Optimization of pretreatments and process parameters for sorghum popping in microwave oven using response surface methodology

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Abstract Sorghum is a popular healthy snack food. Popped sorghum was prepared in a domestic microwave oven. A 3 factor 3 level Box and Behneken design was used to optimize the pretreatment conditions. Grains were preconditioned to 12–20 % moisture content by the addition of 0–2 % salt solutions. Oil was applied (0–10 % w/w) to the preconditioned grains. Optimization of the pretreatments was based on popping yield, volume expansion ratio, and sensory score. The optimized condition was found at 16.62 % (wb), 0.55 % salt and 10 % oil with popping yield of 82.228 %, volume expansion ratio of 14.564 and overall acceptability of 8.495. Further, the microwave process parameters were optimized using a 2 factor 3 level design having microwave power density ranging from 9 to 18 W/g and residence time ranging from 100 to 180 s. For the production of superior quality pop sorghum, the optimized microwave process parameters were microwave power density of 18 Wg⁻¹ and residence time of 140 s.

Keywords Sorghum · Microwave heating · Moisture · Oil · Salt

Introduction

Popped sorghum is a traditional snack food in India and popular among the local population. Popped sorghum is produced by popping process, which is a method of dry heat application; where grains are exposed to high temperature for a short time (HTST). Popping occurs when a superheated vapour is produced inside the grain by instantaneous heating, which cooks the grain and expands the starchy endosperm (Hoseney et al. 1983). Pop sorghum is a primary source of carbohydrates and has better starch and in-vitro digestibility as compared to raw sorghum grain (Saravanabavan et al. 2013). During popping of sorghum, the material practically gets sterilized and most of the seed microflora are destroyed (Hadimani 1994) and had a significant reduction (20 to 25 %) of phytic acid (Saravanabavan et al. 2013). Popping imparts acceptable taste and desirable aroma to pop sorghum (Sharma et al. 2014). Though a broad range of cereals is used for popping; only a few of them pop well. Most of the previous studies showed that the factors responsible for popping qualities of grain sorghum includes season of growing/harvest, grain structure/physical characteristics of the grain, chemical composition, pretreatments and also the method of popping (Mishra et al. 2015; Murty et al. 1983; Malleshi and Desikarhar 1985; Thorat et al. 1988; Gokmen 2004; Yenagi et al. 2005; Gundboudi 2006; Khedker et al. 2008). Sorghum grain with small grain size, high amylose content, medium to hard endosperm, medium pericarp thickness (Thorat et al. 1988; Gupta et al. 1995) have good expansion ratio and popping yield. Moisture content and pre-treatments such as, salt and oil addition also plays a significant role for obtaining high quality popped grain with better popping characteristics (Lin and Anantheswaran 1988; Gaul and Rayas-Durate 2008; Khedker et al. 2008). An optimum moisture content of 12 % (wb) had higher percent of popped grain, expansion ratio and

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popped volume of sorghum grain when popped using sand roasting method (Khedker et al. 2008). The area is still unexplored in microwave popping of sorghum grain.

Currently, there is an increasing trend to use microwaves for food processing due to the fact that microwave heating is more efficient than the traditional heating process with benefits that include: quicker start-up time, faster heating, energy efficiency, space saving, selective heating and final products with improved nutritive quality (Maisont and Narkrugsa 2009). The microwave popcorn has become familiar with the increasing availability of microwave ovens at home scale. Popped sorghum grains have been found to have as good flavor and be as nutritious as popcorn (Subramanian 1956) and also considered to be superior to popped corn as it is tender, has fewer hulls (Mishra et al. 2014). In this regards, to meet the changing consumer taste, expectation and the elusive search for something unique, this investigation was carried out for process development for pop sorghum using a domestic microwave oven. Like microwavable popcorn, sorghum can be tempered to optimum moisture content and coated with different ingredients as pretreatments in order to increase the number of popped kernels and improve their sensory quality. The popping characteristics of cereal grain also depend upon the microwave process parameters such as power density and residence time. Considering the above facts, the present study was undertaken to optimize the pre-treatments prior to popping and microwave process parameters for producing higher quality pop sorghum in a domestic microwave oven.

