Development of novel high power-short time (HPST) microwave assisted commercial decontamination process for dried turmeric powder (*Curcuma Longa* L.)

G. Behera¹ · P. P. Sutar¹ · S. Aditya²

Revised: 16 August 2017 / Accepted: 19 September 2017 / Published online: 6 October 2017
© Association of Food Scientists & Technologists (India) 2017

Abstract The commercially available dry turmeric powder at 10.34% d.b. moisture content was decontaminated using microwaves at high power density for short time. To avoid the loss of moisture from turmeric due to high microwave power, the drying kinetics were modelled and considered during optimization of microwave decontamination process. The effect of microwave power density (10, 33.5 and 57 W g⁻¹), exposure time (10, 20 and 30 s) and thickness of turmeric layer (1, 2 and 3 mm) on total plate, total yeast and mold (YMC) counts, color change (ΔE), average final temperature of the product (T_{af}), water activity (a_w), Page model rate constant (k) and total moisture loss (ML) was studied. The perturbation analysis was carried out for all variables. It was found that to achieve more than one log reduction in yeast and mold count, a substantial reduction in moisture content takes place leading to the reduced output. The microwave power density significantly affected the YMC, T_{af} and a_w of turmeric powder. But the thickness of sample and microwave exposure time showed effect only on T_{af} , a_w and ML. The colour of turmeric and Page model rate constant were not significantly changed during the process as anticipated. The numerical optimization was done at 57.00 W g⁻¹ power density, 1.64 mm thickness of sample layer and 30 s exposure time. It resulted into 1.6×10^7 CFU g⁻¹ YMC, 82.71 °C T_{af} , 0.383 a_w and 8.41% (d.b.) final moisture content.

Keywords Monolayer moisture content · Yeasts and mold count · Water activity · Drying kinetics

Introduction

Turmeric (*Curcuma longa* L.) is one kind of spice. It is dried rhizome of a herbaceous plant and consumed either fresh or in dried form for its colour, aroma and medicinal properties (Hmar et al. 2017; Panneerselvam et al. 2007). India is the largest producer and consumer of turmeric in the world with a production of 337,500 metric tons (Spice Board of India 2016) contributing approximately 80% of total world turmeric production. Contamination of turmeric is common in India due to the poor post harvesting handling causing certain food-borne illnesses and spoilage (Ahene et al. 2011). The microbial contamination in turmeric powder is predominant due to improper cleaning of rhizomes and direct contact with soil during open sun drying. Therefore, it is necessary to decontaminate the turmeric powder before adding to the food. The number of microorganisms present in turmeric powder may reduce in the cleaning and processing but still, there is the presence of some common mold and spore forming bacteria (Parveen et al. 2014). Methylene bromide and ethylene oxide were commonly used for fumigation and microbial decontamination of spices, but are banned due to health concern (Hayashi et al. 1998). Another method to reduce the microbial load in powdered spices is superheated steam treatment (Schweiggert et al. 2007). During steaming, longer heating time causes loss of flavour and colour. In addition to this, the condensed moisture must be removed by drying to prevent mold growth after steam treatment (Suresh et al. 2007; Tainter and Grenis 2001). Irradiation with gamma rays and X-rays are also capable of reducing

✉ G. Behera
gitanjalibehera001@gmail.com

¹ Department of Food Process Engineering, National Institute of Technology, Rourkela, Sundergarh, Odisha 769008, India

² Department of Food Engineering and Technology, Tezpur University, Napaam, Sonitpur 784028, India

the pathogenic microorganisms by a very large number. There is no residual radiation left after the treatment and the food is safe to consume (Schweiggert et al. 2007; Tainter and Grenis 2001). Irradiation at high dose causes oxidation and degradation of aromatic compounds in spices (Hayashi et al. 1998; SádECKá 2007; Variyar et al. 1998). Also, the technology comes at a very high cost, not affordable by most countries, particularly, the developing ones like India (Dhanya et al. 2009). Therefore, there is a need for a new thermal method of turmeric decontamination.

The shelf life and chemical stability of any food product depend on its water activity. Sorption isotherm of a particular product depicts the relationship between water activity and moisture content and it is used in calculating sorption enthalpy, packaging material selection and modeling of drying processes etc. Many theoretical, empirical or semiempirical models have been proposed by several researchers to describe the sorption isotherms (Iglesias et al. 1975; Iglesias and Chirife 1976; Berg and Bruin 1981). But Guggenheim-Anderson-de Boer (GAB) model is successful for many products for describing the sorption isotherm and for calculating the monolayer moisture content.

Microwaves are electromagnetic waves in the frequency range 300–3000 megahertz generated by magnetron. Heat is produced directly in the product (volumetric heating) and the thermal processing time is sharply reduced. Food processed by microwaves retain better colour, texture, and sensory attributes compared to conventional heating methods (Giri et al. 2014; Jeevitha et al. 2016). Generally, microwave frequency of 2450 MHz is used for domestic purpose and 915 MHz is used for industrial purpose. These two frequencies can rapidly achieve product temperature to kill most of the microorganisms in the spices with less quality degradation. The water activity also gets affected by microwave heating. Keeping in view the disadvantages of conventional decontamination methods and advantages of microwave heating, the present study was undertaken with the objective to optimize the high power microwave decontamination process for commercially available dry turmeric powder by considering the drying kinetics and sorption modeling parameters.

Materials and methods

Raw material

Fresh turmeric powder was collected from a local market of Rourkela (India). The samples were cleaned and sieved using 500-µm International Standard sieve. The moisture

content of the sample was determined using hot air oven method at 105 ± 2 °C (AOAC 1990).

Experimental setup for decontamination of turmeric powder using microwaves

A programmable domestic microwave oven (Samsung, Model-CE73JD) with a maximum output of 800 W at 2450 MHz was used for conducting the experiments. The dimensions of the microwave cavity were 310 mm width, 290 mm height and 220 mm depth. The oven was fitted with a fan, a glass turntable (30 cm diameter) and a digital controller to adjust the pulsation of microwave power and total heating time. Before starting the experiments, the microwave oven was standardized for its efficiency. The heat absorbed by water (220 g) was equated to the input energy. The efficiency of the microwave oven was calculated according to USFDA (United State Food and Drug Administration) procedure at different power levels and the average efficiency was found to be 76% (USFDA 1977).

