

Optimization of microwave roasting of peanuts and evaluation of its physicochemical and sensory attributes

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Revised: 4 April 2017 / Accepted: 18 April 2017 / Published online: 24 April 2017
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Abstract In this study, the microwave (MW) roasting (MWR) of peanuts (*Arachis hypogaea* L.) is attempted, optimized and compared with conventional drum roasting. A two factor/three level face centered composite design based MWR experiments was conducted at different roasting time (60, 180 and 300 s) and MW power levels (180, 540 and 900 W). The roasting quality was analyzed by physicochemical and sensory attributes of roasted peanuts and extracted oil viz., moisture loss, hardness, browning index (BI), induction period (IP) based on Rancimat, peroxide value (PV) and overall acceptability (OA), respectively. A roasting time and MW power dependent improvement in the desired quality of roasted peanuts and extracted oil was observed attributable to the formation of antioxidant Maillard reaction compounds. A second order polynomial model adequately described the roasting experimental data ($p < 0.0001$, $R^2 > 0.90$) with an insignificant lack of fit ($p > 0.05$). Using response surface methodology, the MWR was optimized at roasting time of 201 s and MW power level of 900 W which yielded favorable values of quality attributes (moisture loss, 3.06%; hardness, 4528.34 g; BI, 58.89; IP, 8.12 h; PV, 8.80 milliequivalents O₂/kg; OA, 6.40). Furthermore, the quality assessment of ground peanuts for selected time-power combinations (low, optimum and high roasts) was

attempted using scanning electron microscopy, electronic nose and Fourier transform infrared spectroscopy which revealed better quality of optimized MWR peanuts.

Keywords Peanut (*Arachis hypogaea* L.) · Microwave · Roasting · Fourier transform infrared spectroscopy · Scanning electron microscopy · Electronic nose

Introduction

Peanut (*Arachis hypogaea* L.), also known as groundnut, belongs to the *leguminosae* family and widely consumed throughout the world. It is widely used as an economic food supplement to counter malnutrition owing to its high nutritional value (26% protein, 48% oil, and 3% fiber) and high levels of calcium, thiamine, and niacin (Sarvamangala et al. 2011). Peanut is a diverse crop with multiple platform applications such as roasted/processed peanut oil, peanut butter, peanut flour, and peanut confections. The roasted peanuts are widely used to make peanut butter, snack foods and therapeutic food for management of severe acute malnutrition. In the food industry, roasting plays a crucial role which contributes to improve the color, flavor, texture, and sensory acceptability. The critical roasting parameters (roasting time and temperature) greatly influence the roasted product characteristics (Youn and Chung 2012). The content of biological molecules such as free amino acids and peptides, fatty acids, phytosterols, lignans and vitamins changes during the roasting process (Montavon et al. 2003; Murkovic et al. 2004). In addition, the roasting process offers distinct food preservation properties by inactivating of food spoilage enzymes, undesirable microorganisms, toxins and contaminants (Ozdemir and Devres 2000a, b).

Electronic supplementary material The online version of this article (doi:10.1007/s13197-017-2654-0) contains supplementary material, which is available to authorized users.

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During the processing of peanuts such as conventional roasting, some improper procedures may cause quality deterioration in peanuts. The microwave (MW) assisted dry roasting of peanuts has distinct advantages over the conventional roasting process. The intense heat is generated within the food material due to its uniform penetration and distribution upon exposure to MW radiations. This results into the fast heating rate and short processing time. Infact MW's are used in the food industry for baking as well as for other applications such as extraction, drying, blanching, pasteurization and many types of unit operation (Tang et al. 2002; Upadhyay et al. 2012). Knowing the distinct advantages of MW heating viz, operational speed, energy savings and faster start up and shut-down times; different researchers have applied MW roasting (MWR) to various food materials and oil extracted from these foods (Megahad 2001; Yoshida et al. 2002, 2003, 2006; Nebesny and Budryn 2003; Behera et al. 2004; Anjum et al. 2006). In the study of MWR and conventional drum roasting (CDR) of cumin seeds, it was found that the MWR samples showed better retention of characteristic flavor compounds, such as aldehydes, than CDR samples (Behera et al. 2004). In another study on pumpkin seeds, it was concluded that MWR did not have any adverse effects on seed or oil quality, and the use of short-term MWR to reduce seed moisture and to retard seed deterioration was recommended.

The MW roasting of peanuts have profound effect on its physicochemical characteristics (Schirack et al. 2006; Jit-treptoch et al. 2010). Therefore, the need for optimization of MWR process parameters for peanuts has been emphasized which is limited in literature. Although, the effect of roasting conditions on quality of related nuts has been previously investigated, most of the research focused on modeling and optimization of the different CDR (Ozdemir and Devres 2000a; Megahad 2001; Das et al. 2014). The objectives of this study were, firstly, to perform the roasting of peanuts through MW process while optimizing roasting time, and MW power levels using response surface methodology (RSM) to achieve the favorable combination of physico-chemical parameters and sensory attributes. Secondly, the effect of selected time–power combination of MWR on the chemical, micro-structural and sensorial changes in peanuts was investigated using scanning electron microscopy (SEM), electronic nose (E-nose) and Fourier transform infrared spectroscopy (FTIR), respectively.

Material and methods

Materials

A locally available variety of red color peanut (*A. hypo-gaea* L. var. GG 2) were procured from the local market of

Kharagpur, India and used for roasting experiments. Only healthy kernels that were uniform in size were selected for roasting treatment. All the chemicals and solvents (analytical grade) were purchased from Merck, India. Ultrapure water (conductivity less than 3 μ S/cm), purified using a Mili-Q-system (Milipore, Bedford, USA), was used for Rancimat test.