Materials and methods

Raw materials

Commercial popping variety of sorghum grain, *Mugad*, sourced from the Agricultural Produce Market Committee, Hubli, Karnataka, India was selected for the present investigation as it had better popping characteristics (previous study). A bulk sample of 10 kg were procured for the investigation, cleaned, graded and stored. Sodium chloride of analytical grade was purchased from m/s S.D. Fine Chemicals Limited and hydrogenated vegetable oil and paper envelopes used for popping were procured from the local market of Anand, Gujarat, India.

Pre-treatment

Moisture conditioning was performed to bring the moisture content of sorghum grains up to the desired level by spraying with pre-calculated amount of water and spreading the grain onto a muslin cloth in relative humidity chamber (maintained at 24 °C dry bulb, 22 °C wet bulb temperature and 80 % relative humidity) for 24 h (Mitchum 2002). The grains were

evenly conditioned with stirring for every one hour for the first four hour so that the grains at the bottom of the container will not absorb more water. The grain was periodically weighed until the final weight of the grain was high enough to have reached the desired moisture level (12, 16, and 20 % wb).

17 samples, each of 50 g, conditioned to desired moisture content were sprayed with desired solutions of salt (0, 1, and 2 %) and stirred well for uniform coating, and then shed dried in the laboratory. The weight was taken after 30 min till the saline water pre-treated sorghum again attains the desired moisture level. Different combinations of oil (0, 5, and 10 % w/w) were uniformly coated over the conditioned grain by rubbing on the surface thoroughly. The pre-treated grains were weighed and packed in a microwavable paper bag, sealed and stored at room condition until further use.

Microwave popping

Microwave popping experiments were performed in a convective-microwave oven (Samsung, CF1111TL, Korea). The power output of the magnetron specified by the manufacturer was maximum 900 W, and the operating frequency was 2450 MHz. The actual power output of the microwave oven measured by IEC test (Buffler 1993) involves the measurement of the rate of temperature rise of 1000 ml water in Pyrex beaker. The initial temperature of the water was 10 °C and the water was heated for 1 min (subtracting from time at power levels below 100 %) at different power levels. Water was stirred uniformly and rise in temperature of water was noted, and the microwave power density (MWPDP) was calculated using the following formula (Chandrasekaran et al. 2013):

$$MWPDP(Wg^{-1}) = \frac{4.1868 \times V_w \times T}{t \times W} \quad (1)$$

<i>MWPDP</i>	Microwave power density (Wg^{-1})
V_w	Volume of water (ml)
T	Rise in temperature (°C)
t	Residence time
W	Weight of sample (g)

All combinations of the pre-treated and prepacked samples were popped in the domestic microwave oven, set at 900 W for 140 s. The data on the popping qualities of all the samples were obtained and statistically analyzed, and the best combination of the pretreatments was standardized based on popped sorghum of higher popping yield, volume expansion ratio, and sensory score.

Optimized pretreated sorghum grain packed in microwavable paper bags were placed on the rotary glass turntable disk in the microwave oven chamber and popped under different power levels and residence times, keeping sample size

constant as per the experimental design. After each experiment, the oven chamber was cooled for 3 min. The popping conditions viz. microwave power density and residence time were standardized to obtain a superior quality of popped sorghum.

Popping yield

Popping yield is of importance as it would indicate how many grains were fully popped during the microwave heating, as a consumer would expect all the grains to pop to the maximum volume. After popping, the unpopped grains were handpicked, and the weight of total popped grains was recorded. The grains were considered fully popped when they did not have any unpopped part. Popping yield was expressed in percentage (Sharma et al. 2014):

$$PY = \frac{W_{fpg}}{W_{fpg} + W_{spg} + W_{upg}} \quad (2)$$

PY	Popping yield (%)
W_{fpg}	Weight of popped grain (g)
W_{spg}	Weight of semi-popped grain
W_{upg}	Weight of unpopped grain (g)

Volume expansion ratio

The volume expansion was measured by sand replacement method (Chinnaswamy and Bhattacharya 1983a; Joshi et al. 2014a). The initial volume of 50 g unpopped pretreated sorghum grain was taken in a 500-ml cylinder and filled it with fine sand, and the volume was noted. The same sample was then popped in a microwave oven with the process described in the earlier section. Volume expansion ratio was calculated using following expression (Joshi et al. 2014b):

$$\text{Volume Expansion Ratio} = \frac{V_f}{V_i} \quad (3)$$

V_f	Final volume of popped sorghum
V_i	Initial volume of pretreated sorghum

Sensory evaluation

The sensory evaluation of popped sorghum was conducted by a panel of 12 members comprising of staff and post-graduate students. The experimental samples were coded using random three digit numbers and served to the panel members. They were given written instructions and asked to evaluate the

popped sorghum for appearance, taste and overall acceptability based on 9-point hedonic scale.

