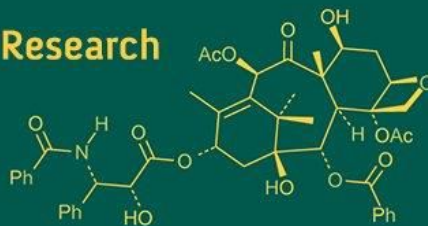
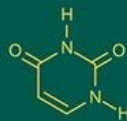


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Optimization of process parameters for production of sorghum pops

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Abstract

Popped sorghum is one of the ready-to-eat snacks which are popularly consumed by local growers. The popping of sorghum was carried out in a semiautomatic multigrain puffing cum popping machine based on HTST principle. Sorghum was dipped in normal water for 30 min and then kept 12 hours for conditioning in a muslin cloth at room temperature to equilibrate the moisture content throughout the grain. Pretreated sorghums was then fed to machine for popping. The optimization of the machine parameters contained two independent variables: popping temperature (°C) and stirrer speed (rpm) assessed at five levels of 170 to 210 °C and 30 to 50 rpm, respectively. Experiments were carried out using Central Composite Rotatable Design (CCRD). The experimental data was analysed using Response Surface Methodology (RSM) and the optimal values of process parameters was found as a popping temperature of 190 °C and stirrer speed of 40 rpm. The developed machine had popping efficiency, popping capacity, for sorghum pops were 85.87% and 48 kg/day, respectively.

Keywords: Sorghum, central composite rotatable design (CCRD), optimization

Introduction

The popping process has been widely used as a technique for obtaining snacks (Castro-Campos *et al.*, 2021) [2]. The popping process involves subjecting the grains to high temperatures in short times (HTST), increasing the vapor pressure inside the kernel. The HTST treatment exploits the thermo-physical properties of starch and prepares expanded grains or flakes (Jaybhaye *et al.*, 2014; Mishra *et al.*, 2015) [10, 15]. Popping process produced a “dry gelatinization-retrogradation of starch” quickly (90 s) (Castro-Campos *et al.*, 2021) [2]. Several cereal kernels have been used in the popping process, such as corn (Paraginski *et al.*, 2016) [21], amaranth (Huang *et al.*, 2018) [9], rice (Mir *et al.*, 2016; Mishra *et al.*, 2014) [13, 14] and sorghum (Liopart and Drago, 2016) [12]. Ready to eat expanded food grains are gaining popularity in modern days due to their ease to digest, lightness, crispiness and most importantly they are ready to eat (Swarnakar *et al.*, 2022) [28]. Popped sorghum grains have good flavor and are as nutritious as popcorn (Subramanian, 1956) [26]. Sorghum pops have been widely used during festivals, such as Nagapanchami; typically, laddoo is produced from sorghum pops grains (Dicko *et al.*, 2006) [6]. Sorghum does not have gluten and hence is a very good ideal gluten-free energy source for people suffering from wheat or gluten allergies. 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) [23]. Popped sorghum contains protein 11.30-12.45%, fat 1.56-1.07%, ash 1.40-1.88%, crude fiber 1.45-1.72 and carbohydrate 75.45-76.98%. The mineral content was well preserved. The zinc content ranges from 1.17-1.43, iron 5.58-6.27, manganese 0.69-0.93 and copper 0.16-0.25 mg/100 g (Dhadke *et al.*, 2022) [4].

To uniform popping and avoid overheating of the product, control of puffing temperature and regulation of stirrer speed is necessary but in the traditional method doing this job is hectic and sometimes impracticable and there are chances of accidental hazards. In order to eliminate the problems in traditional puffing method, a machine was developed and its process parameters optimized for the production of sorghum pops.

Materials and Methods

A multigrain puffing-cum-popping machine was designed and developed at the Department

of Agricultural Process Engineering, College of Agricultural Engineering and Technology, VNMKV, Parbhani (Rupanawar *et al.*, 2025) [22]. This machine works on the High Temperature Short Time (HTST) principle. The standard process for production of popped sorghum was adopted as per the procedure given by Gosavi, (2022) [7]. Sorghum grains were soaked in water for 30 min and then tied in muslin cloth for conditioning up to 12 hours. Pretreated sorghums were then fed to the machine for popping. The experimental design was formulated after selection of the ranges using CCRD. The effect of process variables viz. popping temperature and stirrer speed on quality attributes of popped sorghum was assessed at five levels of each process variables 170 to 210 °C and 30 to 50 rpm, respectively. Total twenty nine experiments were

conducted and the obtained data were analysed by applying Response Surface Methodology (RSM) using Design Expert 8.0.6.

Quality evaluation of popped sorghum prepared within the experimental range

The popping efficiency, expansion ratio, bulk density, color (L-value), hardness and crispness of popped sorghum were determined.

Popping efficiency (%)

Popping efficiency of popped sorghum was calculated by using following formula,

$$\text{Popping efficiency (\%)} = \frac{\text{Weight of Popped grains}}{\text{Weight of popped grains} + \text{Weight of unpopped grains}} \times 100$$

(Mishra *et al.*, 2015; Castro-Campos *et al.*, 2021) [15, 2].