Experimental design

A two factors and three levels experiment based on face centered composite design (FCCD) was planned to optimize the roasting parameters viz., roasting time (60, 180 and 300 s) and MW power (180, 540 and 900 W) using RSM (Table 1). The experimental data was subjected to regression analysis and model fitting was performed using a second order polynomial equation (Eq. 1) to predict the responses under optimum MWR conditions.

$$Y = B_0 + \sum_{i=1}^k B_i X_i + \sum_{i=1}^k B_{ii} X_i^2 + \sum_{i=1}^k \sum_{j=1}^k B_{ij} X_i X_j + E \quad (1)$$

where, Y represents the response, B_0 is a constant term, B_i , B_{ii} and B_{ij} are the coefficients of linear, quadratic and interaction terms, respectively. The term X_i and X_j represented the coded value of independent variables while E represented the error in the measurement. The replicates at center points were used to estimate the pure error and perform lack of fit test which indicates the fitness of selected model. All the experiments were duplicated and performed in random order to minimize the introduction of bias into the measurements. Different physicochemical and sensory parameters, as described in the following section, were chosen as the response variables. Multiple regression analysis was used to estimate the values of model coefficients and subsequently validated by one-way ANOVA. The optimal conditions were deduced by generating three dimensional response surface plots using the fitted model equation followed by numerical optimization using desirability function methodology (Upadhyay and Mishra 2015a). Further, verification was based on the coefficient of determination (R^2) and adjusted R^2 . Additional roasting trials were performed at optimized conditions to compare the predicted and experimental value of response variables. To verify the adequacy of the developed model, triplicate trials was performed under optimized MWR conditions and compared with the predicted values.

Roasting process

A domestic MW oven (LG, MC-7649DW, New Delhi, India) capable of producing MW power ranging 180–900 W was used for roasting experiments. Whole raw

Table 1 Face centered composite design (FCCD) for two independent variables indicating the response variables

Run no.	Independent variables (coded values)		Response variables					
	X ₁	X ₂	Moisture (%)	Hardness (g)	BI	IP (h)	PV (meq. O ₂ /kg)	OA
1	60 (−1)	180 (−1)	6.61 ^{gh}	7262 ⁱ	30.70 ^a	5.11 ^a	12.87 ⁱ	2.58 ^a
2	300 (+1)	180 (−1)	6.04 ^f	6163 ^g	33.36 ^{ab}	8.34 ^f	7.66 ^c	6.76 ^{gh}
3	60 (−1)	900 (+1)	6.37 ^g	5163 ^d	32.19 ^a	5.8 ^c	12.04 ^g	2.91 ^c
4	300 (+1)	540 (0)	3.66 ^{bc}	4783 ^b	54.48 ^e	8.63 ^g	7.34 ^b	6.91 ^h
5	180 (0)	540 (0)	5.06 ^d	5081 ^c	40.33 ^c	7.58 ^d	9.52 ^e	5.85 ^f
6	60 (−1)	540 (0)	6.93 ^h	5731 ^f	34.00 ^{ab}	5.42 ^b	12.36 ^h	2.75 ^b
7	300 (+1)	900 (+1)	1.13 ^a	4145 ^a	80.58 ^f	8.87 ^h	7.11 ^a	7.33 ⁱ
8	180 (0)	540 (0)	5.44 ^c	5153 ^d	42.58 ^c	7.5 ^d	9.45 ^e	5.78 ^f
9	180 (0)	540 (0)	5.85 ^f	5228 ^e	44.91 ^d	7.54 ^d	9.5 ^e	5.81 ^f
10	180 (0)	540 (0)	5.02 ^d	5079 ^c	40.29 ^c	7.52 ^d	9.56 ^e	5.65 ^e
11	180 (0)	900 (+1)	3.17 ^b	4683 ^b	53.54 ^e	7.87 ^e	9.22 ^d	6.33 ^g
12	180 (0)	180 (−1)	6.46 ^g	6587 ^h	34.11 ^b	7.37 ^d	9.87 ^f	4.41 ^d
13	180 (0)	540 (0)	5.82 ^f	5225 ^e	44.83 ^d	7.41 ^d	9.5 ^e	6.25 ^g
Experimental domain (actual values)								
Independent variables	−1	0	+1					
X ₁ : Roasting time (s)	60	180	300					
X ₂ : Microwave power (W)	180	540	900					

All the FCCD trials were conducted in duplicates. The response variables were reported as means of four determinations (two for each set of FCCD trials) with coefficient of variation < 10%. The mean values with different superscripts were significantly different as tested by Duncan’s multiple range test (*p* < 0.05)

peanuts (c.a. 250 g) were arranged a single layer in a glass dish (12 × 8 cm) and placed inside MW cavity. The peanuts were roasted for different combinations of roasting time (60, 180 and 300 s) and MW power levels (180, 540 and 900 W), based on face centered composite design (FCCD). Additionally, CDR was carried out for comparison purpose. Raw peanuts (5 kg) were poured into the roasting drum of an electric rotary roaster (R 15L, MAPL Mumbai, India) and roasted at 140 °C for 10 min at constant rotating speed of 80 rpm. To ensure stable roasting conditions, the roaster was left to run for 30 min at 140 °C prior to placing the peanuts in the roasting drum. The roasted peanuts were cooled to room temperature, ground in an electric grinder (MX-AC400, Panasonic, Japan) and packed in polyethylene bags of 0.08 mm thickness, and kept at 4 °C until use.

Moisture content

The moisture content (wet basis) of ground MWR and CDR peanuts was measured by infrared moisture analyzer (A&D MX-50, A&D Engineering Inc., CA, USA) following the methodology described by Raigar and Mishra (2015). The moisture loss was expressed as the difference of initial (pre-roasting) and final moisture content (post-roasting) of peanuts.