Statistical design and optimization

The coating system was consisted of moisture conditioning salt and oil ranges from 12 to 20 % (wb), 0–2 % and 0–10 % respectively, as decided from the popping characteristics study, as it was observed that most of the grains popped in that range (Gokmen 2004; Gaul and Rayas-Durate 2008; Sweley et al. 2012). Response surface methodology (Mayers and Montgomery 1995) was employed to optimize the pre-treatments. To optimize pre-treatments for MW popping of sorghum, Box–Behnken design for three parameters and three levels was used, and the optimization was done using Design Expert 9.0.0.7 (Trial version StatEase). All the independent variables were tested at three levels (Table 1). The dependent variables are popping yield, volume expansion ratio, and overall acceptability.

Then, the optimized pre-treated sorghum grain was used for optimization of microwave process parameters and operating conditions. A range of microwave power density (9, 12 and 18 Wg^{-1}) at constant sample size and residence time (100, 140 and 180 s) was selected affecting microwave popping quality of sorghum grain. A 3^2 factorial design was used to analyze the effect of microwave process parameters. Analysis of variance (ANOVA) at 5 % significant level was carried out using Microsoft Excel.

Verification of model

The models for which lack of fit was non-significant ($p > 0.05$) were considered for optimization. Three representative trials were conducted under the optimized conditions. The sensory characteristics, volume expansion ratio, and popping yield were calculated, and residuals were computed to test the goodness of fit of the developed model.

Results and discussions

Optimization of Pre-treatments for production of popped sorghum

Effect of pretreatments on popping yield

Popping yield data were collected to obtain an efficient combination of process variables. The popping yield of sorghum grain varied from 42.73 to 83.32 % depending on the severity of pre-treatments given. The effect of pre-treatments on popping yield of sorghum grain is depicted in Fig. 1. At lower moisture content level (12 %) less popping yields (value) was obtained and by increasing the moisture content, the popping

Table 1 ANOVA showing linear, quadratic, and interaction terms of the polynomial model for the responses of pretreated sorghum

Sources of variation	df	Popping yield (%)				Volume expansion ratio (VER)				Overall acceptability			
		Co-efficients	Sum of squares	F-value	p-value Prob > F	Co-efficients	SS	F-value	p-value Prob > F	Co-efficients	Sum of squares	F-value	p-value Prob > F
Model	9	-447.2	4355.22	198.35	< 0.0001	-87.57	160.45	75.89	< 0.0001 ^s	-26.01	22.19	100.05	< 0.0001 ^s
M-Moisture content	1	63.05	257.98	105.74	< 0.0001 ^s	12.14	6.30	26.80	0.001 ^s	3.92	6.13	248.55	< 0.0001 ^s
S-Salt	1	18.4	9.39	3.85	0.0906 ^{ns}	5.28	0.043	0.18	0.6803 ^{ns}	1.92	0.98	39.77	0.0004 ^s
O-Oil	1	1.13	0.65	0.27	0.6219 ^{ns}	0.056	0.0012	0.0054	0.9430 ^{ns}	0.097	0.21	8.57	0.0221 ^s
M × S	1	-0.708	32.14	13.17	0.0084 ^s	-0.21	2.92	12.44	0.0096 ^s	-0.078	0.39	15.85	0.0053 ^s
M × O	1	-0.11	0.20	0.080	0.7849 ^{ns}	6.84	0.075	0.32	0.5897 ^{ns}	-0.0031	0.016	0.63	0.4520 ^{ns}
S × O	1	-0.98	96.17	39.42	0.0004 ^s	-0.17	3.23	13.73	0.0076 ^s	0.027	0.076	3.07	0.1233 ^{ns}
M ²	1	-1.90	3900.15	1598.65	< 0.0001 ^s	-0.36	145.06	617.52	< 0.0001 ^s	-0.11	13.74	557.44	< 0.0001 ^s
S ²	1	-1.62	11.06	4.54	0.0707 ^s	-0.44	0.84	3.58	0.1002 ^{ns}	-0.23	0.23	9.14	0.0193 ^{ns}
O ²	1	-3.37	0.028	0.012	0.9174 ^{ns}	1.56	0.0064	0.028	0.8729 ^{ns}	-4.25	0.048	1.93	0.2075 ^s
Residual	7		17.08				1.64				0.17		
Lack of fit	3		11.15	2.51	0.1977		0.76	1.13	0.4361 ^{ns}		0.097	1.73	0.2979 ^{ns}
Pure error	4		5.93				0.89				0.075		
Cor total	16		4372.30				162.10				22.36		
R ²			0.9961				0.9899				0.9923		
Adj R ²			0.9911				0.9768				0.9824		
SD			1.56				0.48				0.16		
C.V (%)			2.41				4.33				2.07