Modeling sorption phenomena of turmeric

The turmeric powder at 10.34% (d.b.) was conditioned at five different moisture content levels (9.9, 15.45, 16.72, 18.35, 23.85% d.b.) by drying or adding calculated amount of distilled water. After addition of water, the samples were sealed in high density polyethylene (HDPE) bags and stored for 3 days in the refrigerator (5–6 °C) with intermittent mixing in between the days. The water activity of the conditioned sample was measured using a water activity meter (Rotronic, HC2-AW, Rotronic measurement solution, Switzerland) at initial temperature 20.02 °C and relative humidity 53%. The actual moisture content of the samples was determined using hot air oven method at 105 ± 2 °C (AOAC 1990). The Guggenheim-Anderson-de Boer (GAB) model (Bizot 1983) was fitted to water activity and moisture content data which is given below:

$$X = \frac{MCKa_w}{(1 - Ka_w)(1 - Ka_w + CKa_w)} \quad (1)$$

$$\frac{a_w}{X} = \left[\frac{K}{M} \left(\frac{1}{C} - 1 \right) \right] a_w^2 + \left[\frac{1}{M} \left(1 - \frac{2}{C} \right) \right] a_w + \left(\frac{1}{MCK} \right) \quad (2)$$

where X is the moisture content (d.b.), a_w is the water activity, and M, K and C are the three free sorption parameters characterizing sorption properties of the material. The parameter M denotes the monolayer moisture content. The following polynomial equation of second order was fitted to plot of a_w and a_w/X to get coefficients b_1 , b_2 , and b_3 and R^2 value.

$$\frac{a_w}{X} = b_1 a_w^2 + b_2 a_w + b_3 \quad (3)$$

The estimation of the parameters M, K and C was done using following equations:

$$M = (b_2 + 2b_3 K)^{-1} \quad (4)$$

$$K = \frac{-b_2 + (b_2^2 - 4b_3 b_1)^{0.5}}{2b_3} \quad (5)$$

$$C = (b_3 M K)^{-1} \quad (6)$$

The preliminary trials on microwave decontamination of turmeric powder were conducted to select the power density (Sutar and Prasad 2007; Horrungsiwat et al. 2016) and heating time combinations so that the final moisture content of the product should not drop below the monolayer moisture content as well as the process should result in a non-significant colour change. For fulfilling the above conditions of the commercial viability of the process it was decided to use high microwave power density for a short time. The maximum total moisture loss during decontamination was limited to 20–25%. The heating was stopped by pre-calculating the sample weight based on initial moisture content.

Microwave assisted turmeric decontamination experiments

Experiments were planned to decontaminate turmeric powder using Box–Behnken design (Montgomery 1984).

The independent variables were power density (10, 33.5 and 57 W g⁻¹), the thickness of sample (1, 2 and 3 mm) and exposure time (10, 20 and 30 s). During preliminary trials, it was found that the higher exposure time (> 30 s) affected the colour of the turmeric powder and causes loss of moisture and sensory flavour. The literature shows that the microwave power density during drying varies from 0.1 to 10 W g⁻¹. In this study, the moisture content of commercially available turmeric powder was less (10.34% db) and microwave heating was for a very short time due to decontamination process. Therefore, to achieve the high temperature in short time it was compulsory to use such a high level of power density. The power density was maintained by reducing the quantity of the product (300–600 W and 7–21 g in maximum 800 W oven). The experiments consisted 17 runs with five experiments at the centre point (Table 1). The dependent variables considered were total plate count (TPC, CFU g⁻¹), total yeast and mold count (YMC, CFU g⁻¹), colour change (ΔE), average final temperature (T_{af} , °C), water activity (a_w), drying rate constant (k , s⁻¹) of Page model and total moisture loss (ML, %).

The turmeric powder was spread in a glass petri dish at predetermined thickness (1, 2 and 3 mm) without compaction. The microwave oven was set at a prefixed power level (10, 33.5 and 57 W g⁻¹) and exposure time (10, 20 and 30 s). Every 5 s, the weight of the sample was taken by an electronic balance (Contech, CA224, India) having accuracy 1 ± 0.0001 g. At the end of the total heating

Table 1 Experimental results for the Box–Behnken three-factor design matrix with responses

Run no.	Independent variables					Responses					
	D, W g ⁻¹	t, mm	θ, s	TPC, CFUg ⁻¹ × 10 ⁶	YMC, CFU g ⁻¹ × 10 ⁶	ΔE	T _{af} , °C	a _w	k, s ⁻¹	n	ML, %
1	10.00	1	20	54	46	4.47	56.16	0.431	0.0096	1.053	9.13
2	57.00	1	20	48	24	3.29	72.55	0.387	0.0168	1.042	18.72
3	10.00	3	20	25	38	2.65	66.8	0.507	0.0025	1.297	5.60
4	57.00	3	20	29	23	2.37	75.26	0.502	0.0008	1.694	6.01
5	10.00	2	10	41	61	5.49	60.16	0.498	0.0318	0.575	5.09
6	57.00	2	10	33	24	4.34	69.33	0.494	0.0444	0.515	6.13
7	10.00	2	30	8	56	2.53	60.20	0.413	0.0032	1.363	14.16
8	57.00	2	30	19	15	4.77	84.80	0.414	0.0038	1.290	14.14
9	33.50	1	10	30	52	3.27	61.93	0.490	0.0279	0.632	3.84
10	33.50	3	10	31	45	3.04	65.93	0.561	0.0011	1.557	1.79
11	33.50	1	30	31	39	4.98	68.7	0.376	0.0659	0.750	18.52
12	33.50	3	30	38	30	3.72	78.4	0.421	0.0009	1.619	11.82
13	33.50	2	20	28	50	2.91	75.34	0.438	0.0006	1.787	6.37
14	33.50	2	20	30	78	2.90	75.17	0.440	0.0012	1.653	8.94
15	33.50	2	20	31	80	2.91	73.57	0.450	0.0031	1.297	7.20
16	33.50	2	20	29	78	2.91	74.39	0.465	0.0019	1.486	7.78
17	33.50	2	20	31	81	2.90	73.56	0.474	0.0028	1.340	5.06

period, an infrared sensor (IRL380-KUSAM MECO, India) at three locations recorded the temperature of the sample and the average temperature was estimated. The infrared sensor was pre-calibrated with dry surface of known temperature and moist products. Further, treated samples were analyzed to collect the response data.