Expansion ratio

Expansion ratio of popped sorghum was calculated by using following formula

$$\text{Expansion Ratio} = \frac{\text{Total popped volume (mL)}}{\text{Volume of raw grains (mL)}}$$

(Mukhopadhyay *et al.*, 2015, Mishra *et al.*, 2015) [18, 15].

Bulk density

Bulk density was calculated by using following formula

$$\text{Bulk Density (g/cm}^3\text{)} = \frac{\text{Mass of popped sorghum (g)}}{\text{Volume of puffed Sorghum (cm}^3\text{)}}$$

(Subramani *et al.*, 2020; Gosavi, *et al.*, 2023) [25, 8].

Color

The L-value of the sorghum pops was determined using a Hunter Lab colorimeter. It was observed that there was not much variation in the 'a' and 'b' values with changes in the process parameters, therefore only L-value was considered (Tavanandi *et al.*, 2021) [30].

Textural properties (Hardness and Crispiness)

The textural properties of popped sorghum were evaluated using a texture analyzer TA.XT. Plus (Jaybhaye and Srivastav, 2015) [11]. The hardness value was considered the mean peak compression force and crispiness was measured in terms of a major positive number of peaks (Cruzycelis, *et al.*, 1996) [3]. The cylindrical probe P35 with 0.05 N testing force, 50% strain, measure force in compression mode and 1 mm/s pre-test speed was used for sorghum pops (Bourne, 2002) [1].

Optimization of process parameters of popped sorghum

Optimization of process parameters was carried out numerically (Montgomery, 2001; Pawar, *et al.*, 2014) [16, 20] and graphically to obtain the maximum popping efficiency, expansion ratio, optimal values of bulk density, hardness, color and crispiness using Design Expert software. (Version 8.0.6 Stat Ease, Minneapolis, USA). Response surface graphs and contour plots were generated to examine the effects of process parameters on the response variables (Jaybhaye and Srivastav, 2015) [11].

Results and Discussions

Effect of process parameters on popping efficiency of machine for sorghum pops

The computed values for the popping efficiency of machine for sorghum pops ranged from 58.57% to 87.04% (Table 1) within the combination of variables studied. Similar trends were observed by Nakade *et al.* (2020) [19] and Mishra *et al.* (2015) [15] depending on the severity of pre-treatments given.

$$\text{PE (\%)} = -1573.95 + 16.69 J_1 + 3.15 J_2 + 0.01 J_1 J_2 - 0.04 J_1^2 - 0.06 J_2^2 \dots\dots(1)$$

The magnitude of coefficient of linear terms showed that popping temperature (J_1) was most prominent than stirrer speed (J_2). The linear terms of J_1 and J_2 ; interaction term of $J_1 J_2$ and quadratic terms of J_1^2 and J_2^2 were significant (Table 2) at 5% level of significance. The lack of fit was not significant for the model (eq.1) obtained. Model F-value (Table 2) was significant. The lack of fit of F value was non-significant for the model obtained. The coefficient of determination indicated an excellent fit to the experimental data. The predicted R^2 was in reasonable agreement with the adjusted R^2 , that is, the difference was less than 0.2. This revealed that the non-significant terms have not been included in the model. Therefore, this model could be used to navigate the design space.

Table 1: Quality characteristics of sorghum pops by varying process parameters

Treatments	Quality characteristics							
	J ₁	J ₂	Popping efficiency (%)	Expansion ratio	Bulk density (kg/m ³)	Color (L-value)	Hardness (N)	Crisp-ness (number of +ve peaks)
1	-2	-2	61.05	5.97	102.56	69.36	28.14	4
2	2	-2	58.57	4.73	106.67	68.96	27.86	4
3	-2	2	59.22	5.60	102.16	69.26	21.54	5
4	2	2	65.41	5.38	94.06	70.68	23.95	7
5	-2	0	65.34	6.16	96.23	70.80	23.00	6
6	2	0	71.45	5.53	90.18	73.34	25.54	8
7	0	-2	77.52	6.59	87.98	75.88	22.69	8
8	0	2	82.56	7.33	83.58	77.84	17.20	10
9	0	0	87.05	7.78	80.43	78.97	17.97	11
10	0	0	85.14	7.54	79.44	79.39	18.81	10
11	0	0	86.13	7.65	80.41	78.38	18.62	11
12	0	0	83.57	7.67	80.09	78.80	17.94	11
13	0	0	84.96	7.73	82.48	78.75	19.02	11
14	-2	-1	60.56	4.92	101.11	69.75	26.14	5
15	-2	1	62.23	5.10	98.40	70.66	25.42	5
16	-1	-2	67.58	5.61	93.04	72.90	20.80	6
17	-1	-1	69.23	5.94	91.17	73.98	19.89	7
18	-1	0	73.18	6.38	88.10	74.77	16.27	8
19	-1	1	70.56	6.02	90.78	74.55	19.60	7
20	-1	2	68.33	5.43	95.20	73.39	20.42	6
21	0	-1	80.11	7.29	85.93	76.96	14.78	10
22	0	1	80.85	7.39	85.20	77.56	14.10	11
23	1	-2	69.52	6.06	91.48	74.40	19.71	7
24	1	-1	71.35	6.54	89.54	74.77	17.13	7
25	1	0	79.27	7.27	87.38	76.79	15.19	10
26	1	1	76.63	7.05	85.04	76.08	15.39	10
27	1	2	73.63	5.99	97.67	75.87	15.84	8
28	2	-1	64.32	5.26	101.19	72.08	22.10	5
29	2	1	66.30	5.30	100.08	72.44	21.24	6