Color measurement

Surface color of ground MWR and CDR peanuts passed through a 1 mm sieve was measured using colorimeter CM-5 (Konica Minolta, Sensing Americas Inc, NJ, USA.) and recorded in L* (lightness), a* (redness), and b* yellowness color values. The polycarbonate measuring dish (30 mm diameter) was filled with ground roasted peanut sample upto 10 mm height to determine the average value from four replications. The change in the color of peanuts during roasting was determined by calculating browning index (BI) using Eq. (2).

$$BI = \frac{100 \times (x - 0.31)}{0.17} \tag{2}$$

where, $x = \frac{(a+1.75L)}{(5.64L + a - 3.01b)}$ L* is lightness, a* is redness, and b* is yellowness.

Hardness

The hardness of roasted peanuts was analyzed using Texture Analyzer (CT3-100, Brookfield Engineering Lab, Mass, USA). The compression was applied on a peanut sample placed on the plate using a cylindrical probe (6.0 mm in diameter) at a test speed of 1.0 mm/s and deformation of 2 mm. The maximum peak of the first

compression (N) in the force–time curves indicates the hardness value for measuring peak crushing force. The mean value of the peak crushing force was used to indicate the hardness of peanuts. Quadruplicate replications were performed at each roasting level.

Oxidative stability of peanut oil

Peanut oil was extracted from the ground roasted peanuts dissolved in n-hexane using Soxhlet apparatus (C. Gerhardt & Co. KG, Königswinter, Germany) according to manufacturer's protocol. The oxidative stability of peanut oil, extracted post roasting treatment, was examined to evaluate the oxidation rate of the oil using peroxide value (PV, milliequivalents of O₂/kg of oil) according to AOCS official methods (AOCS, 2004) and induction period (IP, h) using Rancimat (Model 743, Metrohm, Herisau, Switzerland). For IP determination, quadruplicate determination of oil samples was made by weighing 5 g into cleaned glass reaction tubes, adding 60 ml of distilled water to the reaction vessels, and adjusting the air flow rate and temperature to 20 L/h and 110 °C, respectively (Upadhyay and Mishra 2015b). The conductivity of the breakdown products was measured to estimate the IP.

Sensory analysis

Overall acceptability (OA) based on different sensory attributes viz, aroma, color, hardness and flavor of the roasted peanut samples were evaluated by 25 semi-trained panelists consisted of research scholars from Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur. Freshly roasted peanuts, coded with three-digit numbers, were presented in air-tight containers to each panelist. The panels determined the OA scores based on the previously mentioned sensory attributes using nine-point hedonic scale system (1 = disliked extremely; 5 = neither liked nor disliked; and 9 = liked extremely).

SEM

The shape and surface morphology of selected ground MWR peanuts (light, optimum and high MW roasts) was examined by SEM (JSM-6400, JEOL Ltd., Tokyo, Japan). Small amount of ground peanut powder, spread on aluminum stubs, was placed in the SEM chamber and coated with palladium with an auto-fine coater for 180 s. The specimens were viewed with a JEOL JSM 6400 SEM attached to EDX (Energy Dispersive X-ray) at working distance and accelerated voltage of 22 mm and 20 kV, respectively.

E-nose

The headspace of selected time–power combination of ground MWR peanuts [light (A), optimum (B) and high roast (C)] and CDR peanuts (D) was analyzed with a Fox 4000 E-nose (ALPHA MOS, Toulouse, France) equipped with 18 metal oxide semiconductor based sensors and an auto sampler (HS 100, Toulouse, France). Before injection of peanut volatiles into E-nose system, the ground peanut sample (ca. 5 g) was kept inside tightly crimped 10 ml glass vials and heated inside an incubation chamber thermostatically maintained at 60 °C for 10 min at constant agitation of 600 rpm. The volatiles were withdrawn from the headspace and injected into the sensor chambers with carrier gas at constant pressure and flow rate of 5 psi and 150 ml/min, respectively. The data acquisition was performed for 2 min with a delay of 7.5 min between the subsequent sample injections. All the peanut samples (A, B, C and D) were evaluated individually in three replicates. The Alpha Soft version 14.0 software package (Alpha MOS) was used to perform the multivariate data processing operations on raw sensor signals and selection of sensors which enables the highest degree of sample differentiation (Upadhyay et al. 2017).

FTIR spectroscopy

Surface functional groups of the selected time–power combination of ground MWR peanuts (light, optimum and high roast) and ground CDR peanuts were detected using FTIR spectrometer (NICOLET 6700, Thermo Scientific, Madison, WI, USA). The samples were first dispersed using potassium bromide into pellets and later pressure compressed into discs. The sample discs were kept in the light path which enabled the passing of IR light through them and IR spectra was recorded. The IR ranges of 4000–400 cm⁻¹ with a resolution of 4 cm⁻¹ at 128 scans were used to obtain spectral information for each sample. After each measurement, the ATR plate was carefully wiped using acetone (analytical-grade) and dried before the analysis of the next sample.

Statistical analysis

All the FCCD trials were conducted in duplicate sets. The response variables were reported as means of four determinations, two for each set of trials, unless otherwise mentioned. Design expert (Version 7.0.0, Stat-Ease Int. Co., MN, USA) was used to construct the FCCD trials. The data obtained by FCCD trials were statistically analyzed using ANOVA followed by post hoc test (Duncan's multiple range test) and paired *t*-test in order to test the model

significance and compare MWR and CDR, respectively ($p < 0.05$, $p < 0.01$, $p < 0.001$, $p < 0.0001$).