Modeling drying kinetics during microwave decontamination

During microwave heating, it was observed that high power density microwave heating results into substantial moisture loss from turmeric. Therefore, the all the decontamination experiments were repeated to collect the total moisture loss (ML) data. The ML data at different time intervals (10, 20, 30 s) during all pre-treatments is given in Table 1. For modeling drying kinetics during decontamination, the total duration of the experiment was subdivided into smaller time intervals (5 s). The Page model was fitted to data and model constants were estimated. Page's equation is one of the most successful empirical equations applied to describe water migration during food drying processes. The constant k and n describe the drying phenomena accurately compared to other models. The drying rate constant k increases with increase in temperature. The value of n indicates the diffusion phenomenon ($n > 1$ is super diffusion and $n < 1$ is sub-diffusion) in drying of food stuffs. Therefore, unlike other empirical model constants the Page model gives insight of the drying process (Simpson et al. 2017). The model is given below (Sutar and Prasad 2007):

$$MR = \exp(-kt^n) \quad (7)$$

where MR is the moisture ratio (fraction), t is heating time (s) and k is moisture desorption rate constant (s^{-1}). The MR is calculated using the following formula:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (8)$$

where M_t is the moisture content at any time t (% d.b.), M_0 is the initial moisture content (% d.b.), M_e is the equilibrium moisture content (% d.b.). In this case, M_e was considered as 0 as it is quite small compared to M_t and M_0 .

Also, the root mean squared error (RMSE) values were calculated to check the goodness of fit of Page model to the data. It was calculated using the following equation:

$$RMSE = \sqrt{\frac{\sum_1^N (MR_e - MR_p)^2}{N}} \quad (9)$$

where MR_e is experimental moisture ratio, MR_p is predicted moisture ratio and N is the number of observations (Sutar and Prasad 2011). Average drying rates were

calculated using following equation and plotted with the average moisture content.

$$\text{Average drying rate} = \frac{M_{t+dt} - M_t}{dt} \quad (10)$$

where M_{t+dt} is moisture content at time t , M_t is initial moisture content, dt is the time interval (Sutar and Prasad 2011).

Quality analysis

Total plate count (TPC)

Total plate count before and after microwave treatment of turmeric, was estimated by serial dilution of the sample with 28 g of nutrient agar (High Media, M001, India) per one litre of distilled water by pour-plates method (AOAC 1994). The media was sterilized in an autoclave (RELITECH, ModelVTA-78, India) at 15 psig and $121^\circ \pm 1^\circ \text{C}$ for 15 min. The plates were inverted and incubated (REMI, CIS24-plus, India) at 35°C for 48–72 h (Lebai Juri et al. 1986). After incubation, colonies appeared were counted by using a colony counter (LA663-1NO, Hi-Media, India) and the calculation was done to determine the number of total plate count.

Total yeast and mold count (YMC)

Total yeast and mold count before and after microwave treatment of turmeric, was estimated by serial dilution of the sample with 18 g of potato dextrose agar (Hi Media M096, India) per one little of distilled water by pour-plates method (AOAC 2000). The media was sterilized in an autoclave (RELITECH, ModelVTA-78, India) at 15 psig and $121^\circ \pm 1^\circ \text{C}$ for 15 min. All the glassware was also sterilized in autoclave at $121 \pm 1^\circ \text{C}$ for 15 min. The plates were inverted and incubated at 25°C for 48–72 h and the total yeast and mold count was determined.

Colour difference (ΔE)

Hunter Lab Colorimeter (Color Flex F2, India) was used to measure the colour of the turmeric powder before and after microwave treatment in terms of CIE L , a and b values. The total colour difference (ΔE) was calculated using following equation:

$$\Delta E = \left[(L - L^*)^2 (a - a^*)^2 (b - b^*)^2 \right]^{\frac{1}{2}} \quad (11)$$

where L is the lightness/brightness of sample, a is redness/greenness and b is yellowness/blueness. The

superscript * indicates the value associated with microwave untreated sample.

Water activity (a_w)

The water activity is an indicator of the stability of the product. Therefore, the a_w of the turmeric powder before and after microwave treatment, was measured by a water activity meter (Rotronic, HC2-AW, Rotronic measurement solution, Switzerland). The probe was directly connected to a personal computer running HW4 software (version:v2, Rotronic AG, Switzerland) enabling water activity measurement capability. The water activity was measured after the temperature and relative humidity became stable.

Statistical analysis and optimization

Design-Expert 10.0 (Statease, Minneapolis), a commercial statistical package was used for the analysis of the experimental data. Multiple regression analysis was done by fitting a second order polynomial model to the experimental data. The response function was partitioned into linear, quadratic and interactive components as given below:

$$Y_k = b_{k0} + \sum_{i=1}^3 b_{ki}X_i + \sum_{i=1}^3 b_{kii}X_i^2 + \sum_{i \neq j=1}^3 b_{kij}X_iX_j \quad (k = 0, 1, 2, 3, \dots) \quad (12)$$

where Y_k is the response, b_{k0} , b_{ki} , b_{kii} and b_{kij} are the constant, linear, quadratic and cross-product regression coefficients, respectively. X is the code independent variable.

TPC and YMC data were transformed before the analysis. Taking the logarithms of response makes the characteristics of data fit better and overcomes the problems associated with non-normal distribution. Analysis of variance (ANOVA) was done ($p \leq 0.05$) to find the effects of the independent variables in linear, quadratic and interaction terms. The regression coefficients were estimated and significance of each term was judged statistically by computing probability (p). The adequacy of the model was tested using the lack of fit and R^2 . The models were then used to interpret the effect of independent variables on the response.