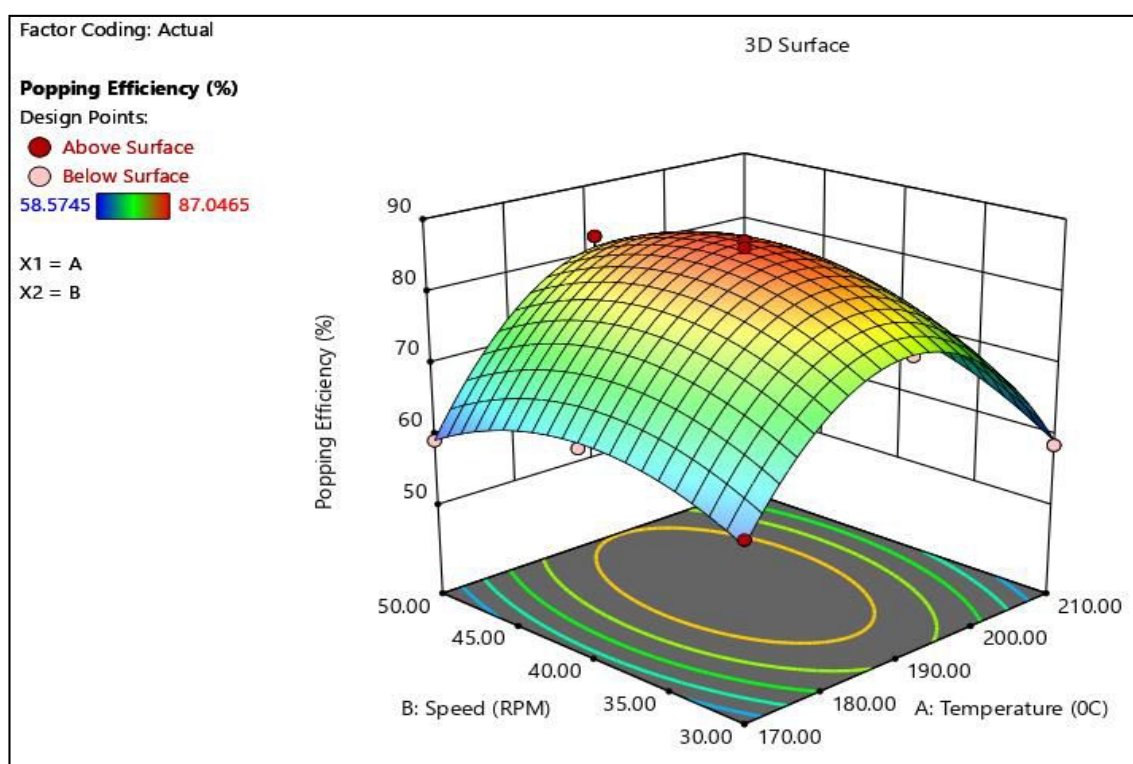
J₁ = Popping temperature, J₂ = Stirrer speed**Fig 1:** Effect of popping temperature and stirrer speed on popping efficiency of machine for sorghum pops

Table 2: ANOVA for process parameters showing effect on responses of sorghum pops

