of color change (ΔE) 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. Darker color of shrimps can be attributed to the process of Maillard browning reaction that might have occurred during drying. The development of redness was due to the release of astaxanthin during the breakdown of carotenoproteins. Yellowness of shrimp increased as a consequence of the formation of yellow pigments due to browning reactions during drying. Çelen (2019) evaluated the color of persimmon dried using MW radiation and obtained values of 13.25 and 24.320 for ΔL and ΔE, respectively, at MW power of 600 W. It was also observed that higher MW powers may cause unstable MW field that may affect the color quality of products. Taib and Ng (2011) also showed that in MW drying of catfish slices, HA treatment imparted brighter color to dried products shifting towards red and yellow.

3.7 | Shrinkage

Removal of moisture during dehydration of food is followed by volume change in the dried products. This change in volume causes shrinkage of the dried products and the extend of shrinkage depends on the method of drying. Shrinkage percentage of dried shrimp was observed to be 14.14%. Shorter drying time could be the reason for lesser shrinkage values (Tapaneyasin et al., 2005). Reduction in shrinkage percentage was due to the rapid evaporation of moisture by MW radiation that created a vapor flux thereby preventing case hardening. Giri and Prasad (2007) reported that MW vacuum drying of mushrooms resulted in dried products with very less shrinkage compared to HA-dried samples. MW-dried herbs exhibited lesser shrinkage and better retention of biochemical constituents as reported by Kathirvel et al. (2006). The reason for a lower percentage of shrinkage was due to controlled drying of shrimp which has resulted in the rapid removal of moisture and thus created an internal porous structure in the dried shrimp.

3.8 | Rehydration ratio

The structural and cellular degradation occurred within the sample during drying is explained by rehydration ratio. The values of rehydration ratio of dried shrimp with respect to time are shown in Figure 8. Within the first hour of soaking shrimp in water, a rapid rise was seen in rehydration ratio. Average rehydration ratio was observed to be 2.51. Rehydration ratio of Tilapia fillets increased with MW power and air temperature during HAMW drying of the fish (Duan et al., 2011). Akonor et al. (2016) also reported similar range of rehydration ratio for shrimp. Initially, a high rate of rehydration was observed which may be due to the porosity of the samples. However, after the first hour, rehydration is slowed down for the next four hours, and thereafter, the process reached equilibrium at the end of 7 h. Hence, the rehydration ratio of 2.51 for the dried shrimp shows that less structural damage could have occurred in the product during drying.

3.9 | Water activity

In this study, water activity value of dried shrimp was determined to be 0.552 that indicated the product to be stable microbiologically. Oxidative and enzymatic reactions were suppressed by lowering water activity leading to shelf-life extension of products (Jayaraman & Gupta, 2020).

3.10 | Microbiological quality

The TPC of raw shrimp was 3.6×10^6 CFU/g of a sample. Drying reduced the TPC value of shrimp to 2×10^4 CFU/g, which is lower than raw samples. The extent of microbial reduction required to conform with the acceptable microbiological limit of dried fish is less than 10^5 CFU/g of a sample (IS 14950 2001). This confirms that dried shrimps prepared with HAMW dryer were microbiologically safe for consumption. A similar result of microbial reduction was reported by Murali et al. (2021) for shrimp drying.

3.11 | Proximate and biochemical analysis

Results of proximate analysis of fresh and dried shrimp are shown in Figure 9. The moisture content of the fresh shrimp was decreased from 80.55% (w.b) to 16.5% (w.b) in the dryer. Moisture removal was due to the MW power applied with the assistance of HA generated in the dryer. Similar result was reported by Tein et al. (1999) for drying shrimp from 83% to 20% moisture levels under vacuum-assisted MW drying system. Protein content of shrimp increased from 15.12% to 60.24% due to the evaporation of moisture during drying which resulted in aggregation of protein and increased the concentration of protein in dried shrimp. Rasul et al. (2018) reported similar increase in protein content of dried silver carp during drying. This ensures the maximum retention of fat during drying. The higher ash content in dried shrimp was due to the moisture reduction as the ash content is directly related to moisture content and temperature. As moisture content decreases, ash content increases (Adeyeye, 2000). Akonor et al. (2016) reported ash content increase in shrimp during drying due to moisture reduction and concentration of chemical components.

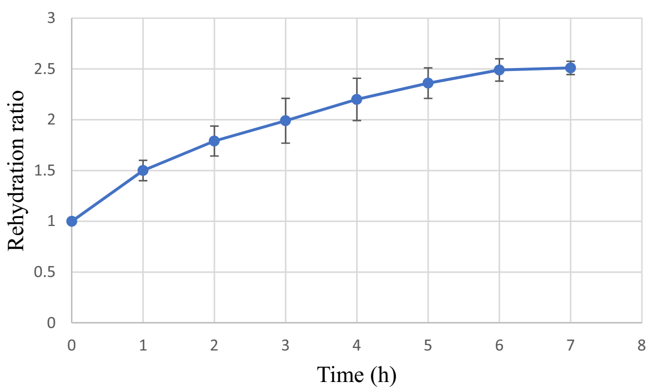

FIGURE 8 Rehydration ratio of dried shrimp as a function of time.