Results and discussion

Significance of mathematical models

The experimental values of response variables viz, moisture loss, hardness, BI, IP, PV and OA of the MWR peanuts are shown in Table 1. A summary of the linear, quadratic and interaction terms for the MWR peanuts is given in Table 2. The linear terms of roasting time and MW power were highly significant ($p < 0.0001$) for all the measured response variables. The quadratic term was significant for IP, PV ($p < 0.0001$) and hardness ($p < 0.0001$), PV ($p < 0.05$) for roasting time and MW power, respectively. The interaction term of roasting time and MW power has significant influence on moisture loss ($p < 0.001$), BI ($p < 0.0001$) and PV ($p < 0.001$). The coefficient of determination (R^2) and adjusted R^2 of all the proposed equations for all the quality indicators of the MWR peanuts were more than 0.9, with the lack of fit being insignificant ($p > 0.05$). This result indicates that the proposed model was adequate, possessed no significant lack of fit, and showed high values of R^2 for all the responses.

Effect of roasting time and MW power

The regression coefficients of second order polynomial equations fitted to the experimental data are given in

Table 2. The three dimensional response surface plots for response variables viz, moisture loss, hardness, BI, IP, PV and OA of the MWR peanuts are presented in Fig. 1. The moisture loss was found to be a function of the linear and interaction effect of roasting time and MW power (Table 2). The moisture loss tends to increase with increasing roasting time and MW power levels (Fig. 1c). The highest moisture loss was obtained with roasting time and MW power of 201.7 s and 896.73 W, respectively.

The hardness was linearly related to roasting time and MW power, while the quadratic effect of MW power significantly influences the hardness of MWR peanuts (Table 2). The hardness of peanuts tends to decrease with increase in roasting time and MW power due to increase in brittleness associated with moisture loss (Fig. 1b). This might be the evidence of slightly softer and crisp texture in the roasted peanuts (Kahyaoglu and Kaya 2006). These results indicate the roasting performed for longer duration at higher MW power levels can significantly affect the texture of peanuts. The optimal hardness was obtained with roasting time and MW power of 201.17 s and 898.57 W, respectively.

The BI was linearly related to roasting time and MW power. The interaction effect of roasting time and MW power has significant influence on the BI of MWR peanuts (Table 2). The BI of peanuts found to increase with increase in roasting time and MW power due to increase in the rate of non-enzymatic browning reactions (Fig. 1c). These results indicate the roasting performed for longer duration at higher MW power levels can significantly affect the color of peanuts (Yaylayan and Kaminsky 1998). The

Table 2 Summary of ANOVA of the regression coefficients of the fitted polynomial equation for the response variables

Coefficients of independent variables [‡]	Response variables					
	Moisture (%)	Hardness (g)	BI	IP (h)	PV (meq. O ₂ /kg)	OA
Intercept (B_0)	5.39	5160.86	42.76	7.51	9.50	5.79
B_1	-1.51 ^d	-510.83 ^d	11.92 ^d	1.59 ^d	-2.53 ^d	2.13 ^d
B_2	-1.41 ^d	-1003.50 ^d	11.36 ^d	0.29 ^d	-0.34 ^d	0.47 ^a
B_{12}	-1.17 ^c	20.25 ^{ns}	11.43 ^d	-0.04 ^{ns}	0.07 ^c	0.06 ^{ns}
B_1^2	0.03 ^{ns}	76.98 ^{ns}	1.04 ^{ns}	-0.53 ^d	0.36 ^d	-0.77 ^{ns}
B_2^2	-0.45 ^{ns}	454.98 ^d	0.63 ^{ns}	0.07 ^{ns}	0.05 ^a	-0.23 ^{ns}
Model (F-value, p value)	48.78, <0.0001 ^d	329.47, <0.0001 ^d	78.42, <0.0001 ^d	660.93, <0.0001 ^d	6620.54, <0.0001 ^d	37.69, <0.0001 ^d
Lack of fit (F-value, p value)	0.64, 0.625 ^{ns}	0.88, 0.523 ^{ns}	1.13, 0.436 ^{ns}	0.97, 0.487 ^{ns}	0.43, 0.744 ^{ns}	6.15, 0.055 ^{ns}
R^2	0.971	0.996	0.982	0.998	0.998	0.964
Adj. R^2	0.951	0.993	0.970	0.988	0.988	0.939
Pred. R^2	0.885	0.980	0.906	0.980	0.980	0.714

[‡] B_1 , regression coefficient of roasting time (s); B_2 , regression coefficient of MW power (W)

^{ns} Not significant ($p > 0.05$), ^a significant ($p < 0.05$), ^b significant ($p < 0.01$), ^c significant ($p < 0.001$), ^d significant ($p < 0.0001$)