Fig. 1 Combined effect of moisture content and salt on popping yield of sorghum grain (keeping third variable at center)

yield significantly increased but further higher moisture content was found to be having negative impact on the popping yield. The grain acts as a pressure vessel and the steam generated due to thermal or pressure gradient built enough pressure to blow up the starch before escaping out (Moraru and Kokini 2003). The popping process can be explained vis-a-vis corn is popping in microwave environment. During MW exposure, heat is generated mostly due to molecular friction of polar molecules like water and some amount of ionic conduction (Oliveira and Franca 2002). The volumetric heat generated inside the grain kernel produces superheated steam, which tries to escape out. However, it is restricted due to some physical barriers like horney endosperm in case of corn (Pordesimo et al. 1990) or pericarp in case of sorghum (Mohamed et al. 1993). As a result, enough steam pressure is generated inside the grain kernel that corresponds to a temperature of 177 °C, which is equivalent to 135 psi pressure. This condition propels the free and bound water to evaporate suddenly, resulting in expanded starch (Hoseney et al. 1983) and due to sudden pressure release, cooking and expansion of the endosperm takes place. Therefore, the reason for the positive impact of moisture conditioning on popping yield sorghum grains may be due to the development of sufficient vapour pressure inside the grain so that maximum number of grains popped well. But, further higher moisture content might have softened the grain, which negatively impacted the popping yield. Pretreatment of salt or oil alone in combination with higher moisture levels (16 %) increased the popping yield (Fig. 1). The reason behind increase of popping yield with combined pretreatment of moisture and oil may be due to sufficient vapour pressure development and rapid heating within a microwave as oil coating has provided a barrier to the evaporated moisture for escaping out. The oil coating along with the sorghum pericarp has provided the barrier; so that enough vapour pressure was build up before cooking and expansion of starchy endosperm. The combined effect of salt and oil on popping yield of sorghum in a microwave oven was

complex. By adding salt and oil alone, the popping yield increased, but the increase in sodium chloride in the presence of higher levels of oil had the reverse effect. A similar trend was found by Singh and Singh (1999) in case of popping of corn in a microwave oven. Though ionic heating is affected by salt content, oil has a lower dielectric loss and constant value as well specific heat values. Therefore, it would generate less heat in the sample. The lower yield of higher oil and higher salt content may be explained by the fact that higher oil content retarded the popping process.

The results showed that, for the selected range of variables, moisture content (M) had significant effect at 1 % level of significance (LOS), while amount of salt (S) and oil (O) had highly non-significant effect on popping yield as shown in the Table 1. The combination of moisture and salt pretreatment ($M \times S$) as well as the combination of salt and oil pretreatment ($S \times O$) showed significant effect on popping yield ($p < 0.01$), while the combination of moisture and oil ($M \times O$) had non-significant effect. However, all the coefficients of combinations are negative; therefore, the increase in moisture level and salt may reduce the popping yield. The regression equations describing the effects of pretreatments on popping yield of sorghum grain in terms of actual levels of variables are given as:

$$\begin{aligned}
 PY = & -447.2 + 63.05 M + 18.4 S + 1.13 O \\
 & - 0.708 M \times S - 0.11 M \times O - 0.98 S \times O \\
 & - 1.90 M^2 - 1.62 S^2 - 3.37 O^2
 \end{aligned} \quad (4)$$

