Twin Screw Extrusion of Sorghum and Soya Blends: A Response Surface Analysis

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ABSTRACT

Blends of sorghum and soybean flours were processed in a co-rotating twin screw extruder to prepare expanded product. Response surface methodology (RSM) was used to study the effect of soya level (SL), feed moisture (FM), barrel temperature (BT) and screw speed (SS) on extruder system parameters and physical properties of the extrudate. Response variables were product temperature (PT), motor torque (MT), specific mechanical energy (SME), expansion ratio (ER), bulk density (BD), hardness (H), crispness (C), water absorption index (WAI), and water solubility index (WSI). Second order polynomial models were developed to determine the responses as a function of process variables. *FM*, *BT*, and *SS* had a significant effect on all the responses except *BT* on *WAI*, while *SL* considerably affected *ER*, *BD*, *H*, *C*, and *WAI*. All the models were found to be statistically significant (\mathbb{R}^2 > 0.85; insignificant lack of fit). Sorghum-soya extruded product was found to be feasible and the optimum values of processing variables were: *SL*: 14 per cent; *FM*: 14 per cent wb; *BT*: 129°C; and *SS*: 422 rpm.

Keywords: Extrusion, RSM, SME, Sorghum, Soybean.

INTRODUCTION

Extrusion cooking high -a processtemperature/short time is an important food processing technique to develop products such as puffed snack and breakfast cereals (Brncic et al., 2010; Mahasukhonthachat et al., 2010; Santillan-Moreno et al., 2011). Extrusion has been reported to be the most effective method for enhancing protein and starch digestibility of the extrudates. Additionally, it has been used inactivate several antinutritional to compounds that limit the use of grain as a staple food (Shimelis and Rakshit, 2007; Yagc and Gogus, 2008; Alex et al., 2009).

Sorghum (Sorghum bicolor) is the fifth most important cereal crop in the world (Al-Rabadi *et al.*, 2011). India is the second largest producer and consumer in the world (Charyulu *et al.*, 2013). Sorghum is

composed of carbohydrate (84.0%), protein (11%), fat (2.5%), crude fiber (2.2%), and ash (1.6%) and has an energy value of approximately 3.29 kcal g⁻¹ (Shobha et al., 2008). Also sorghum is a potentially important source of nutraceuticals such as antioxidant phenolics and cholesterollowering waxes (John et al., 2006). Although sorghum is nutritionally well comparable with other food grains, it has poor quality of protein, which leads to low solubility, deficiencies in essential amino acids (lysine and tryptophan), and interactions with tannin (Pelembe et al., 2002; Awadalkareem et al., 2008). The protein quality of sorghum can be improved by combining it with other proteinrich sources. Soybean (Glycine max) is an important legume, rich in quality protein (rich in lysine) and has potential to complement sorghum which is rich in sulfur containing amino acids (Pracha and Chulalak, 2000).

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Thus, the blending of sorghum and soya in appropriate proportion will make up the individual deficiencies. It has been previously reported that extruded cereal-legume products have higher protein content, high protein efficiency ratio, and improved amino acid profile (Narayan *et al.*, 2007; Alex *et al.*, 2009; Vargas-Solorzano *et al.*, 2014).

From nutritional and economic point of view, fortifying sorghum with soybean flour for the production of extruded product appears to be promising. Mainly the studies involving extrusion of sorghum-based material are focused on physical and/or nutritive properties of the expanded products. The effect of extrusion on the system parameters and functional properties of sorghum-based products has not been studied in detail. Hence, the present study was conducted to investigate the effects of feed formulation and extrusion conditions on the extrusion system parameters and physical sorghum-soya extruded properties of a Response product using Surface Methodology (RSM).

RSM is a statistical mathematical method that uses quantitative data in an experimental design to determine and simultaneously solve multivariate equations to optimize processes and products. RSM is also a useful tool to minimize the numbers of trials and provide multiple regression approach to achieve optimization (Dibyakanta and Gopirajah, 2012).

MATERIALS AND METHODS

Materials

Sorghum (DSV-4 variety) and Soybean (MAUS-2 variety) grains were procured from Directorate of Sorghum Research, Hyderabad, India, and AICRP on Soybean, Bangalore, India, respectively. After thorough cleaning, both sorghum and soya grains were ground to flour in a laboratory scale hammer mill, equipped with 60-mesh IS sieve.