Source		Popping Efficiency	Expansion Ratio	Bulk Density	Color L-value	Hardness	Crispness
Model	ΣX_i^2	1497.47	13.87	1114.66	219.94	173.43	88.53
	F-value	117.71	89.52	85.98	121.6	134.16	106.76
	p-value	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*
J_1	ΣX_i^2	16.07	0.73	16.81	2.11	3.63	2.67
	F-value	6.32	23.71	6.48	5.84	14.06	16.08
	p-value	0.0402*	0.0018*	0.0383*	0.0463*	0.0072*	0.0051*
J_2	ΣX_i^2	16.81	0.18	50.55	2.14	42.67	6
	F-value	6.61	5.68	19.5	5.92	165.03	36.18
	p-value	0.037*	0.0487*	0.0031*	0.0453*	< 0.0001*	0.0005*
$J_1 J_2$	ΣX_i^2	18.76	0.26	37.18	0.83	1.81	1
	F-value	7.37	8.39	14.34	2.29	7	6.03
	p-value	0.03*	0.0231*	0.0068*	0.174*	0.0332*	0.0438*
J_1^2	ΣX_i^2	888.66	7.89	546.01	136.57	87.21	41.93
	F-value	349.27	254.56	210.59	377.57	337.31	252.85
	p-value	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*	< 0.0001*
J_2^2	ΣX_i^2	109.58	0.92	121.37	13.9	4.63	9.93
	F-value	43.07	29.63	46.81	38.43	17.89	59.9
	p-value	0.0003*	0.001*	0.0002*	0.0004*	0.0039*	0.0001*
Lack of Fit	ΣX_i^2	10.97	0.18	12.96	1.99	0.84	0.36
	F-value	2.14 ^{NS}	7.41 ^{NS}	3.33 ^{NS}	4.93 ^{NS}	1.15 ^{NS}	0.6 ^{NS}
	p-value	0.238	0.041	0.138	0.079	0.43	0.648
R-Squared		0.988	0.985	0.984	0.989	0.989	0.987
Adj R-Squared		0.979	0.974	0.973	0.981	0.982	0.979
Pred R-Squared		0.926	0.878	0.895	0.908	0.945	0.947
C.V.%		2.14	2.67	1.79	0.81	2.34	4.99

*Significant at 5% level, NS-Non significant. Where, J_1 = puffing temperature ($^{\circ}\text{C}$), J_2 = stirrer speed (rpm), ΣX_i^2 = sum of square

It was observed by fig. 1, that popping efficiency increased with increase in popping temperature (J_1) up to 190 $^{\circ}\text{C}$ and stirrer speed (J_2) up to 40 rpm. Further, popping efficiency of machine decreased at higher levels of these process parameters. This may be due to low vapor pressure inside the kernel and resulted in less expanded structure and hence getting less popped. 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) ^[17]. Excessive stirrer speed adversely affected popping efficiency. Similar trends were observed by Nakade *et al.* (2020) ^[19] and Daheriya (2022) ^[5] for sorghum pops.

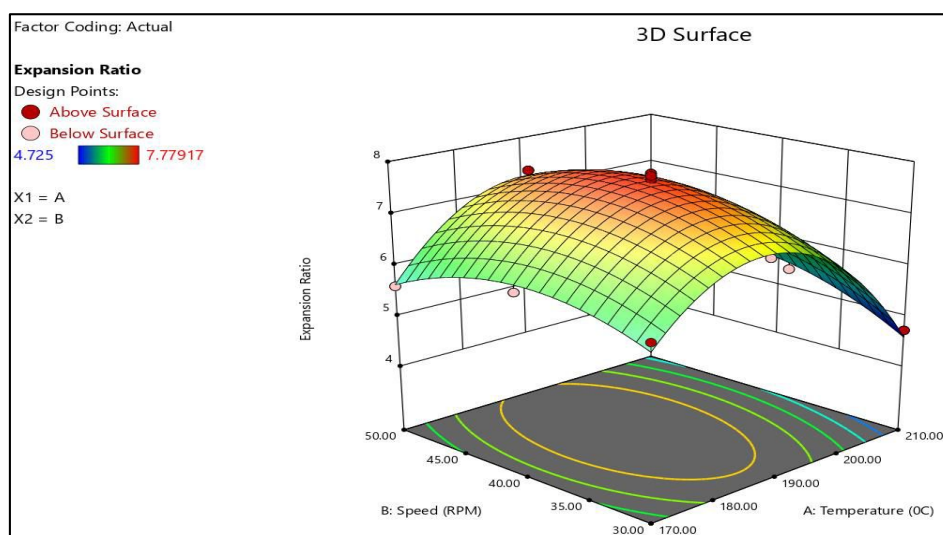
Effect of process parameter on expansion ratio (ER) of sorghum pops

From Table 1, it could be observed that expansion ratio

ranged from 4.72 to 7.77 within the range of experimental values studied. Volume expansion ratio of pretreated sorghum grain in microwave heating found to be 7.9 to 14.96 for the experimental range (Mishra *et al.*, 2015) ^[15].

$$\text{ER} = -141.77 + 1.54 J_1 + 0.24 J_2 + 1.27\text{E-}002 J_1 J_2 - 4.22 \text{E-}002 J_1^2 - 5.77 \text{E-}002 J_2^2 \quad \dots\dots\dots(2)$$

In the given regression equation (2) the magnitude of the coefficient of the linear terms showed that popping temperature (J_1) had the most prominent effect on expansion ratio, followed by stirrer speed (J_2). The coefficient of determination indicates that the model strongly fits the data. The ANOVA (Table 2) shows that all-linear terms coefficient, interaction term coefficient and quadratic terms coefficient showed significant effects.