Effect of Pre-treatments on volume expansion ratio

Volume expansion ratio (VER) of pretreated sorghum grain found to be in the range of 7.9–14.96 for the experimental range. The 3D surface graphs (Fig. 2) for effect of pre-treatments on

Fig. 2 Combined effect of salt and oil on volume expansion ratio of sorghum grain (keeping third variable at center)

volume expansion ratio showed moisture conditioning of the sorghum grains prior to popping increased the volume expansion ratio up to a certain level, then further increase in moisture content resulted in low expanded popped grains (Fig. 2). Higher moisture content provided more pressure development within the grain, which ultimately expanded suddenly to give greater volume expansion ratio. The presence of salt at a higher moisture content of grain increased the volume expansion, but the effect was found to be non-significant. The positive effect of salt may be due to a higher loss factor dielectric constant of sodium chloride. Similarly, oil pretreatment at higher moisture content without salt increased the volume expansion. But, more oil has to be added for significant positive effect. The combined effect of salt and oil on volume expansion ratio was complex. Oil has low dielectric constant and loss factor, but it has low specific heat that would have led to a lower temperature around the kernel. But in the presence of salt, it retards the gelatinization of starch resulting lower expansion volume.

For the selected range of variables, linear term of only moisture content (M) had highly significant effect on VER ($p \leq 0.05$) and linear terms of salt (S) and oil (O) pretreatment had non-significant effect ($p > 0.05$). The combined effect of moisture and salt ($M \times S$) as well as the combined effect of salt and oil ($S \times O$) showed significant effect on VER at 1 % level of significance (LOS), while the combination of moisture and oil was found to be non-significant. From ANOVA Table 1, it can be observed that the coefficient of $M \times S$ and $S \times O$ are negative; indicating that by increasing moisture and salt as well as increasing salt at higher oil content may reduce the volume expansion ratio. The Model F-value of 75.89 implies the model is significant (Table 1). The regression equations describing the effects of pretreatments on volume expansion ratio of sorghum grain in terms of actual levels of variables are given as:

$$\begin{aligned} VER = & -87.57 + 12.14M + 5.28S + 0.056O - 0.21M \\ & \times S + 6.84M \times O - 0.17S \times O - 0.36M^2 \\ & - 0.44S^2 + 1.56O^2 \end{aligned} \quad (5)$$

Effect of Pre-treatments on overall acceptability

Sensory evaluation of all the pretreated pop sorghum was done by taking one criterion of overall acceptability (OAA), and the average score of the 12 panel members and OAA scores ranged from 5.5 to 8.8. The 3D surface graphs (Fig. 3) of combined effect of all the pre-treatments showed that increased in the moisture content level significantly increased the overall acceptability of the popped grains, due to highly expanded and bright colored popped grains. At lower moisture contents, the grain did not expand well due to insufficient pressure development, which ultimately produced

Fig. 3 Combined effect of salt and oil on overall acceptability of sorghum grain (keeping third variable at center)

charred popped grains and was not liked by the panel members. Similarly, at higher moisture content, the overall acceptability slightly decreased due to the production of poor expanded grains as a result of softening of kernels. The addition of salt at higher moisture levels increased the overall acceptability significantly. The reason could be the higher volume expansion and better taste of popped grains due to the treatment of salt. The combined effect of salt and oil showed that by adding more salt and oil the sensory panel liked the product the most, because salt and oil enhanced the flavour of pop sorghum. The results are in line with other researchers (Lin and Anantheswaran 1988; Singh and Singh 1999), who had reported that the addition of salt and oil improved the flavor of the popped corn.