Extrusion Cooking

Extrusion experiments were performed on a laboratory scale co-rotating twin-screw extruder (Basic Technology Pvt. Ltd., Kolkata, India). The length to diameter ratio (L/D) was 8:1. The extruder had two barrel zones. Temperature of the first zone was maintained at 74°C throughout the experiments, whereas at the second zone (die section) was varied according to the experimental design. The circular die of 3.0 mm was used in the entire study. Blends of sorghum and soya flour were prepared as per the experimental design using a ribbon blender (GL Extrusion Systems, New Delhi, India) for 20 minutes. Simultaneously, the moisture content of the blends were also ascertained. Moisture conditioning of blends done through moisture addition were (AACC, 1983; Liu et al., 2000).

Preconditioned feed mixture was metered into the extruder by a twin-screw volumetric feeder equipped with it. The speed of the feeder screw was adjusted so as to get a feed rate of 5 kg h⁻¹ for the entire study. Extruded samples were collected in stainless steel trays for 5 minutes after the extruder system parameters (PT and MT) reached a steadystate condition. The trays were then kept in a cabinet drier (MSW-216, Marco Scientific Works, New Delhi) at 60°C for 1 hour and cooled to room temperature. The dried samples were stored in polythene bags at room temperature ($25\pm4^{\circ}C$) until analyzed. All trials were conducted in 3 replications.

Experimental Design and Statistical Analysis

RSM was used to investigate the effects of SL and extrusion conditions on the process and product responses. The independent variables considered for this study were: Soya Level (SL): 10-30%; Feed Moisture (FM): 12-20% wb; Barrel Temperature (BT): 110-150°C, and Screw Speed (SS): 250-450 rpm. The levels of each variable were established according to the literature and preliminary

trials. Dependent variables were the product temperature (PT), motor torque (MT), specific mechanical energy (SME), expansion ratio (ER), bulk density (BD), hardness (H), crispness (C), water absorption index (WAI), and water solubility index (WSI). Central composite rotatable design was used to design the experiment. The design required 30 experimental runs (6 central, 8 axial, and 16 factorial points). Regression analysis was done to assess the effects of *SL*, *FM*, *BT* and *SS* on dependent variables. The experimental data obtained were analyzed after fitting them into a second order polynomial model

$$y_i = b_o + \sum_{i=1}^4 b_i X_i + \sum_{i=1}^4 \sum_{j=1}^4 b_{ij} X_i X_j$$

Where, X_{i} , X_iX_i , and X_iX_j are linear, quadratic, and interaction effect of the input variables which influence the response y, respectively, and b_o , b_b and b_{ij} are the regression coefficients to be determined. RSM was applied using a commercial statistical package, Design-Expert version 8.0.7 (Stat-Ease Inc., Minneapolis, USA), for the generation of response surface plots. The adequacy of the models was determined using model analysis, lack-of-fit test and coefficient of determination (\mathbb{R}^2) analysis.

Determination of Responses

System Responses

PT and MT as displayed on the extruder control panel were recorded twice, in the beginning and the end of product collection. *SME* (Wh kg⁻¹) was calculated from the rated screw speed (1445 rpm), motor power rating (5.5 kW), actual screw speed, percentage *MT*, and mass flow rate (5 kg h⁻¹) using the following formula (Normell *et al.*, 2009):

Expansion Ratio

To determine the *ER*, the cross-sectional diameter of the extrudates was determined with a digital Vernier caliper. The ratio of diameter of extrudate and the diameter of die was used to express the expansion of extrudate (Pansawat *et al.*, 2008). The *ER* values were obtained from 10 random samples for each extrusion condition.

Bulk Density

BD was calculated by measuring the actual dimensions of the extrudates. After weighing the extrudate, its diameter and length were measured using a digital Vernier caliper. The *BD* was estimated using the following formula, assuming a cylindrical shape of the extrudate (Sibel and Fahrettin, 2008).

Bulk density=
$$\frac{4m}{\pi d^2 1}$$

Where, m is mass of the extrudate (g), d is diameter (cm), and l is the length (cm). Ten pieces of extrudates were randomly selected and their average taken.