**Fig 2:** Effect of popping temperature and stirrer speed on expansion ratio of sorghum pops

The lack of fit F value was non-significant. In fig.2, shows that expansion ratio increased with increase in popping temperature (J_1) up to 190 °C and stirrer speed (J_2) up to 40 rpm further expansion ratio decreased at higher levels of these process parameters. This may be due to pressure inside the kernel is low and resulted in less expanded structure. These results are close to the ranges reported by Surpam (2019) [27]. The sorghum grain's expansion capacity related to the total carbohydrate content (Mishra *et al.*, 2015) [15]. Popping process modified the microstructure of the sorghum, forming a honeycomb structure with concave cavities was observed (Castro-Campos *et al.*, 2021) [2]. The formation of these structures has been attributed to the increase in the steam inside the grain due to heat, bubble formation (nucleation) and rapid expansion of the endosperm after the pericarp breaks (Sweley *et al.*, 2013) [29].

Effect of process parameter on bulk density (BD) of sorghum pops

Higher the degree of expansion volume of sorghum pops,

lower is bulk density. Bulk density of sorghum pops ranged from 79.44 to 106.66 kg/m³ within the range of experimental values studied (Table 2). Similar results were observed by Gosavi (2022) [7].

$$BD \text{ (kg/m}^3\text{)} = 1366.84 - 12.83 J_1 - 2.69 J_2 - 0.02 J_1 J_2 + 0.04 J_1^2 + 0.07 J_2^2 \quad \dots(3)$$

The negative coefficients in the case of first order term of popping temperature (J_1) and stirrer speed (J_2) indicated that excessive increase in this parameter resulted in decrease of bulk density while positive coefficients of quadratic terms suggested that increase of these parameters resulted in increase of bulk density. The quadratic model (eq. 3) was found to fit well for the data and the model F value is significant (Table 2). The linear terms, interaction terms and quadratic terms are significant. The R^2 value showing good fit of model (eq. 3) to the data. Lack of fit test was not significant and predicted R^2 value is compatible with adjusted R^2 value.

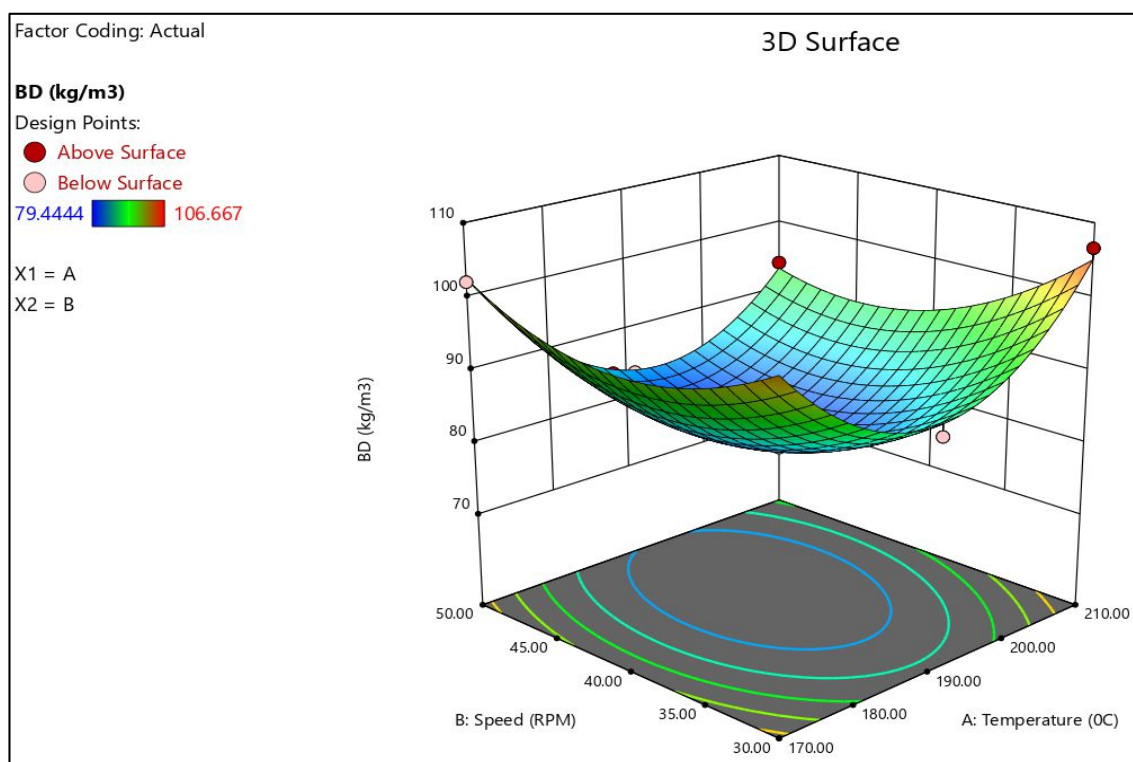


Fig 3: Effect of popping temperature and stirrer speed on bulk density of sorghum pops

In fig.3, bulk density decreased with increase in popping temperature (J_1) up to 190 °C and stirrer speed (J_2) up to 40 rpm, further bulk density increased at higher levels of these process parameters. This may be due to pressure inside the kernel is low and resulting in less expanded structure. Excessive stirrer speed adversely affected bulk density. Similar results were observed by Gosavi, (2022) [7].