According to ANOVA (Table 1), the coefficient of linear terms of moisture content (M), salt (S) and oil (O) were positive, for selected range of variables. The combination of moisture content and salt ($M \times S$) was found to affect the overall acceptability significantly. But, the combination of moisture and oil ($M \times O$) as well as salt and oil ($S \times O$) had a non-significant effect on overall acceptability score; the coefficients were found to be negative. Therefore, a further increase in salt and oil in combination with higher moisture levels had reduced the overall acceptability of popped grains. The combination of salt and oil ($S \times O$) was found to have positive effect on overall acceptability score, but the effect was non-significant. The Model F-value of 100.05 implied the model was significant. The regression equations describing the effects of pretreatments on overall acceptability of sorghum grain in terms of actual levels of variables is given as:

$$\begin{aligned} OAA = & -26.01 + 3.92M + 1.92S + 0.097O \\ & - 0.078M \times S - 0.0031M \times O + 0.027S \\ & \times O - 0.11M^2 - 0.23S^2 - 4.25O^2 \end{aligned} \quad (6)$$

Table 2 Validation of the SOP model for popping of sorghum grain in microwave

Responses	Observed _{avg} ± std. dev	Predicted	Residuals
Popping yield	80.967 ± 1.561	82.2283	1.26 ± 1.561
Volume expansion ratio	14.216 ± 0.484	14.564	0.384 ± 0.484
Overall acceptability	8 ± 0.15	8.49	0.49 ± 0.15

Optimization of Pre-treatments based on analysis and statistical data

From the results obtained through various analytical data discussed above, a suitable combination of moisture content, salt and oil was calculated, for the popped sorghum product with optimum quality and optimum values for the responses stated and discussed above. During the optimization process using response surface methodology, the specific constraints such as maximum popping yield, volume expansion ratio, and overall acceptability were applied. The 23 optimum solutions were found by software showing the optimum conditions of independent variables with the predicted values of responses. The best solution was found with the desirability value of 0.950 with optimum moisture content of 16.62 % (wb), salt 0.55 % and oil 10 % with popping yield of 82.228 %, volume expansion ratio of 14.564 and overall acceptability of 8.495.

Verification of model analysis of optimized pretreated popped sorghum product

The verification of the optimum solution was also done by conducting the experiment at the optimized point for the variables considered, and it had been observed that the experimental values obtained were similar to predicted values that are presented in Table 2. Therefore, it can be concluded that the developed models were a good fit to predict the popping characteristics of sorghum using different pre-treatments in a

Fig. 4 Popped sorghum at optimized pretreatments

domestic microwave oven. The models had R^2 value more than 0.9, and lack-of-fit terms were non-significant, the models are good fit to the experimental values, and the verification of the results also had residual values <5 %, which is in the acceptable range (Mohapatra and Bal 2010). The present study fulfills all the conditions for getting desirable results. Photograph of the product from the optimized solutions is shown in Fig. 4.

Optimization of microwave process variables for producing popped sorghum from pretreated sorghum grains

Effect of processing parameters on popping yield

Effect of microwave power density and residence time on popping yield is depicted in Fig. 5. Popping yield was found to increase as the microwave power density (MWPD) was increased at all the residence times (t) and ranged from 31.89 to 81.72 % at different residence times. It was observed from the graph that popping yield was significantly higher when popped at more than 9 Wg^{-1} MWPD and residence time more than 100 s. However, at higher MWPD of 18 Wg^{-1} , no such increase in popping yield was found when microwaving for 180 s. No further increase in popping yield at the highest MWPD and residence time might have been due to charring of the sample. Most of the samples achieved at least 70 % of yield within 140 s, at higher power densities (12 and 18 Wg^{-1}); for low power density at 9 Wg^{-1} ; however, residence time was much higher to achieve same yield level. Highest popping yield was found at 18 Wg^{-1} MWPD by keeping the samples for 140 s in the microwave oven.

Fig. 5 Effect of microwave power density on popping yield of pretreated sorghum for different residence times

Table 3 Single-factor ANOVA test for effect of microwave power density on popping characteristics and organoleptic quality at different residence times

Responses	Residence times	F-value	<i>p</i> -value	SEM	CD _{0.05}
Popping yield	100	1067.02	2.2E-08	0.51	3.74
	140	438.33	3.14E-07	1.02	7.42
	180	382.74	1.73E-07	0.75	5.56
Volume expansion ratio	100	303.40	9.39E-07	0.21	1.55
	140	219.72	2.44E-06	0.24	1.74
	180	273.03	1.33E-06	0.19	1.44
Overall acceptability	100	16.46	1.77E-10	0.14	0.81
	140	283.96	7.83E-11	0.11	0.62
	180	50.22	1.53E-10	0.26	1.47

One-factor ANOVA test was carried out to check the effect of microwave power density on popping yield (Table 3), for different residence times and effect of residence time on popping yield for various power densities (Table 4). The results implied that power density showed highly significant ($p < 0.01$) variation in the popping yield among all residence times. Similarly, residence time also found to have a highly significant effect on popping yield of sorghum grain for all power densities considered for the experimentation.