Perturbation analysis

A perturbation analysis was performed to study the effect of all the independent variables on the responses. For this purpose, the range of variables was selected between -1 and $+1$. To study the individual effect of each variable, its level was varied between -1 and $+1$ at an interval of 0.5

while other variables were maintained at 0 . A steep slope or curvature in a variable shows the sensitivity of response to the variable and a relatively flat line shows insensitivity or less sensitivity.

Numerical optimization and desirability function

A numerical optimization was done to find the best combination of independent variables with responses. For this purpose, microwave power density, the thickness of sample and exposure time were set in the range. Goals for all the variables were decided. In order to search a solution maximizing multiple responses, the goals were combined into an overall composite function, $D(f)$, called the desirability function (Montgomery 1984; Myers and Montgomery 2002) which is given below:

$$D(f) = [d_1 \times d_2 \cdots \times d_m]^{\frac{1}{m}} \quad (13)$$

where $D(f)$ is the desirability function, Y_i ($i = 1, 2, \dots, m$) are the responses and m is the total number of responses in the measure. Desirability is an objective function that ranges from zero outside of the limits to one at the goal. The numerical optimization finds a point that maximizes the desirability function.

Results and discussion

Modeling sorption phenomena of turmeric powder

The moisture content of the conditioned turmeric powder ranged between 10.34 to 22.35% (d.b.). The water activity corresponding to the moisture content ranged between 0.563 and 0.880 . The sorption data was fitted to GAB model which was solved by using following second-order polynomial equation:

$$a_w/X = -6.681 + 39.21a_w - 32.43b_3a_w^2 \quad (R^2 = 0.977) \quad (14)$$

From the coefficients of above equation, the GAB model constants were estimated using Eqs. 4, 5 and 6. For the turmeric powder, the monolayer moisture content was estimated at 3.86% db and GAB constants C and K were found to be -3.891 and 0.996 , respectively.

Microwave decontamination

Untreated turmeric powder was heated by using a microwave oven. The effect of three independent variables (power density, thickness of sample and exposure time) on the dependent variables (TPC, YMC, T_{af} , ΔE , a_w , k and ML) was analyzed. A wide variation was observed in all

responses ($p \leq 0.05$). The data is given in Table 1. The initial moisture content of untreated turmeric powder was found to be 10.34% (d.b.).

Effect of the independent variables on TPC

TPCs (CFU g⁻¹) at different experimental combinations are given in Table 1. In fresh turmeric powder TPC was 2×10^9 CFU g⁻¹ and after microwave decontamination, it varied between 8×10^6 and 54×10^6 CFU g⁻¹. A maximum of 1.57–2.39 log reduction of bacteria was found in the microwave treated turmeric powder. In the experimental range, ANOVA showed the nonsignificant ($p > 0.05$) effect of independent variables on TPC. Lower reduction in TPC may be related to the smaller exposure time and insufficient temperature of bacterial inactivation achieved by product due to a lower initial moisture content of turmeric powder (10.34% d.b.). During preliminary trials, it was found that the higher exposure time (> 30 s) affected the colour of the turmeric powder. Therefore, TPC was not reduced significantly ($p > 0.05$). The result was in agreement with few findings for other spices. Dehne and Bögl (1993) applied microwave heating to cinnamon. They found that microwave treatment of cinnamon results into a maximum 3.5 log cycle reduction of bacteria. Vajdi and Pereira (1973) sterilized black pepper, paprika, garlic, oregano and celery seeds powder using microwaves and compared with ethylene oxide and gamma irradiation. They reported a nonsignificant reduction of bacteria with microwave (25 W) treatment because of less exposure time. The perturbation, contour and response surface plots for TPC are shown in Fig. 1a–c. A relatively smooth slope in the plots showed the insensitivity of the independent variables to TPC.

Effect of the independent variables on YMC

YMCs obtained at different experimental combinations are given in Table 1. YMC in untreated turmeric powder was 2×10^8 CFU g⁻¹. After the microwave heating, YMC varied between 15×10^6 and 81×10^6 CFU g⁻¹ (0.4–1.13 log reduction). International Commission on Microbiological Specifications for Foods (ICMSF) allows a maximum limit of 10^6 CFU g⁻¹ of YMC in spices (ICMSF 2005). Jeevitha et al. (2016) reported a 0.42 log cycle reduction in the YMC of black pepper powder at microwave power density 40 W g⁻¹ and treatment time 1 min. Also, they found an unsafe level of YMC still after 7 min of microwave heating and further increasing the treatment time caused discolouration. Aydin and Boston (2006) treated powdered black pepper at a microwave power of 450 W for 150 s and reported a 90.7% reduction of YMC compared to the initial value. Multiple regression analysis

was done by fitting the Eq. 12 to YMC. ANOVA was done to find significant ($p \leq 0.05$) terms of multiple regression. The complete second-order correlation for YMC was developed after removing insignificant terms which is given below:

$$\begin{aligned} \text{Log}_{10}(\text{YMC}) = & 15.54 + 0.05D - 9.37 \times 10^{-4}D^2 - 0.32t^2 \\ & - 2.57 \times 10^{-3}\theta^2 \\ (R^2 = & 0.92) \end{aligned} \quad (15)$$

where D is microwave power density (W g⁻¹), t is the thickness of the turmeric layer (mm) and θ is exposure time (s). The ANOVA of the individual, interactive and quadratic effects on logarithmically transferred YMC have been given in Table 2. The coefficient of determination (R^2) for the regression model was 0.92. The model was highly significant ($p \leq 0.01$) and lack of fit was found to be nonsignificant ($p > 0.05$). It was found that microwave power density had a significant effect at 1% level of significance at the linear condition. The thickness of sample and exposure time significantly affected the YMC at 1 and 5% levels of significance, respectively. A relatively steep slope was observed from the perturbation plot showing the sensitivity of the independent variables to YMC. Microwave power density has a greater influence on the YMC compared to the thickness of samples and exposure time (Fig. 1d).