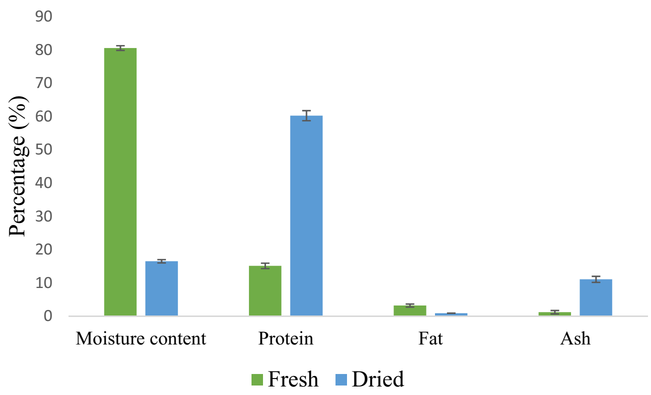

FIGURE 9 Proximate composition of fresh and HAMW dried shrimp.

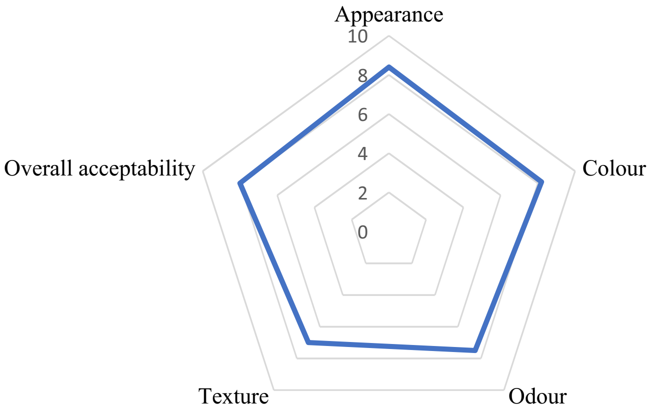

FIGURE 10 Radar diagram for sensory evaluation of dried shrimp.

3.12 | Sensory evaluation

The scores of sensory evaluation of dried shrimp are depicted in Figure 10. Twenty-five semi-trained panel members comprising of research scholars and staff assigned maximum score to "overall acceptability" of the samples. This can be due to the degree of uniformity in the samples, final moisture content and better color retention of the samples. Mounir et al. (2020) also reported highest overall acceptability to the intermittent MW dried shrimp snacks coupled with instant controlled pressure drop treatment.

4 | CONCLUSIONS

MW drying produced better quality shrimp with respect to shrinkage, rehydration ratio, moisture diffusivity and drying times and hence finds application in the production of bulk quantity of high-quality dried shrimp. The developed HAMW drying system was found to be suitable for shrimp drying under controlled conditions. The shrimp samples were dried to a final moisture content of 16.5% within 3.5 h of drying. EMD of MW dried shrimp was found to be 6.7×10^{-7} m^2/s. Logarithmic model was the suitable fit for the data under study (R^2 = 0.9984, RMSE = 0.0.01552 and χ^2 = 0.000134). The drying efficiency and SEC for HAMW drying of shrimp were calculated to be 35.71% and 1.75 kWh/kg, respectively. The total value of color change (ΔE) determined for dried shrimp was 16.95 ± 2.14. Water activity, rehydration ratio and shrinkage of the dried shrimp samples were 0.552%, 2.51% and 14.14%, respectively. Proximate and microbiological analysis of fresh and dried shrimp were carried out and were found to be within safe limits. This dryer is capable of producing high-quality dried shrimp with economic viability and can be used for commercial production of dried shrimp. Development of a pilot scale prototype of the existing system can reduce drying times and thereby the related electricity consumption making it more energy saving and environment friendly with reduced greenhouse gas emissions as compared to a conventional electrical dryer.

AUTHOR CONTRIBUTIONS

Palli V. Alfiya developed the original concept, performed formal analysis and methodologies, prepared the original draft and contributed to reviewing and editing. Gourikutty K. Rajesh contributed to the administration, supervision, provision of resources, curation of data, reviewing and editing. Subramaniam Murali contributed to formal analysis, reviewing and editing. Dhanapaul S. Aniesrani Delfiya contributed to formal analysis, reviewing and editing. Manoj P. Samuel contributed to administration and supervision. Manadan V. Prince contributed to administration and supervision.

ACKNOWLEDGMENTS

The work received funding from Indian Council of Agricultural Research under All India Coordinated Research Projects for Tavanur Centre. Authors would like to acknowledge the Director, ICAR-CIFT, Kochi, Dean, KCAET, Tavanur and Head, Division of Engineering, ICAR-CIFT, Kochi for providing the necessary facilities for the research work.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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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How to cite this article: Alfiya, P. V., Rajesh, G. K., Murali, S., Aniesrani Delfiya, D. S., Samuel, M. P., & Prince, M. V. (2022). Development and evaluation of hot air-assisted microwave dryer for shrimp (*Metapenaeus dobsoni*). *Journal of Food Processing and Preservation*, *00*, e17112. https://doi.org/10.1111/jfpp.17112