Texture

Force-deformation data for each extrudate were obtained using a Texture Analyzer (TA HDi, Stable Micro Systems Ltd., UK) fitted with 50 kg load cell and 2 mm diameter test probe. Tests were conducted in compression mode and the probe was allowed to penetrate the product a depth of 3 mm. The peak force in N was taken as a measure of H (Meng *et al.*, 2010) whereas C was measured in terms of number of positive peaks (Subir *et al.*, 2011). The test settings included pre-test speed of 5 mm s⁻¹, test speed of 2 mm s⁻¹, and post-test

$$SME = \frac{actual \ screw \ speed, \ rpm}{rated \ screw \ speed, \ rpm} \times \frac{\% \ motor \ torque}{100} \times \frac{motor \ power \ rating, \ kW}{mass \ flow \ rate, \ kg/h} \times 1000$$

speed of 5 mm s⁻¹. Force-deformation curve was recorded and analyzed using an inbuilt software program. Ten randomly collected samples were measured for each extrusion condition and the mean of the observations was recorded.

Water Absorption and Solubility Indices

WAI and WSI of extrudates were determined by a method used by Sibel and Fahrettin (2008). The extrudate samples were ground and sieved through 500 µm sieve. A 0.5 grams of sample (extrudate flour) was weighed into a centrifuge tube along with 10 mL of distilled water at 25°C and thoroughly mixed to produce a smooth dispersion. Samples were allowed to settle for 30 minutes with intermittent shaking for every 5 minutes, then, centrifuged (SIGMA 3-18K, SciQuip, UK) at 1,800×g for 15 minutes. The supernatant was decanted into a tared aluminum pan and dried to constant weight at 105°C. The weight of the gel remaining in the centrifuge tube was noted. The results were expressed as the average of two measurements.

WAI,
$$g/g = \frac{\text{Weight gain by gel}}{\text{Dry weight of extrudate}}$$

WSI, $\% = \frac{\text{Weight of dry solids in supernatant}}{\text{Dry weight of extrudate}} \times 100$

Optimization

Optimum values of the processing variables were obtained with the help of the numerical optimization technique of the Design-Expert software (ver. 8.0.7). The software necessitates assigning goals to the processing variables and the responses. The software was used to generate optimum processing conditions and also to predict the corresponding response.

RESULTS AND DISCUSSION

Effects of extrusion conditions on the process and product responses are shown in

Table The 1. estimated regression coefficients of the second order polynomial models for the various responses and their statistical validity defining values are reported in Table 2. The regression models for all the responses were highly significant (P < 0.01), with a high coefficient of determination ($R^2 > 0.86$). Furthermore, Fvalues reflected that all the models were significant. Coefficient of variation being lower than 10 per cent suggests the reasonable accuracy of the experiments and reproducibility of the models. Non significant lack-of-fit (P< 0.05) indicate that models correlated well with the the measured data.

Process Response

Product Temperature (PT)

The predicted response model (Table 2) indicated that the linear effects of *FM*, *BT*, and *SS*, and the quadratic effects of *BT* and *SS* were the determining factors for *PT*. Among the four variables, *BT* had a prominent effect on *PT*. The response surface plots [Figure 1, (a and b)] showed that increase in *BT* and *SS* led to an increased *PT*, whereas increase in *FM* lowered the *PT*. The interaction term *BT-SS* had a significant (P<0.1) negative effect. *PT* values ranged between 116 and 156°C (Table 1).

PT plays an important role in changing the rheological properties of the extruded melts, which in turn affects the degree of expansion. The recorded temperatures were higher than the set BT (110-150°C), which could be due to the generation of heat through dissipation of mechanical energy during extrusion. Frame (1994) reported that the heat was generated during extrusion by inter-particulate friction, and friction between the material, the screw elements, and the barrel. Similar results were observed by Pansawat et al. (2008) and Meng et al. (2010). The significant (P< 0.05) negative effect of FM could be due to the reason that