Effect of the independent variables on ΔE

During the microwave assisted decontamination of turmeric powder, the colour was considered as an important quality attribute. The L, a and b values of untreated turmeric powder were found to be 55.04, 24.62 and 64.54, respectively. The values of ΔE of microwave-treated turmeric at different experimental combinations are given in Table 1. The maximum ΔE was 5.49 while the minimum was 2.37. The effect of independent variables on ΔE was found to be non-significant ($p > 0.05$) which was expected. This may be due to very short microwave exposure time (10–30 s). Jeevitha et al. (2016) had reported the discolouration of microwave-treated black pepper powder due to high treatment time (7.5 min). A relatively smooth slope can be observed from the perturbation plot (Fig. 1e) showing the insensitivity of the independent variables to colour change.

Effect of the independent variables on average final temperature of the product (T_{af})

The average final temperature (T_{af}) of turmeric powder was significantly ($p \leq 0.01$) affected by independent variables

Fig. 1 **a** Perturbation plot for total plate count. **b** Contour plot for TPC. **c** Effect of power density and exposure time on TPC at constant thickness of turmeric layer (2 mm). **d** Perturbation plot for total yeast and mould count. **e** Perturbation plot for colour change. **f** Effect of power density and thickness of turmeric layer on T_{af} at constant exposure time (20 s). **g** Effect of power density and exposure time on T_{af} of treated turmeric powder at constant thickness of sample

(2 mm). **h** Perturbation plot for Page model drying constant. **i** Effect of power density and exposure time on Page model drying constant at constant thickness of turmeric layer (2 mm). **j** Effect of power density and exposure time on n at constant thickness of turmeric layer (2 mm). **k** Perturbation plot for moisture loss. **l** Effect of power density and exposure time on moisture loss at constant thickness of turmeric layer (2 mm)

Fig. 1 continued

(Table 2). At the time of the decontamination experiment, the ambient temperature was 30.12 °C. The maximum T_{af} reached by turmeric was 84.8 °C while the minimum was 56.16 °C. Multiple regression analysis was done by fitting Eq. 12 to the T_{af} data and correlation was developed which is given below:

$$\begin{aligned}
 T_{af} = & 29.95 + 0.56D + 16.54t + 0.54\theta - 6.18 \times 10^{-3} D^2 \\
 & - 3.29t^2 - 0.024 \theta^2 \\
 & - 0.08D t + 0.02D \theta \quad (R^2 = 0.98)
 \end{aligned}
 \quad (16)$$

Table 2 ANOVA table for total plate count (TPC), total yeast and mould count (YMC), average final temperature (T_{af} , °C), water activity (a_w), Page model rate constant (k), n and total moisture loss (ML, %)

Source	Sum of Squares	Df	Mean square	F Value	<i>p</i> value
Total plate count (TPC)					
Model	0.31	9	0.03	1.20	0.4261
D	0.01	1	0.01	0.38	0.5596
t	0.02	1	0.02	0.88	0.3802
θ	0.09	1	0.09	3.1	0.1218
$D \times t$	3.341×10^{-3}	1	3.341×10^{-3}	0.12	0.7440
$D \times \theta$	0.055	1	0.055	1.91	0.2097
$t \times \theta$	1.376×10^{-3}	1	1.376×10^{-3}	0.05	0.8336
D^2	7.969×10^{-3}	1	7.969×10^{-3}	0.28	0.6160
t^2	0.08	1	0.08	2.78	0.1397
θ^2	0.04	1	0.04	1.52	0.2580
Residual	0.20	7	0.29	—	—
Lack of fit	0.20	3	0.067	182.73	< 0.0001
Pure error	1.46×10^{-3}	4	3.669×10^{-4}		
Total	0.51	16			
R^2	0.61				
Adj R^2	0.099				
Pred R^2	−5.2658				
C.V. %	2.28				
SD	0.17				
Total yeast and mould count (YMC)					
Model	3.76	9	0.42	8.94	0.0043*
D	1.45	1	1.45	30.95	0.0008*
t	0.051	1	0.051	1.10	0.3298
θ	0.19	1	0.19	4.17	0.0805
$D \times t$	5.513×10^{-3}	1	5.513×10^{-3}	0.12	0.7414
$D \times \theta$	0.037	1	0.037	0.79	0.4035
$t \times \theta$	3.47×10^{-3}	1	3.47×10^{-3}	0.074	0.7932
D^2	1.13	1	1.13	24.14	0.0017*
t^2	0.42	1	0.42	9.09	0.0195**
θ^2	0.28	1	0.28	5.95	0.0448
Residual	0.33	7	0.047	—	—
Lack of fit	0.16	3	0.052	1.22	0.4100
Pure error	0.17	4	0.043		
Total	4.09	16			
R^2	0.9199				
Adj R^2	0.8170				
Pred R^2	0.3216				
C.V. %	1.23				
SD	0.094				
Average final temperature (T_{af} , °C)					
Model	887.32	9	98.59	47.36	< 0.0001*
D	429.54	1	429.54	206.35	< 0.0001*
t	91.46	1	91.46	43.94	0.0003*
θ	150.95	1	150.95	72.51	<0.0001*
$D \times t$	15.72	1	15.72	7.55	0.0286**
$D \times \theta$	59.52	1	59.52	28.59	0.0011*
$t \times \theta$	8.12	1	8.12	3.90	0.0888