Pair comparison t-test was carried out to check the significance of the different power densities and residence times. It was observed that microwave power density had significant effect on popping yield of pre-treated sorghum, for the range tested (9–18 Wg⁻¹), while having non-significant effect for the range 12–18 Wg⁻¹ ($p > 0.05$) for t two- and t one-tailed test (data not shown). At lower power densities (9 Wg⁻¹), the sorghum grain samples did not get a continuous supply of energy as a requirement for popping. This result implied that, by choosing the microwave power density ranged from 12 to 18 Wg⁻¹ considered in the study, there would not be much difference in the popping yield of sorghum obtained in a microwave oven. However, higher residence time should be selected for 12 Wg⁻¹ power density for better popping efficiency, because pair comparison t-test between the residence times showed that residence time had significant effect on popping

yield of pre-treated sorghum when tested at the range of 100 to 180 s for all microwave power densities.

Effect of processing parameters on volume expansion ratio

The variation in volume expansion ratio in various microwave power densities (Wg⁻¹) and residence times (s) is represented in Fig. 6. Volume expansion ratio changed significantly with MWPD and ranged from 5.5 to 14.12 at different residence times in the microwave oven. It can be seen that at lower MWPD, the VER was found to be very low at all residence times. The probable reason could be the absence of enough thermal gradients, which was necessary for the starch to expand. At higher MWPD of 18 Wg⁻¹, continuous heating resulted in greater pressure development and hence caused higher VER at all residence times. But, by placing the pre-treated sorghum samples for 180 s at MWPD of 18 Wg⁻¹, no significant increase in VER was found due to charring of initially popped grains inside the package. Similarly, the effect of residence time can be explained as the volume expansion ratio almost increased for all the samples as the residence time was increased, for all the MWPDs. But, as the residence time was increased over 140 s at MWPD of 18 Wg⁻¹, no further increase in VER was found. This could be due to the fact that, as the residence time progressed, the starchy grain exposed to higher microwave

Table 4 Single-factor ANOVA test for effect of residence time on popping characteristics and organoleptic quality at different microwave power densities

Responses	MWPD (Wg ⁻¹)	F-value	<i>p</i> -value	SEM	CD _{0.05}
Popping Yield	9	86.74	3.74E-05	0.94	6.90
	12	292.74	1.04E-06	0.14	1.08
	18	201.04	3.18E-06	0.72	5.27
Volume expansion ratio	9	37.72	0.0004	0.22	1.62
	12	292.74	1.04E-06	0.14	1.08
	18	8.04	0.020038	0.26	1.92
Overall acceptability	9	92.64	9.91E-07	0.12	0.72
	12	4.32	0.038496	0.17	0.94
	18	356.86	2.04E-11	0.27	1.40

Fig. 6 Effect of microwave power density on volume expansion ratio of pretreated sorghum for different residence times

energy, which transformed into thermal energy in sorghum, for volume expansion; however, when residence time increased over a certain period, no further expansion was there and charring of the grains started. Highest VER value found out was at MWPDP of 18 Wg^{-1} and residence time of 140 s.

The effect of power density and residence time on volume expansion was investigated by a single-factor ANOVA analysis (Tables 3 and 4). It was observed that power density had highly significant effect ($p < 0.01$) on volume expansion ratio for all levels of residence times. Similarly, residence time had highly significant effect on VER of sorghum at 1 % level of significance for power density of 9 and 12 Wg^{-1} , while having significant effect at 5 % level of significance for power density of 18 Wg^{-1} .

Pair comparison t-test was carried out to check the significance of different power densities and residence times in the domestic microwave oven. The result showed that microwave power density had a significant effect on VER. When tested in the range $9\text{--}12 \text{ Wg}^{-1}$ ($p < 0.05$), while having non-significant effect for the range $12\text{--}18 \text{ Wg}^{-1}$ ($p > 0.05$). This could be the fact that at lower power densities, the thermal gradient required for better expansion of the sorghum grain was not achieved due to intermittent heating, as 30 % of the residence time power remained discontinuous (off time). Residence time was found to have significant effect on volume expansion ratio for microwave power densities in the range $9\text{--}12 \text{ Wg}^{-1}$ tested in the microwave oven for t-one tail test, but in the t-two tail test residence time showed non-significant effect on VER for all microwave power densities tested. From the results, it was implied that since required thermal expansion of starch was provided through higher power densities, then residence time did not show any significant deviation in VER during microwave heating over 100 s.