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E	Extrusion con	ndition		Pro	cess respons	es			Product r	esponses		
SL^{a}	FM^{b}	\mathbf{BT}^c	SS^{q}	PT e	MT^{f}	SME ⁸	ER^{h}	BD^{i}	Hardness	Crispness	WAI^{j}	WSI ^k
$(0_0')$	(% wb)	(°C)	(rpm)	(°C)	(0_0)	(Wh kg ⁻¹)		(kg m ⁻³)	(N)		$(g g^{-1})$	(%)
15	14	120	300	126	50.65	115.67	3.096	196	156.1	19.0	4.68	18.36
25	14	120	300	126	49.77	113.65	2.551	231	197.2	16.9	4.12	18.55
15	18	120	300	124	46.25	105.63	2.643	275	178.1	23.2	4.88	18.28
25	18	120	300	125	50.58	115.52	2.357	285	217.8	17.0	4.32	17.70
15	14	140	300	144	45.39	103.65	3.123	155	80.2	27.3	4.32	20.75
25	14	140	300	143	44.14	100.8	2.619	202	115.5	26.2	4.24	19.35
15	18	140	300	142	38.36	87.61	2.894	200	165.9	22.6	5.35	15.94
25	18	140	300	141	35.61	81.33	2.532	270	166.3	19.1	4.59	17.51
15	14	120	400	134	48.12	146.53	3.166	132	84.1	25.2	4.56	22.51
25	14	120	400	134	40.42	123.09	2.842	164	100.4	24.3	3.78	22.97
15	18	120	400	127	35.75	108.86	2.843	248	214.7	20.5	4.80	18.92
25	18	120	400	128	35.41	107.81	2.518	291	240.7	18.3	4.29	19.41
15	14	140	400	143	38.36	116.81	3.279	103	39.4	29.4	4.28	23.21
25	14	140	400	145	35.54	108.22	2.864	153	51.9	26.8	3.89	22.48
15	18	140	400	142	30.87	93.99	3.045	169	195.0	22.3	4.82	19.45
25	18	140	400	143	30.25	92.11	2.655	268	180.5	19.5	4.45	19.72
10	16	130	350	142	41.46	110.45	3.475	131	70.6	26.4	4.76	18.24
30	16	130	350	139	46.89	124.92	2.666	226	116.1	25.7	4.16	19.71
20	12	130	350	142	41.59	110.82	2.889	159	110.1	23.6	4.07	21.10
20	20	130	350	135	30.66	81.68	2.609	377	295.2	17.3	5.01	14.59
20	16	110	350	116	46.20	123.09	2.617	175	194.5	20.3	4.32	18.47
20	16	150	350	156	35.49	94.56	3.004	134	93.4	27.8	4.20	22.41
20	16	130	250	134	45.96	87.47	2.694	244	167.6	22.2	4.27	16.41
20	16	130	450	140	37.40	128.11	2.938	157	96.7	26.5	4.22	22.34
20	16	130	350	136	42.37	112.89	2.846	157	59.3	27.8	4.39	19.21
20	16	130	350	141	35.68	95.06	2.861	167	73.0	27.6	4.14	19.51
20	16	130	350	137	38.36	102.21	2.798	169	65.9	26.9	4.25	19.72
20	16	130	350	141	36.86	98.22	3.004	150	71.4	25.1	4.36	20.10
20	16	130	350	139	38.22	101.84	2.894	175	82.6	27.5	4.43	18.14
20	16	130	350	140	36.83	98.14	2.824	169	79.9	28.5	4.46	19.92