Effect of process parameter on color of sorghum pops

Color L-value of sorghum pops (Table 1) a ranged between 68.96 to 79.39, within the combinations of variable studied. Similar results were observed by Gosavi (2022) [7] and

Daheriya (2022) [5] for sorghum pops.

$$\text{Color, L-value} = -582.35 + 6.62 J_1 + 1.42 J_2 + 2.28 E-002 J_1 J_2 - 0.02 J_1^2 - 0.02 J_2^2 \quad \dots(4)$$

The magnitude of the coefficient of linear terms of model (eq.4) revealed that popping temperature is the most influencing process variable followed by stirrer speed. From Table 2, the model F value is significant. The linear terms of J_1 , J_2 ; interaction term $J_1 J_2$ and the quadratic terms of J_1^2 and J_2^2 are significant. The lack of fit is not significant.

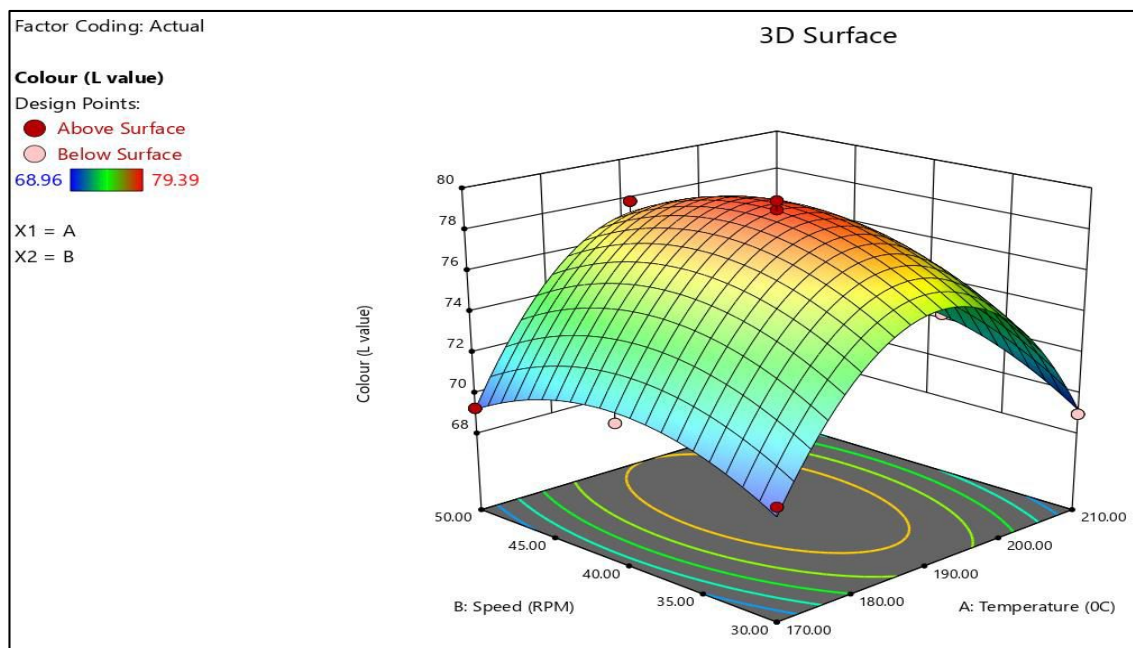


Fig 4: Effect of popping temperature and stirrer speed on L-value of sorghum pops

From fig. 4 exhibits, that popping temperature is a key factor influencing brightness followed by other parameters, but excessive temperatures may have negative impact, its possibly due to thermal degradation. Similar trends were observed by Nakade *et al.* (2020) ^[19]. Stirrer speed has a comparatively less impact on color value of sorghum pops.

Effect of process parameter on hardness of sorghum pops

The hardness values varied between 17.2 to 28.14 N within the combination of variable studied (Table 1). Similar trends were observed by Nakade *et al.* (2020) ^[19].

$$Hd (N) = 575.18 - 5.43 J_1 - 1.94 J_2 + 3.36 E-002 J_1 J_2 + 0.01 J_1^2 + 0.01 J_2^2 \quad \dots\dots\dots (5)$$

In the equation (5) magnitude of popping temperature was

the most influential parameter on Hd, followed by stirrer speed. The negative linear effect of J_1 and J_2 indicated that Hd of sorghum pops decreased with increasing J_1 and J_2 but the positive quadratic terms and inter-active term indicates that beyond a certain threshold, Hd was increased. The linear terms of J_1 , J_2 ; interaction term $J_1 J_2$ and the quadratic terms of J_1^2 and J_2^2 were significant. From fig. 6 it is clear that hardness decreased with increase in popping temperature (J_1) up to 190 °C and stirrer speed (J_2) up to 40 rpm, further hardness value was increased at higher levels of these process parameters. This may be caused due to the fact that at higher temperature, water evaporated from the surface of the grain which form condition of case hardening and created very hard surface and further removal of water from the grain and thus increases the hardness (Srivastav *et al.*, 1994) ^[24].