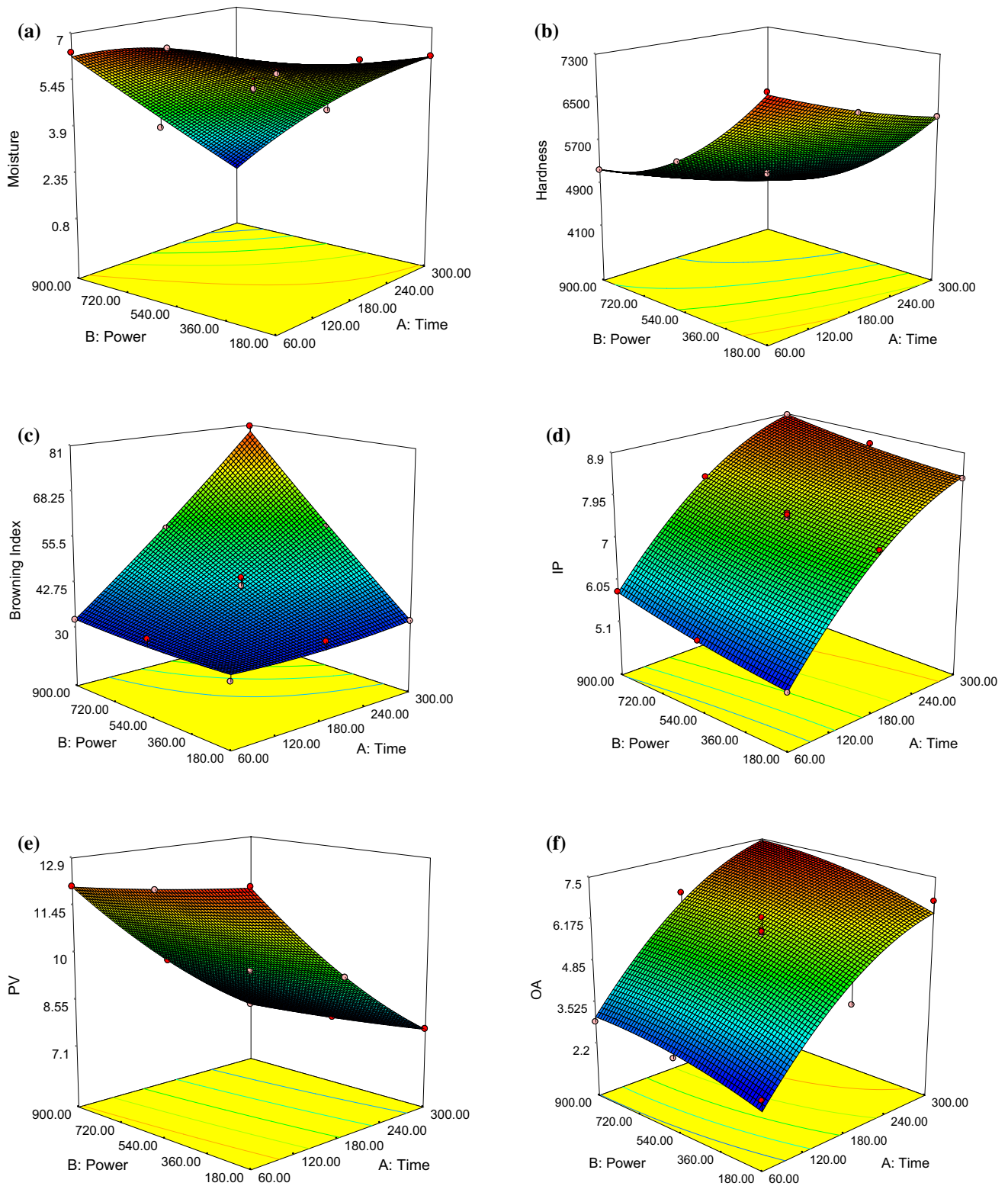


Fig. 1 Effect of microwave roasting conditions (roasting time and microwave power) on **a** moisture loss (%); **b** hardness (g); **c** browning index; **d** induction period (IP, h); **e** peroxide value (PV, meq. O₂/kg oil); **f** overall acceptability (OA)

optimal BI was obtained with roasting time and MW power of 201.2 s and 896.73 W, respectively.

The IP was linearly related to roasting time and MW power, while the quadratic effect of roasting time significantly influences the IP of the oil extracted from MWR peanuts (Table 2). Generally, IP of an oil is inversely related to temperature (Upadhyay and Mishra 2015c); Interestingly, for peanuts it tends to increase with roasting time and MW power (Fig. 1d). This effect can be attributed to the increased formation of maillard reaction products which possess antioxidant properties (Ozdemir and Devres 2000a). The maillard reaction products are adducts formed between free amino acids and reducing sugars and known to contain phenolic structures which could bring the functionality of free radical scavenger (Durmaz and Alpaslan 2007). These results indicate the controlled roasting for optimal duration and MW power levels can significantly improve the oxidative stability of roasted peanut oils. The optimal IP was obtained with roasting time and MW power of 201 s and 900 W, respectively. The results indicate that applying the correct conditions for the roasting of peanuts prior to oil extraction can increase the oxidative stability of roasted peanut oil.

PV was linearly related to roasting time and MW power, while the quadratic and interaction effects of roasting time and MW power also influences the PV of MWR peanuts (Table 2). PVs of peanuts tend to decrease with increase in roasting time and MW power (Fig. 1e). PV indicates the progression of oxidation reactions and is influenced by the presence of antioxidant content of the oil. The content of moisture is critical to the oxidation of oil as higher temperatures are generated due to moisture driven localized heating of peanuts. Thus, higher values of peroxides noted for lower roasting time and MW power can be explained by moisture driven temperature dependent oxidation of peanut oil. In addition, the better stability of peanut oils at higher roasting time and MW power can also be attributed to antioxidant maillard reaction compounds formed in roasted peanuts. The antioxidant effects of maillard reaction products substantially lowered the rate of lipid oxidation in peanuts at higher MW power for longer duration. The optimal PV was obtained with roasting time and MW power of 202 s and 898.57 W, respectively.

OA was scored to assess the sensory quality of the MWR peanuts. OA was linearly related to roasting time and MW power (Table 2). The OA of peanuts increased with increase in roasting time and MW power levels (Fig. 1f). The observed trend can be explained by increase in the roasting associated formation of flavor compound and maillard reaction compounds which contributes to the overall sensory quality of peanuts. The optimal OA was obtained with roasting time and MW power of 201 s and 898 W, respectively.