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				R	egression coeffic	cients			
	PT "	\mathbf{MT}^{f}	SME ⁸	ro h	BD^{i}	Hardness	Cuicanacco	\mathbf{WAI}^k	MSI ¹
Parameters	(°C)	(%)	$(Wh kg^{-1})$	EK	(kg m ⁻³⁾	(N)	Crispiless	$(g g^{-1})$	(\mathscr{Y}_{0})
Intercept	139.00	38.05	101.39	2.87	164.5	72.01	27.23	4.334	19.433
X_1^a	-0.125	-0.05	-0.30	-0.2^{***}	24.0^{***}	10.33^{***}	-0.94^{**}	-0.22^{***}	0.092
\mathbf{X}_2^{-b}	-1.54^{**}	-2.97^{***}	-8.08^{***}	-0.11^{***}	46.1^{***}	46.00^{***}	-1.88^{***}	0.23^{***}	-1.43^{***}
$\mathbf{X}_{3}{}^{c}$	8.29***	-3.33^{***}	-8.72^{***}	0.07^{***}	-16.0^{***}	-24.86^{***}	1.82^{***}	0.01	0.40*
\mathbf{X}_4^{d}	1.54^{**}	-3.46^{***}	6.45^{***}	0.08^{***}	-19.2^{***}	-13.01^{***}	0.98^{***}	-0.07^{**}	1.42^{***}
$\mathbf{X}_1 \mathbf{X}_2$	0.06	0.83	2.35	0.02	3.6	- 3.36	-0.50	-0.02	0.20
$\mathbf{X}_1 \mathbf{X}_3$	- 0.06	-0.18	-0.18	-0.01	9.1^{**}	-5.58^{**}	0.089	0.05	-0.05
$X_1 X_4$	0.31	- 0.68	-2.10	0.01	3.9	-4.78*	0.276	-0.00	0.04
$\mathbf{X}_2 \mathbf{X}_3$	0.56	-0.46	-0.83	0.03*	-5.1	6.69^{**}	-1.24^{***}	0.08*	-0.32
$\mathbf{X}_2 \mathbf{X}_4$	- 0.56	- 0.69	-3.01	-0.01	11.1^{***}	23.50^{***}	-1.10^{**}	0.00	-0.38
$X_3 X_4$	- 1.19*	0.56	0.12	-0.00	1.1	3.02	-0.58	- 0.03	0.02
X_1^2	-0.05	1.57^{***}	4.06^{***}	0.04^{***}	4.9*	6.33^{***}	-0.52	0.05	-0.08
\mathbf{X}_2^2	-0.55	-0.44	- 1.29	-0.04^{**}	27.3^{***}	33.65^{***}	-1.92^{***}	0.07^{**}	-0.30
X_3^2	-1.17^{**}	0.74	1.85	-0.02	- 1.08	18.98^{***}	-1.02^{***}	-0.00	0.35^{**}
\mathbf{X}_4^2	-0.93*	0.95*	1.59	-0.02	10.42^{***}	16.04^{***}	-0.95^{***}	-0.01	0.09
ANOVA									
\mathbb{R}^2	0.94	0.887	0.86	0.955	0.973	0.987	0.908	0.884	0.890
Model F-value	18.6^{***}	8.41^{***}	6.87^{***}	22.6^{***}	38.62^{***}	82.5***	10.6^{***}	8.1^{***}	8.6^{***}
Lack of fit (p value)	0.242	0.311	0.301	0.536	0.119	0.3115	0.17	0.190	0.182
C.V, %	1.95	6.88	7.01	2.56	7.10	7.79	6.84	3.60	4.90
^{<i>a</i>} Coded soya level; ^{<i>b</i>} Code Expansion Ratio, ^{<i>i</i>} Bulk De (P< 0.01).	d feed moisture nsity, ^k Water A	s; ^c Coded barre Absorption Index	l temperature; ^d , Water Solubil	Coded screw s ity Index. * Sig	peed; ^e Product gnificant at 10%	Temperature; ^f N (P< 0.1); ** Sig	Motor Torque; ⁸ mificant at 5% (Specific Mecha P< 0.05), *** S	nnical Energy; ^h ignificant at 1%



Figure 1. Response surface plots for *PT* as a function of (a) *BT* and *FM* (b) *SS* and *SL* while other variables are at center point

the water acts as a plasticizer in the extruder; therefore any increase in FM reduces the melt viscosity and dissipation of mechanical energy (Ilo et al., 1996). SS had a significant (P < 0.05) positive effect on *PT*. This may be attributed to dependence of shear or mechanical energy on SS (Meng et al., 2010). A higher screw speed generates a greater amount of mechanical energy or frictional heat and, hence, increases PT. Furthermore, mean residence time also influence heat generation and mass temperature. Decrease in PT at very high SS (Figure 1-b) could be due to reduced mean residence time at high SS.

Motor Torque and Specific Mechanical Energy

MT provides information about the amount of energy absorbed by the material, while SME is the mechanical energy input per unit mass of the extrudate (Altan et al., 2008; Pansawat et al., 2008). The regression analysis results (Table 2) indicated that the liner terms of FM and BT had a significant (P < 0.01) negative effect on MT and SME, while SS had a significant negative effect on MT and positive effect on SME. The effect of SL was mainly quadratic (P < 0.01). interaction However. between the independent variables had no significant effect. The measured *MT* values ranged from 30.25% to 50.65 per cent and the calculated *SME* from 81.33 to 146.53 Wh kg⁻¹ (Table 1).