Table 2 continued

Source	Sum of Squares	Df	Mean square	F Value	<i>p</i> value
D ²	49.12	1	49.12	23.60	0.0018*
t ²	45.80	1	45.80	22.00	0.0022*
θ ²	23.61	1	23.61	11.34	0.0120**
Residual	14.57	7	2.08		
Lack of fit	11.70	3	3.90	5.43	0.0678
Pure error	2.87	4	0.72		
Total	901.89	16			
R ²	0.9838				
Adj R ²	0.9631				
Pred R ²	0.7875				
C.V. %	2.06				
SD	1.44				
Water activity (a _w)					
Model	0.035	9	3.838×10^{-3}	9.24	0.0039*
D	3.419×10^{-4}	1	3.419×10^{-4}	0.82	0.3945
t	0.012	1	0.012	27.96	0.0011*
θ	0.022	1	0.022	52.60	0.0002*
D × t	3.706×10^{-4}	1	3.706×10^{-4}	0.89	0.3765
D × θ	5.760×10^{-6}	1	5.760×10^{-6}	0.014	0.9096
t × θ	1.563×10^{-4}	1	1.563×10^{-4}	0.38	0.5591
D ²	1.581×10^{-5}	1	1.581×10^{-5}	0.038	0.8509
t ²	1.279×10^{-4}	1	1.279×10^{-4}	0.31	0.5963
θ ²	4.413×10^{-5}	1	4.413×10^{-5}	0.11	0.7540
Residual	2.909×10^{-3}	7	4.156×10^{-4}	—	
Lack of fit	1.922×10^{-3}	3	6.406×10^{-4}	2.60	0.1897
Pure error	9.872×10^{-4}	4	2.468×10^{-4}		
Total	0.037	16			
R ²	0.9223				
Adj R ²	0.8225				
Pred R ²	0.1378				
C.V. %	4.46				
SD	0.02				
k, s ⁻¹					
Model	1.034×10^{-3}	9	1.149×10^{-4}	1.40	0.0049*
D	9.901×10^{-6}	1	9.901×10^{-6}	0.12	0.3359
t	4.606×10^{-4}	1	4.606×10^{-4}	5.61	0.7385
θ	1.620×10^{-6}	1	1.620×10^{-6}	0.020	0.0496
D × t	5.290×10^{-6}	1	5.290×10^{-6}	0.064	0.8922
D × θ	6.502×10^{-6}	1	6.502×10^{-6}	0.079	0.8068
t × θ	1.729×10^{-4}	1	1.729×10^{-4}	2.11	0.7864
D ²	1.274×10^{-6}	1	1.274×10^{-6}	0.016	0.1898
t ²	4.312×10^{-5}	1	4.312×10^{-5}	0.53	0.9043
θ ²	3.205×10^{-4}	1	3.205×10^{-4}	3.91	0.4920
Residual	5.742×10^{-4}	7	8.203×10^{-5}	—	—
Lack of fit	5.733×10^{-4}	3	1.911×10^{-4}	888.91	< 0.0001
Pure error	8.600×10^{-7}	4	2.150×10^{-7}		
Total	1.608×10^{-3}	16			
R ²	0.6429				

Table 2 continued

Source	Sum of Squares	Df	Mean square	F Value	<i>p</i> value
Adj R ²	0.1838				
Pred R ²	−4.7054				
C.V. %	144.84				
SD	9.057×10^{-3}				
n					
Model	2.12	9	0.24	3.03	0.0789
D	8.064×10^{-3}	1	8.064×10^{-3}	0.10	0.7569
t	0.91	1	0.91	11.64	0.0113**
θ	0.38	1	0.38	4.88	0.0628
D × t	0.042	1	0.042	0.54	0.4874
D × θ	4.225×10^{-5}	1	4.225×10^{-5}	5.428×10^{-4}	0.9821
t × θ	7.563×10^{-4}	1	7.563×10^{-4}	9.716×10^{-3}	0.9242
D ²	0.21	1	0.21	2.68	0.1456
t ²	1.461×10^{-3}	1	1.461×10^{-3}	0.019	0.8949
θ ²	0.53	1	0.53	6.80	0.0350**
Residual	0.54	7	0.078	—	—
Lack of fit	0.37	3	0.12	2.90	0.1650
Pure error	0.17	4	0.043		
Total	2.67	16			
R ²	0.7958				
Adj R ²	0.5332				
Pred R ²	−1.3395				
C.V. %	22.63				
Std. dev.	0.28				
Total moisture loss (ML, %)					
Model	362.58	9	40.29	8.57	0.0049*
D	15.18	1	15.18	3.23	0.1154
t	78.06	1	78.06	16.60	0.0047*
θ	218.30	1	218.30	46.42	0.0003*
D × t	21.07	1	21.07	4.48	0.0721
D × θ	0.28	1	0.28	0.06	0.8139
t × θ	5.41	1	5.41	1.15	0.3192
D ²	14.27	1	14.27	3.04	0.1250
t ²	3.83	1	3.83	0.81	0.3968
θ ²	3.95	1	3.95	0.84	0.3898
Residual	32.92	7	4.70	—	—
Lack of fit	24.37	3	8.12	3.80	0.1149
Pure error	8.55	4	2.14		
Total	395.50	16			
R ²	0.9168				
Adj R ²	0.8098				
Pred R ²	−0.0196				
C.V. %	24.53				
SD	2.17				

* 1% level of significance, ** 5% level of significance

The results of ANOVA showing the effects of the independent variables and their individual, interactive and quadratic effects ($p \leq 0.05$) on T_{af} are given in Table 2. All the independent variables had a positive correlation with T_{af} . The coefficient of determination (R^2) for the regression model was found to be 0.98. The Model F-value of 47.31 implied the model is significant. The “predicted R^2 ” of 0.79 is in reasonable agreement with the “adjusted R^2 ” of 0.96; that is the difference is less than 0.2. The model was highly significant ($p \leq 0.01$) and lack of fit was found to be non-significant ($p > 0.05$). All the independent variables were highly responsible to cause a change in T_{af} . (Fig. 1f, g).

Effect of the independent variables on a_w

The a_w values measured at different experimental combinations are given in Table 1. The a_w of the fresh sample was 0.599. After microwave heating, the a_w of turmeric sample was varied between 0.387 and 0.561. Multiple regression analysis was done on water activity and a complete second-order model was developed. The ANOVA of the independent variables and their individual, interactive and quadratic effects on water activity is given in Table 2. The correlation developed for a_w is given below:

$$a_w = 0.53 + 0.015t - 5.44 \times 10^{-3} \theta (R^2 = 0.92) \quad (17)$$

It was found that exposure time and thickness of sample had a significant effect on a_w at 1% level of significance at the linear condition. Water activity was increased with thickness but decreased with exposure time. The higher thickness might have offered a barrier for moisture removal whereas longer exposure time increased the moisture loss. The coefficient of determination (R^2) for the regression model was found to be 0.92. The Model F-value of 9.24 implied the model is significant ($p \leq 0.01$) as well as the lack of fit was found to be non-significant ($p > 0.05$). Therefore, the above model was found to be adequate in describing the change in a_w with respect to the thickness of sample and exposure time. From the perturbation analysis, it was observed that the thickness of sample and exposure time were highly sensitive to the a_w .