Optimization of roasting conditions

Using numerical optimization, the optimal MWR conditions were deduced at roasting time and MW power level of 201.13 s and 900 W, respectively, giving predicted moisture loss of 3.06%, hardness of 4528.34 g, BI of 58.89, IP of 8.12 h, PV of 8.80 meq. O₂/kg oil, and OA of 6.40 with desirability of 0.67. The validation of MWR carried out under optimized conditions resulted in moisture loss of 3.18%, hardness of 4528.34 g, BI of 61.34, IP of 8.23 h, PV of 8.52 meq. O₂/kg oil, and OA of 6.69, which were statistically indifferent ($p > 0.05$) to model predicted values.

Comparison between MWR and CDR

Considering the values of measured responses viz, moisture loss, hardness, BI, IP, PV and OA of roasted peanuts, the optimized MWR condition was compared with CDR (Table 3). The quality parameters of drum roasted peanuts were significantly different than optimized MW process ($p < 0.05$). The MWR can be preferred on the ground of lesser roasting time leading to energy efficient roasting with favorable quality parameters and sensory acceptability of roasted peanuts.

SEM

SEM was used to visualize and monitor the fractural pattern and structural morphology of selected time–power combinations (light, 60 s/180 W; optimum, 201 s/900 W and high, 300 s/900 W) of MWR peanuts. The microphotographs of the roasted peanuts at different MWR levels (low, optimum and high) are shown in Fig. 2a–c. For light MWR peanuts (Fig. 2a), the surface was quite smooth, without many pores, except for some occasional cracks. Increasing MWR treatment from low power (180 W) to high power (900 W) changed the surface topology from smooth into rough (Fig. 2b, c). During light roasting (60 s/180 W), the comparatively higher moisture content of peanuts was responsible for structural integrity; thus, the surface was smooth and there were more granules (starch and proteins) of larger size than high roast peanuts (300 s/900 W). As roasting duration and MW power increased, the moisture was evaporated and diffused out from the peanuts which caused the disintegration of larger globules. This might have facilitated the creation of micropores on the surface allowing the release of volatile matter. In terms of surface fracturability, the peanut surface became more collapsed from light to high roasting with the advent release of flavor compounds which created the sensory differences.

Table 3 Comparison of peanut physicochemical and sensory parameters during optimized microwave roasting (MWR) and conventional drum roasting (CDR)

Parameters	Optimized MWR (roasting time: 201 s; MW power: 900 W)	CDR (roasting time: 10 min; temperature: 140 °C)
Moisture loss (%)	3.18 ± 0.03 ^a	3.44 ± 0.08 ^b
Hardness (g)	4528.34 ± 2.04 ^a	4877.34 ± 3.24 ^b
Browning index	61.34 ± 0.11 ^a	83.34 ± 0.12 ^b
Induction period (h)	8.23 ± 0.06 ^a	5.65 ± 0.14 ^b
Peroxide value (meq. O ₂ /kg oil)	8.52 ± 0.13 ^a	12.35 ± 0.21 ^b
Overall acceptability	6.69 ± 0.09 ^a	5.88 ± 0.11 ^b

Values were expressed as mean ± standard deviation ($n = 3$). Means in a row were compared using paired t -test. The mean values with different superscripts were significantly different ($p < 0.05$)

E-nose analysis

The responses of all the 18 MOS sensors generated from the volatiles of ground MWR peanuts can be seen in Fig. 3a. The X and Y coordinates correspond to the acquisition time and sensor signal response intensity, respectively. During the progress of signal acquisition, it can be seen that after an initial increase in the signal intensity, the sensors output gradually decreases and finally stabilized to the baseline. The PCA plot of E-nose data for peanut samples subjected to MWR (low roast, A, optimum roast, B and high roast, C) and CDR (D) is depicted in Fig. 3b. The PCA result shows that the MOS based sensors are strongly correlated since the first two principal components (PC), PC1 and PC2, represent almost 97.3% of the data variance. A clear segregation of peanut samples was observed in accordance with roasting treatment and aroma fingerprint. The result indicates that the E-nose is capable of differentiating the smells of peanuts subjected to different processing treatments which resulted in odors differences.

After sensor optimization, the radar chart (Fig. 3c) shows that all the 18 MOS sensors detected a significant difference in the headspace compounds of roasted peanut samples (A, B, C and D). The changes in the values of the sensors reflected corresponding changes in the matrix of roasted peanuts which subsequently affected the release of volatiles. The more intense the MW treatment, the further the peanut samples move towards the right of the score plot. The odor difference between high roast MW treated peanuts (C) and CDR peanuts (D) was mainly reflected in PC1 axis, while the same difference between the low roast (A) and optimum roast (B) peanuts was reflected in PC2 axis. Furthermore, the distance between A and B was much greater than the distance between C and D. The results indicate that the CDR has greater effect on the flavor profile of peanuts oil than MWR treatment. Among the

MWR peanuts, light roast had little impact on the odor profile of peanuts followed by optimum roast and high roast. Therefore, MW treatment is an important factor to be considered while designing the roasting process of peanuts.

FTIR

The FTIR spectra of peanuts obtained under selected time-power combination of MW roasting (light, 60 s/180 W; optimum, 201 s/900 W; high level, 300 s/900 W) and CDR (10 min/140 °C) are presented in supplementary Fig. S1a–d. Figure S1 (supplementary figure) revealed similar band positions in MWR and CDR which is an indicative of similar compounds in each roast. The major difference between the MWR and CDR peanuts was the percentage transmittance (%T) of identical carbonyl compounds instead of the types of carbonyl compounds. The detailed assignment of spectral bands is presented in supplementary Table S1 and labeled in supplementary Fig. S1.