Any variable affecting the viscosity of the food melts in the extruder would correspondingly effect MT and SME (Akdogan, 1996). Elevating the BT or FM caused a decline in the melt viscosity, consequently, decreasing the SME (Figure 2) and MT. The degree of fill in the extruder barrel manipulates the torque requirement (Jin et al., 1994; Meng et al., 2010). At a constant feed rate, an increase in SS decreased the length of filled flights resulting in reduced load on the screw shaft thereby lowering the MT (Figure 3). Although a decrease in SME was expected as melt viscosity would decrease with increasing SS, the present study indicates that the effect of SS dominates the effect of melt viscosity. This could be attributed to the increased shear rate with increase in SS and is a well-documented observation in various studies (Akdogan, 1996; Altan et al., 2008; Normell et al., 2009). The significant effect (P< 0.01) of quadratic term of SL on MT and SME implies a considerable increase in these two responses after a certain level of soya. This is also reflected on the surface plot (Figure 3) with a curved surface. This result revealed that the viscosity effect, at lower levels of soya, was dominated by the



Figure 2. Response surface plot for SME as a function of FM and BT while other variables are at center point.

binding action of high protein content in the feed blend at high *SL*.

Product Response

Expansion Ratio and Bulk Density

ER and BD describe the degree of expansion undergone by the melt as it exits the extruder, while ER considers expansion only in the direction perpendicular to the extrudate flow, BD considers expansion in all directions (Altan et al., 2008). The regression results (Table 2) indicated that all the investigated variables had a significant (P< 0.01) effect on ER and BD. ER was significantly affected by the quadratic term of SL, while BD by BT and SS. Interaction terms of SL-BT and FM-SS were found to be significant on BD. The ER of extrudates varied between 2.357 and 3.475, while BD varied between 103 and 377 kg m⁻³ (Table 1).

The significant effect of FM on ER and BD could be due to either changed molecular structure of amylopectin, which reduces the melt elasticity (Ilo *et al.*, 1996), or extrusion cooking is not enough to cause vaporization of moisture resulting in reduced expansion and increased density (Asare *et al.*, 2012). Increase in BT increased ER



Figure 3. Response surface plot for *MT* as a function of *SL* and *SS* while other variables are at center point.

while reducing BD, probably due to enhanced gelatinization of starch, which increases the volume of extrudates (Case et al., 1992). In addition, high temperature provides higher potential energy for flashoff of super-heated water from extrudates with increased linear velocity at the die favoring expansion (Koksel et al., 2004). At low moisture levels, ER increased with BT before it reached a critical level after which it declined (Figure 4). This may be caused by dextrinization of starch and weakening of structure (Dogan and Karwe, 2003). ER decreased and BD increased with increase in SL. This could be attributed to the dilution effect of soya on starch, which may affect the extent of starch gelatinization and, thus, the rheological properties of the melted material (Sibel and Fahrettin, 2008). The significant (P < 0.01) negative effect of SS on BD (Figure 5) and ER could be attributed to the structural breakdown under increased shear environment. Increasing SS tends to increase the shearing effect, this causes protein and starch molecules to be stretched farther apart, weakening bonds and resulting in a puffer product (Filli et al., 2012). The effect of FM and SS were found to be dependent on each other (Table 3). Similar results have been reported earlier for different types of the extruded products



Figure 4. Response surface plot for ER as a function of FM and BT while other variables are at center point.

(Meng *et al.*, 2010, Asare *et al.*, 2012; Filli *et al.*, 2012).

Hardness and Crispness

Hardness (H) of the expanded extrudates is a sensory perception of the human being and is associated with expansion and cell structure of the product, while crispness (C) is typically a textural attribute (Meng et al., 2010). *H* and *C* were significantly (P < 0.01) affected by the linear terms of all predictor variables. Increasing SL and FM and decreasing BT and SS significantly increased H, while reducing C (Table 2). The variables also had a significant quadratic effect (P< 0.01) on H and C, except SL on C. Comparing the regression coefficients, it was observed that the FM had a maximum influence on H and C, followed by the BT, SS, and SL. Hardness of the extrudates varied between 39.4 and 295.2 N, while C, as the number of positive peaks, ranged between 16.9 and 29.4 (Table 1).