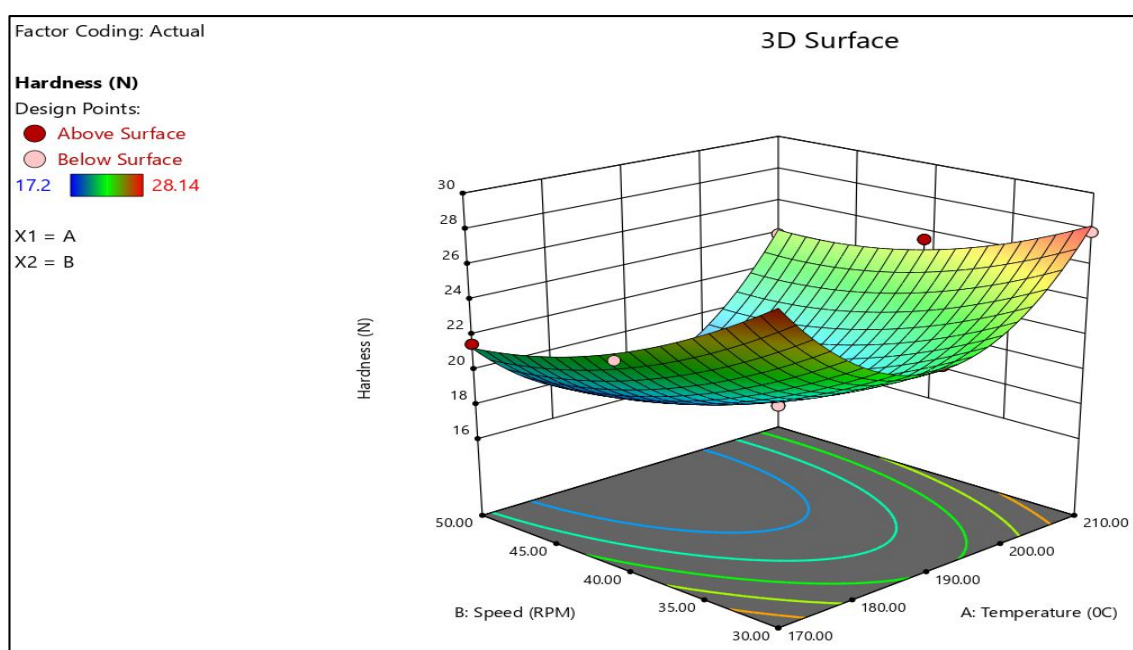


Fig 6: Effect of popping temperature and stirrer speed on hardness of sorghum pops

Effect of process parameter on crispness of sorghum pops

The experimental values of crispness were in the range of 4 to 11 (Table 1). Similar results were observed by Nakade *et al.* (2020)^[19].

$$\text{CSP} = -362.51 + 3.64 J_1 + 1.14 J_2 + 2.50 \times 10^{-2} J_1 J_2 - 9.74 \times 10^{-2} J_1^2 - 0.02 J_2^2 \quad \dots\dots\dots(6)$$

The magnitude of the coefficient of the linear terms showed

that popping temperature (J_1) had the most prominent effect on crispness, followed by stirrer speed (J_2). The coefficient of determination indicated an excellent fit to the experimental data. The model (eq. 6) F-value was significant and lack of fit was not significant. The coefficients of the linear terms of J_1 , J_2 ; the interaction term $J_1 J_2$ and the quadratic terms of J_1^2 , J_2^2 are significant. The predicted R^2 was in reasonable agreement with the adjusted R^2 .