Effect of the independent variables on drying rate

The Page model was fitted to the data and model constants (k and n) were estimated. The effect of independent variables on k was found to be nonsignificant ($p > 0.05$) as expected (Table 2). It was due to the very short duration of microwave heating experiments that didn't allow drying rates to establish properly. Therefore, k values for the

initial period were not significantly ($p > 0.05$) different for all experiments. The same result can be observed from a perturbation plot for the drying rate constant (Fig. 1h, i). The constant n was only affected significantly ($p < 0.05$) by the exposure time. The effect of power density and thickness of sample were found to be nonsignificant. The same can be also observed from perturbation plot of constant n (Fig. 1j).

Effect of the independent variables on total moisture loss

The total moisture loss (ML) data at different experimental combinations are given in Table 1. The ML from turmeric was found in the range 1.79–18.72% due to microwave decontamination. Multiple regression analysis was done by fitting Eq. 12 to the ML data and correlation was developed keeping significant terms which is given below:

$$ML = 0.389 - 1.34t + 0.41 \theta (R^2 = 0.92) \quad (18)$$

The ANOVA of the independent variables and their individual, interactive and quadratic effects on ML are given in Table 2. It was found that exposure time and thickness of sample had a significant effect on individual parameters at 1% level of significance at the linear condition. The coefficient of determination (R^2) of the regression model was found to be 0.92. The Model F-value of 8.57 implied the model is significant ($p \leq 0.01$) as well as the lack of fit was found to be nonsignificant ($p > 0.05$). Perturbation analysis and surface plots showed high sensitivity of the thickness of sample and exposure time to ML (Fig. 1k, l). The choice of the reference point in the plot was based on centre level experimental conditions which is usually used in response surface methodology.

Modeling drying kinetics during microwave decontamination process

Table 3 gives the data of total moisture loss (ML), Page model constants (k , n), R^2 and RMSE values. The Page model showed a good fit to the drying data with higher R^2 (> 0.90) and lower RMSE (< 0.02) values. The drying rate constant (k) varied from 0.0003 to 0.0383 s^{-1} at different D , t and θ combinations. The k value increased from 0.0044 to 0.0192 s^{-1} with increases of microwave power density from 10 to 57 $W\ g^{-1}$ at constant t and θ . This may be due to increased microwave power increases the driving force for heat and mass transfer. The values of constant “ n ” ranged between 0.5 to 1.6. The sample drying curves indicating (run numbers 7, 8 and 12) the variation of moisture ratio with drying time and variation of average moisture content with average drying rate are shown in Figs. 2 and 3, respectively. The choice of sample runs was

Table 3 Page model drying constants with R^2 and RMSE values

Run no.	D, $W \text{ g}^{-1}$	t, mm	θ , s	ML, %	k, s^{-1}	n	R^2	RMSE
1	10.00	1	20	9.13	0.0044	1.053	0.95	0.137
2	57.00	1	20	18.72	0.0083	1.042	0.96	0.260
3	10.00	3	20	5.60	0.0011	1.297	0.99	0.073
4	57.00	3	20	6.01	0.0004	1.694	0.99	0.072
5	10.00	2	10	5.09	0.0138	0.575	0.99	0.088
6	57.00	2	10	6.13	0.0192	0.515	0.99	0.108
7	10.00	2	30	14.16	0.0015	1.363	0.99	0.193
8	57.00	2	30	14.14	0.0018	1.290	0.99	0.181
9	33.50	1	10	3.84	0.0121	0.632	0.91	0.087
10	33.50	3	10	1.79	0.0005	1.557	0.99	0.026
11	33.50	1	30	18.52	0.0383	0.750	0.87	0.701
12	33.50	3	30	11.82	0.0004	1.619	0.98	0.994
13	33.50	2	20	6.37	0.0003	1.787	0.99	1.026
14	33.50	2	20	8.94	0.0006	1.653	0.98	0.105
15	33.50	2	20	7.20	0.0014	1.297	0.99	0.093
16	33.50	2	20	7.78	0.0009	1.486	0.99	0.098
17	33.50	2	20	5.06	0.0013	1.340	0.99	0.092

Fig. 2 Variation of moisture ratio with drying time (Run nos. 7, 8 and 12) **Fig. 3** Variation of average moisture content with average drying rate (run nos. 7, 8 and 12)

based on microwave power density ($D, W \text{ g}^{-1}$). In the first few seconds, approximately constant drying rate was observed. But most of the drying occurred in the falling rate period. It was due to the application of high microwave power density that rapidly increased the product temperature resulting in increased moisture loss per unit time.

Response surface analysis and optimization of the process

Response surfaces were generated from the developed regressions for all responses. Further the numerical optimization was done by using the equations and desirability function. For this purpose, microwave power density, the thickness of sample and exposure time were set in the range, TPC and k were set in none, YMC and water activity were minimize, average final temperature was maximize, n and ML were set in range. The optimum conditions were found to be microwave power density 57.00 W g^{-1} , the thickness of samples 1.64 mm and exposure time 30 s . YMC, T_{af} , a_w , n and ML at these conditions were $1.6 \times 10^7 \text{ CFU g}^{-1}$, 82.71°C , 0.383 , 1.026 and 18.71% , respectively with desirability 0.94 .

Conclusion

The microwave decontamination process with high power density for short time was found to reduce significantly the yeast and mould count in the low moisture turmeric powder without affecting original colour. Also, the microwave

decontamination maintained the final moisture content of turmeric above (by > 4% d.b.) the monolayer moisture content to make it a commercially viable process. The thickness of turmeric layer and microwave exposure time significantly affected the a_w and ML without significantly changing the colour (E) and rate constant (k). The optimum conditions were found at 57.00 W g⁻¹ microwave power density, 1.64 mm thickness of the turmeric powder layer and 30 s exposure time. At these conditions the 1.1 log reduction of YMC, 82.71 °C average final temperature of the product and 8.41% db final moisture content were achieved.