Effect of processing parameters on overall acceptability

The variation in overall acceptability score at different microwave power densities and residence times is depicted in Fig. 7. The score changed significantly with MWPDP and, ranged from 2.10 to 8.66 at different residence times in the

Fig. 7 Effect of microwave power density on overall acceptability of pretreated sorghum for different residence times

microwave oven. But, it was clearly observed that at higher microwave power densities, the overall acceptability of pop sorghum grains was higher at all residence times, except for 180 s. The reason may be due to the fact that by keeping the pre-treated sorghum samples for longer time in the microwave condition, the initially popped grains burned and imparted burning flavour to the popped product resulting in rejection by the penal members. Highest OAA found was at MWPDP of 18 Wg^{-1} and residence time of 140 s, followed by 12 Wg^{-1} MWPDP and residence time of 180 s.

Single factor ANOVA was carried out to investigate the effect of power density and residence time on overall acceptability of the pretreated popped sorghum. Microwave power density and residence time had highly significant effect ($p < 0.01$) on overall acceptability of popped sorghum among all the variables tested.

Pair comparison t-test was carried out to check the significance in overall acceptability between different power densities and residence times in the domestic microwave oven. Observations of sensory quality of pop sorghum showed that MWPDP and residence time had a non-significant effect on overall acceptability for the range tested ($12\text{--}18 \text{ Wg}^{-1}$). This result implied that by choosing any of the MWPDP between 12 and 18 Wg^{-1} , the sensory quality of pop sorghum would not be much affected. But both t-one tail and two tail test showed overall acceptability scores were significantly different in the range of 9 and 12 Wg^{-1} for all the residence time tested. The reason could be at lower power densities and lower residence times the popped grains produced by very low volume expansion, therefore it would not be liked by the sensory panel as compared to the popped grains popped at higher power densities over 12 Wg^{-1} .

Optimization of microwave process parameters

From the above study, it can be concluded that the highest popping yield, volume expansion ratio, and overall acceptability were observed at 18 Wg^{-1} for 140 s followed by 12 Wg^{-1} for 180 s. Therefore, the optimized microwave process parameters for popping of the pre-treated pre-packed sorghum grains

were: microwave power density: 18 Wg^{-1} and residence time: 140 s. Similar results can be obtained by popping the grains at 12 Wg^{-1} power density for 180 s.

Conclusion

From this investigation, it can be concluded that starchy grains like sorghum need sufficient thermal gradient and moisture content for expansion, which corroborated earlier reports. Physical barriers like pericarp help the pressure to build up inside the grain that ultimately escapes suddenly, resulting expanded endosperm. The optimum combination of pre-treatments for pop sorghum with maximum popping yield, maximum volume expansion ratio and higher overall acceptability were moisture conditioning up to 16.62 % (wb), 0.55 % salt and 10 % oil with popping yield of 82.228 %, volume expansion ratio of 14.564 and overall acceptability of 8.495. The higher amount of sodium chloride showed a negative effect on popping qualities of sorghum grain in the presence of higher levels of oil; however, showed a positive impact on sensory qualities imparting taste and flavour to the pop sorghum. Popping yield, volume expansion ratio, and overall acceptability were found to increase as microwave power density (MWPD) increased at all residence times. However, at MWPD of 18 Wg^{-1} there was no increase in the popping characteristics, while with reduced sensory qualities when popping for 180 s due to charring of the samples. At lower MWPDs the higher residence time was required for sufficient popping, but volume expansion ratio was low due to insufficient pressure development inside the grain because of intermittent heating. However, at higher MWPDs, comparatively lesser residence time required for popping. For the production of superior quality pop sorghum, the optimized microwave process parameters decided were MWPD of 18 Wg^{-1} and residence time of 140 s. The data may be useful for popping of sorghum grains conveniently and hygienically in a domestic microwave oven.

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