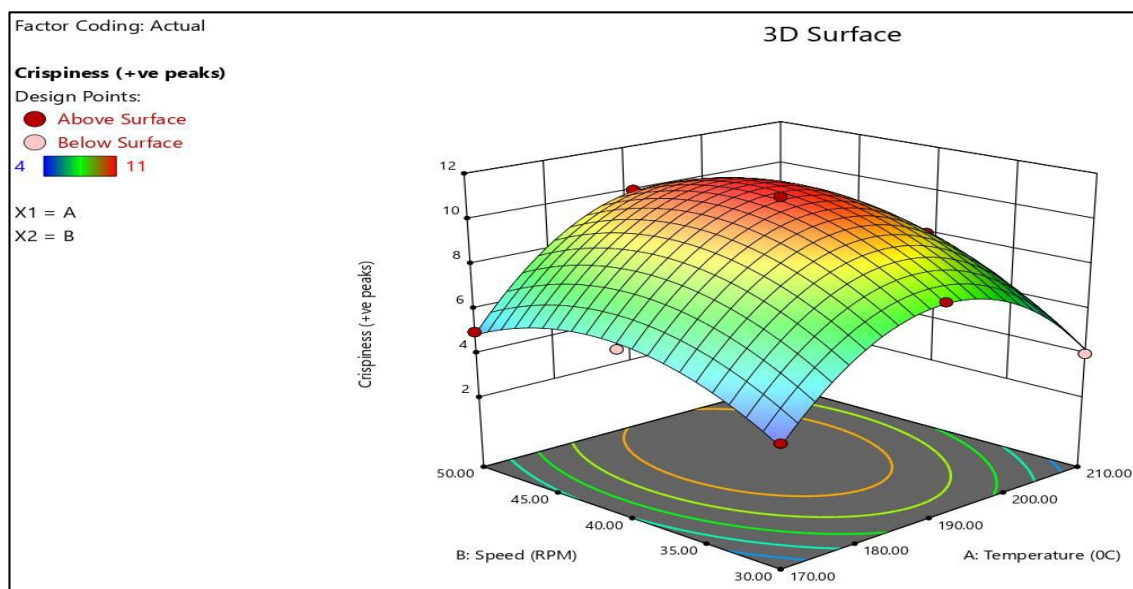


Fig 6: Effect of popping temperature and stirrer speed on crispness of sorghum pops

From fig. 6, it is clear that crispness value increased with an increase in popping temperature (J_1) up to 190 °C and stirrer speed (J_2) up to 40 rpm, further crispness value decreased at higher levels of these process parameters. This may be due to vapor pressure inside the kernel is low and resulted in less expanded structure and increased the crispness value. Similar trend was observed by Surpam (2019)^[27] and Nakade *et al.* (2020)^[19].

Optimization of sorghum pops

The optimization of process parameters such were necessary

to obtain better quality of sorghum pops. The optimum value by numerical optimization were 189.71 $\approx$ 190 (°C) and 41.38 $\approx$ 40 rpm, respectively and the graphical optimization (Fig.7) were 189.61 $\approx$ 190 (°C) and 41.08 $\approx$ 40 rpm, respectively. The optimum values of responses by graphical optimization were popping efficiency 85.65 (%), expansion ratio 7.65, bulk density 79.97 (kg/m³), L-value 79.19, hardness 18.57 (N), crispness 10.89 $\approx$ 11 (number of +ve peaks).

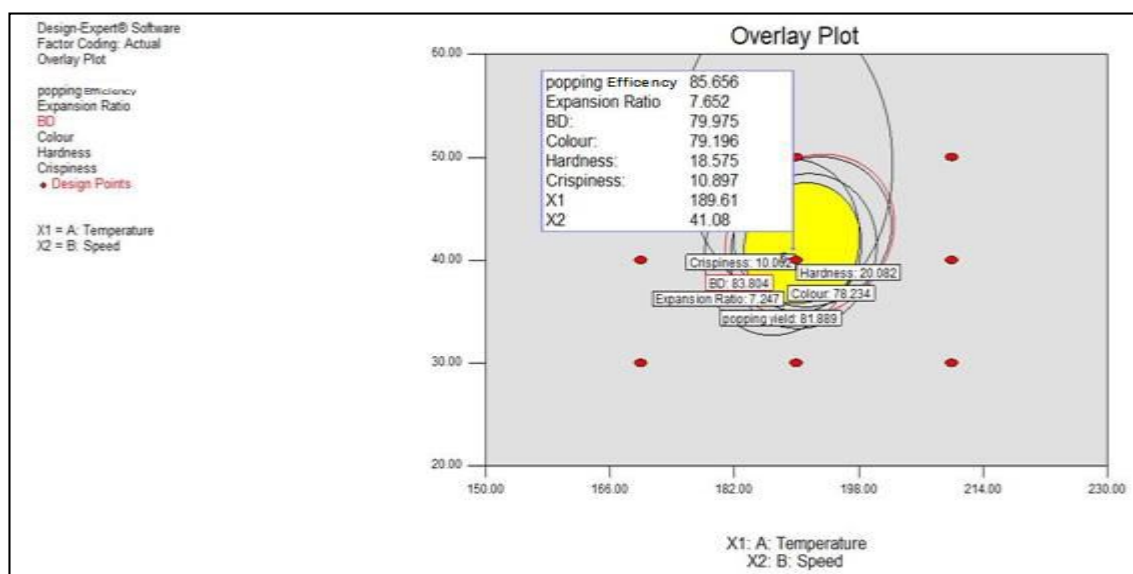


Fig 7: Overlay plot showing predicted values of quality characteristics of sorghum pops

Conclusions

The optimized values of the process parameters for the production of sorghum pops for developed batch-type semi-automatic puffing-cum-popping machine were popping temperature (J_1) 190 °C and stirrer speed (J_2) 40 rpm. The optimum values of responses obtained by graphical optimization was 85.65% popping efficiency, 7.65 expansion ratio, 79.97 kg/m³ bulk density, 79.19 L-value, 18.57 N hardness and crispness value 11. The quantity of popped sorghum obtained was 740 g per kg of raw sorghum grains.

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