The major difference between light MW roast (supplementary Fig. S1a) and optimum MW roast (supplementary Fig. S1b) can be found from the %T of three compound types: ester, carboxylic acid and amines. The %T was increased for esters (1000–1300 cm^{-1}) whereas it was found to decrease for carboxylic acid (3289 cm^{-1}), esters (1743 cm^{-1}) and primary and secondary amines (1637 and 1535 cm^{-1} , respectively). The optimum MWR peanuts were more desirable (high OA) with enhanced nutty roasted aroma owing to the better development of flavor compounds (esters and acids) than light MWR counterparts. This is supported by the results of Lyman et al. (2003) who analyzed brewed coffee. The increase in %T in ester might be due to the release of volatiles during roasting of nuts whereas the decrease of %T in primary and secondary amines might be due to the Maillard reaction and the formation of color and aroma. Results of the optimum

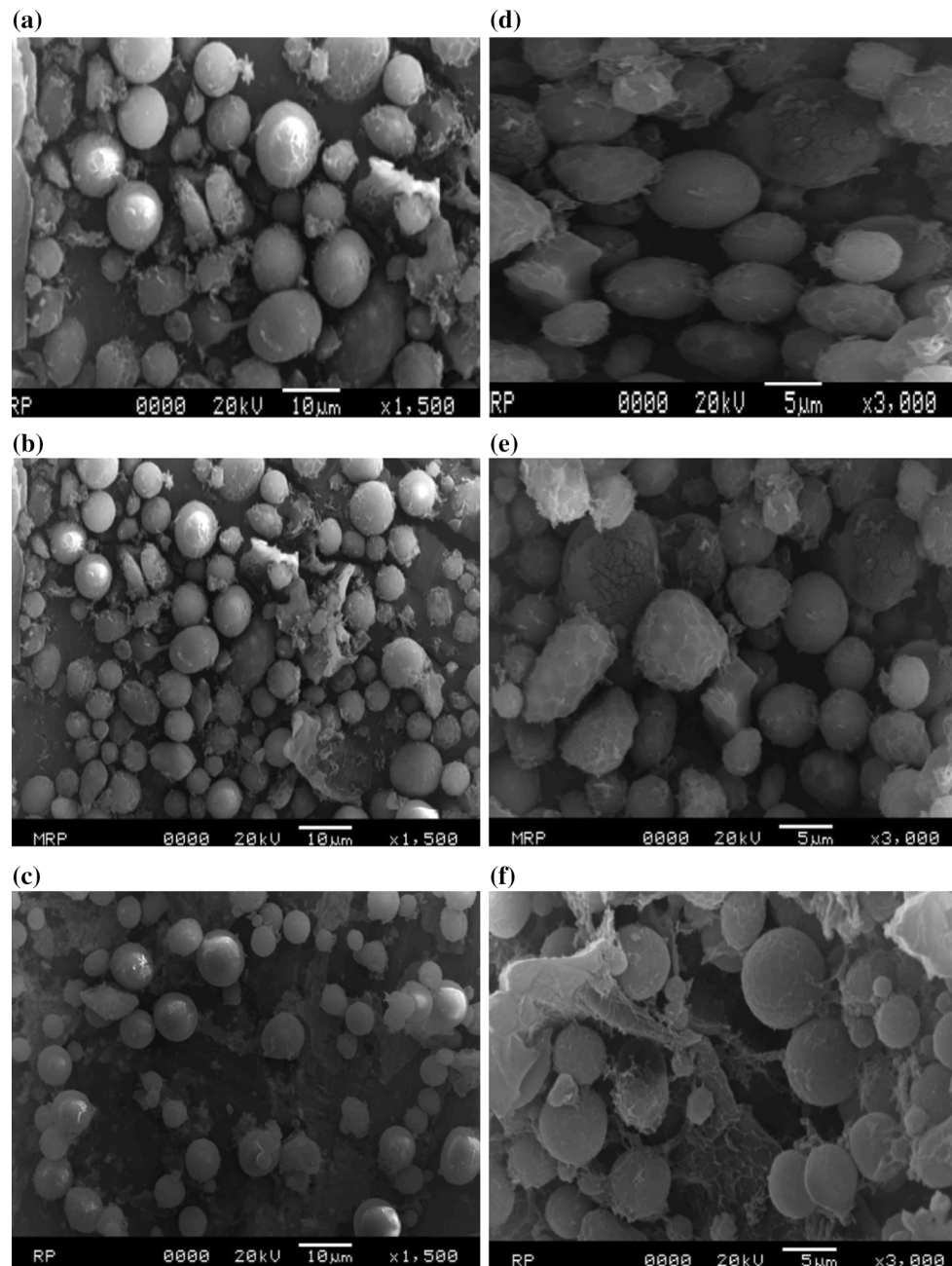
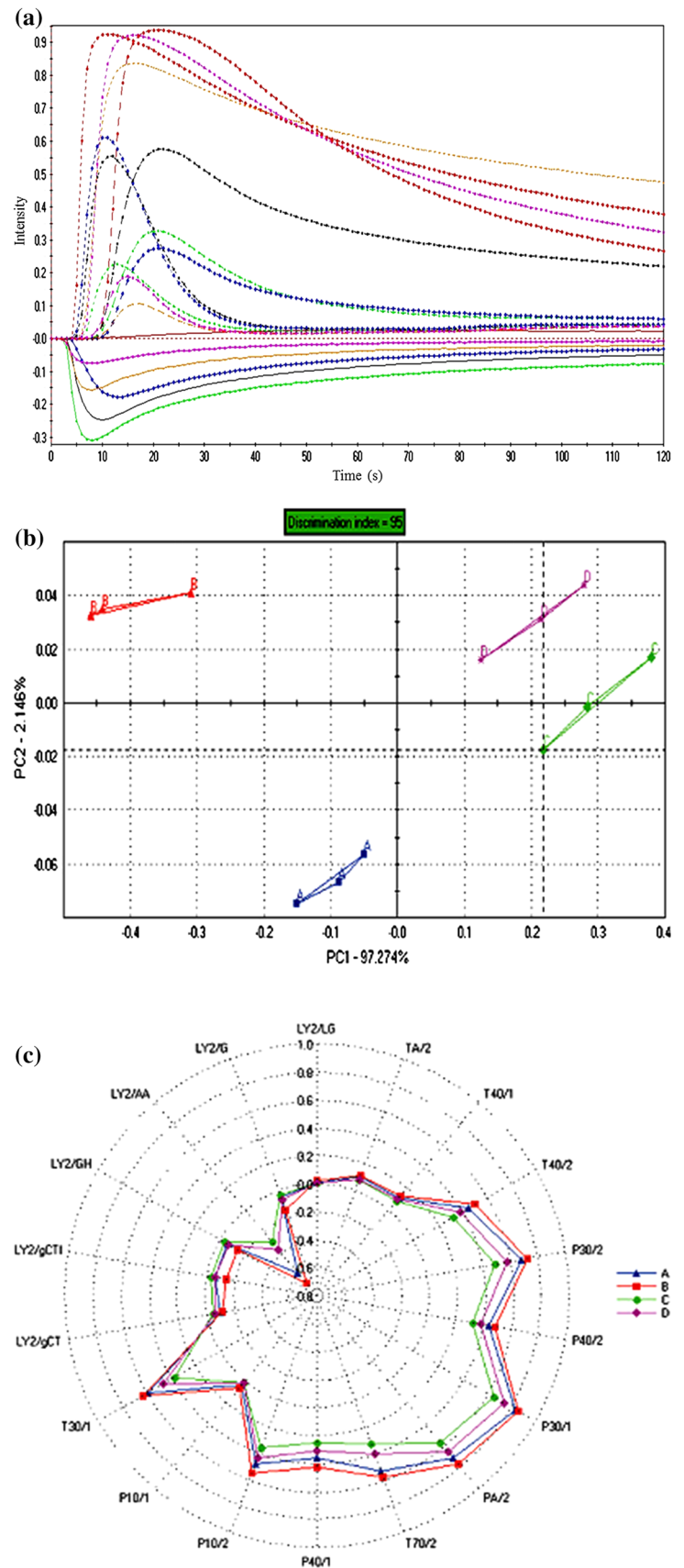