Acknowledgements The authors are thankful to Ministry of Food Processing Industries (MoFPI) and Ministry of Human Resource Development (MHRD), Government of India for their financial support to this research work.

References

- Ahene R, Odamtten G, Owusu E (2011) Fungal and bacterial contaminants of six spices and spice products in Ghana. *Afr J Environ Sci Technol* 5(9):633–640
- AOAC. Official Methods of Analysis (1990) Association of Official Analytical Chemists Inc. 15th Edn. Arlington, Virginia, USA
- AOAC. Official methods of analysis (1994, 1990.12) Association of Official Analytical Chemists. Aerobic plate count in food. Pour plate method, Washington, DC, USA
- AOAC. Official methods of analysis (2000, 1997.02) Association of Official Analytical Chemists. Yeast and Mold count in food. Pour plate method, Washington, DC, USA
- Aydin A, Boston K (2006) Microbial decontamination of powdered black pepper (*Piper nigrum* L.) by using microwave. *J Food Sci Tech* 43(6):575–578
- Berg C, Bruin S (1981) Water activity and its estimation in food systems: theoretical aspects
- Bizot H (1983) Using the GAB model to construct sorption isotherms. *Phys Prop Foods Appl Sci* 2:43–54
- Dehne L, Bögl K (1993) Pasteurization of spices by microwave and high frequency. *Food Mark Technol* 7(5):35–38
- Dhanya R, Mishra B, Khaleel K, Cheruth AJ (2009) Shelf life extension of fresh turmeric (*Curcuma longa* L.) using gamma radiation. *Radiat Phys Chem* 78(9):791–795
- Giri S, Sutar P, Prasad S (2014) Effect of process variables on energy efficiency in microwave vacuum drying of button mushroom. *J Food Res Technol* 2(1):31–38
- Hayashi T, Takahashi Y, Todoriki S (1998) Sterilization of foods with low-energy electrons (“soft-electrons”). *Radiat Phys Chem* 52(1):73–76
- Hmar BZ, Kalita D, Srivastava B (2017) Optimization of microwave power and curing time of turmeric rhizome (*Curcuma Longa* L.) based on textural degradation. *LWT-Food Sci Technol* 76:48–56
- Horrungsiwat S, Therdthai N, Ratphitagsanti W (2016) Effect of combined microwave-hot air drying and superheated steam drying on physical and chemical properties of rice. *Int J Food Sci Technol* 51(8):1851–1859
- ICMSF (2005) International Commission on Microbiological Specifications for Foods, Spices, Herbs, and Dry Vegetable Seasonings. Kluwer Academic/Plenum Publishers, London
- Iglesias HA, Chirife C (1976) A model for describing the water sorption behavior of foods. *J Food Sci* 41:984–992
- Iglesias HA, Chirife J, Lombardi JL (1975) An equation for correlating equilibrium moisture content in foods. *Int J Food Sci Technol* 10(3):289–297
- Jeevitha GC, Sowbhagya HB, Hebbar HU (2016) Application of microwaves for microbial load reduction in black pepper (*Piper nigrum* L.). *J Sci Food Agric* 96(12):4243–4249
- Lebai Juri M, Ito H, Watanabe H, Tamura N (1986) Distribution of microorganisms in spices and their decontamination by gamma-irradiation. *Agric Biol Chem* 50(2):347–355
- Montgomery DC (1984) Design and Analysis of Experiments, 2nd edn. John Wiley and Sons, New York
- Myers R, Montgomery DC (2002) Response Surface Methodology. Wiley, New York
- Panneerselvam R, Jaleel CA, Somasundaram R, Sridharan R, Gomathinayagam M (2007) Carbohydrate metabolism in *Dioscorea esculenta* (Lour.) Burk. tubers and *Curcuma longa* L. rhizomes during two phases of dormancy. *Coll Surf B Biointerfaces* 59(1):59–66
- Parveen S, Das S, Begum A, Sultana N, Hoque M, Ahmad I (2014) Microbiological quality assessment of three selected spices in Bangladesh. *Int Food Res J* 21(4)
- SádEcká J (2007) Irradiation of spices—a review. *Czech J Food Sci* 25:231–242
- Schweiggert U, Carle R, Schieber A (2007) Conventional and alternative processes for spice production—a review. *Trends Food Sci Technol* 18(5):260–268
- Simpson R, Ramírez C, Nuñez H, Jaques A, Almonacid S (2017) Understanding the success of Page’s model and related empirical equations in fitting experimental data of diffusion phenomena in food matrices. *Trends Food Sci Technol* 62:194–201
- Spice board of india. Production of turmeric in India. (2016). www.indianspices.com/Accessed 18th June 2016
- Suresh D, Manjunatha H, Srinivasan K (2007) Effect of heat processing of spices on the concentrations of their bioactive principles: turmeric (*Curcuma longa*), red pepper (*Capsicum annum*) and black pepper (*Piper nigrum*). *J Food Compos Anal* 20(3):346–351
- Sutar PP, Prasad S (2007) Modeling microwave vacuum drying kinetics and moisture diffusivity of carrot slices. *Drying Technol* 25(10):1695–1702
- Sutar PP, Prasad S (2011) Modeling mass transfer kinetics and mass diffusivity during osmotic dehydration of blanched carrots. *Int J Food Eng* 7(4):1–5
- Tainter D, Grenis A (2001) Spices and Seasonings: A Food Technology Handbook (2nd, Edition edn. Wiley, New York
- USFDA (1977) United State Food and Drug Administration. HEW publication (FDA), Rockville, Maryland, Montgomerypp, Procedure for field testing microwave oven, p 13
- Vajdi M, Pereira R (1973) Comparative effects of ethylene oxide, gamma irradiation and microwave treatments on selected spices. *J Food Sci* 38(5):893–895
- Variyar PS, Bandyopadhyay C, Thomas P (1998) Effect of γ -irradiation on the volatile oil constituents of some Indian spices. *Food Res Int* 31(2):105–109