Fig. 2 Scanning electron micrographs of microwave (MW) roasted peanuts at a magnification of $\times 1500$ (a)–(c) and $\times 3000$ (d)–(f), where **a** and **d**: light MW roast (60 s/180 W); **b** and **e**: optimum MW roast (201 s/900 W); **c** and **f**: high MW roast (300 s/900 W)

MW roast to high MW roast (dark roast) revealed major alterations in the transmittance of the carbonyl compounds. There were increases in the %T of carboxylic acid (at $2400\text{--}3400\text{ cm}^{-1}$), esters (around 1047 cm^{-1}), primary amines (around 1636 cm^{-1}) and secondary amines (around 1533 cm^{-1}) respectively. There were also decreases in the amount of esters (around 1743 cm^{-1} and $1236\text{--}1240\text{ cm}^{-1}$). These changes are compatible with the sensory panelists' evaluations of a stronger aroma, taste

and aftertaste of peanuts. For high MWR peanuts (dark roast), the caramelization of sugar resulted in darker color and over roasted flavor leading to slightly lower sensory appeal. Overall, there was a significant increase in %T from light to high MW roasted peanuts in terms of the carboxylic acid, primary amines and secondary amines; however, there was a significant decrease in %T for esters formation from light roasted peanuts nuts to high roasted peanuts.

Fig. 3 **a** Signal responses of 18 different MOS sensors for ground MWR peanut (low roast); **b** Score plot of principal component analysis (PCA) applied to roasted peanuts (A, B, C and D); **c** Radar chart of four differently roasted peanuts (A, B, C and D) indicating the signal responses of 18 MOS sensors during electronic nose analysis. A, light microwave (MW) roast (60 s/180 W); B, optimum MW roast (201 s/900 W); C, high MW roast (300 s/900 W); D, conventional drum roast (10 min/140 °C)



Conclusion

Roasting is one of the important step in the processing of peanuts. In this study, RSM was used successfully for modeling the roasting of peanuts in a MW based on FCCD experimental plan. It was shown that the moisture content, BI, sensory acceptability and IP of roasted peanuts and extracted peanut oil, respectively, were significantly influenced by increasing levels of roasting time and MW power. The optimum MW roasting conditions deduced at 201 s at 900 W gave optimum physicochemical quality and sensory acceptable peanuts. The FTIR, SEM and E-nose results showed that the MW roasting can be effectively controlled by selecting an appropriate combination of time and power level. From this study, we managed to build a better understanding of how the quality parameters and sensory attributes of peanuts subjected to roasting treatment, could be affected by different dry heating processes based on MW and conventional drum roasting in food manufacturing processes. It is hoped that the findings from this study will enable better decisions to be made when it comes to selecting the appropriate MW process parameter for roasting of raw peanuts.

Acknowledgements The financial support by Department of Biotechnology, Government of India (No. BT/PR4204/FNS/20/534/2011 Dated 21/03/2012) for this research is highly acknowledged.

Compliance with ethical standard

Conflict of interest The authors declare that they have no competing interests.

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