Chang *et al.* (1998) suggested that the degree of expansion affects density, fragility, and softness of the extruded products. *H* increased (Figure 6) and C decreased with increase in *SL* and *FM*. This is in agreement with the degree of cooking, as indicated by *ER* in this study. Increasing *SL* and *FM* decreased the degree of starch



Figure 5. Response surface plot for *BD* as a function of *SS* and *SL* while other variables are at center point.

gelatinization and, as a result, pore wall became thicker and hard and heavy product was obtained (Adrian et al., 2008). This result is in consistent with those of Liu et al. (2000), Li et al. (2005) and Normell et al. (2009). The significant (P < 0.01) negative effect of BT on H is in line with the BD, where an increase in BD was observed (Table 2). Ding et al. (2005) reported that the increase in BT would decrease the melt viscosity, but increases the vapor pressure of water which favors the bubble growth and, consequently, expansion. Thus increase in BT resulted in a soft and crispy product. Similar results were reported by Altan et al. (2008). Increase in SS increased C (Figure 7) while reducing H. This may be attributed to the relative increase in the amount of mechanical energy delivered to the extruded material at higher SS. In this study, this could be explained by the significant positive influence of SS on SME (Table 2). This increased mechanical energy delivered to the material at higher SS might have enhanced starch conversion, leading to crispier product (Meng et al., 2010). The interaction between FM and SS was significant (P< 0.01), which means that the higher values of H at high levels of FM were dependent on SS. Similar effect of SS has been observed in corn (Altan et al., 2008), barley (Liu et al., 2000) and chickpea (Meng et al., 2010) based extrudates.



Figure 6. Response surface plot for hardness as a function of FM and SL while other variables are at center point.

Water Absorption and Water Solubility Indices

WAI and WSI are two important measures related to the degree of starch conversion or damage as a result of extrusion processing (Normell et al., 2009). WAI measures the amount of water absorbed by starch and can be used as an index of starch gelatinization, while WSI indicates degradation of starch molecules (Sibel and Fahrettin, 2008). The statistical analysis demonstrated that linear terms of SL, FM and SS had a significant effect on the WAI and WSI, with the exception of SL on WSI. The interaction between the variables had no significant effect, except FM and BT interaction on WAI (P < 0.1). The quadratic terms of *FM-BT* had a significant (P< 0.05) positive effect, respectively, on WAI and WSI. The value of *WAI* ranged between 3.78 and 5.35 g g^{-1} dry sample, while WSI varied between 14.59 and 23.21% (Table 1).

The WAI decreased significantly (P < 0.01) as SL increased (Figure 8), mainly because of reduction in the starch content. Relative decrease in starch content with addition of soya may affect the extent of starch gelatinization in barrel and caused reduced



Figure 7. Response surface plot for crispness as a function of *SS* and *SL* while other variables are at center point.

water absorption. Similar effects of adding non-starch components on WAI have been reported earlier for millet-legume blend (Subir et al., 2011). It is generally agreed that FM exerts the greatest effect on the extrudate by promoting gelatinization (Ding et al., 2005). At high moisture content, the viscosity of the starch would be low, which allows extensive internal mixing and uniform heating that would account for enhanced starch gelatinization while diminishing starch degradation (Miranda et al., 2011). Further, low moisture conditions results in greater shear degradation of starch during extrusion (Anastase et al., 2006). Therefore, WAI increased and WSI decreased with increase in FM. Similar effects were reported earlier for rice based extrudates (Ding et al., 2005). The significant (P< 0.05) negative effect of SS on WAI suggests that higher SS degraded starch into smaller fragments, which are more soluble in water. High input of thermal energy due to high residence time (at low SS) may enhance starch degradation and increase WSI (Figure 9). The effect of SS on molecular degradation and gelatinization of starch is in agreement with van den Einde et al. (2004) and Normell et al. (2009). WSI is reported to be related to the presence of soluble molecules that have sometimes been



Figure 8. Response surface plot for *WAI* as a function of *SL* and *SS* while other variables are at center point.

attributed to dextrinization (Anastase *et al.*, 2006). The significant (P< 0.05) quadratic positive effect of *BT* on *WSI* could be probably due to increased dextrinization at higher *BT*.

Optimization

Optimization was carried out under the following constraints: maximize soya level, *ER*, *SME*, *C*, *WAI*, and *WSI*; minimize *BD* and *H*. The optimum conditions obtained for *SL*, *FM*, *BT*, and *SS* were 14 per cent, 14 per cent wb, 129°C and 422 rpm, respectively. The corresponding optimum values of *ER*, *SME*, *C*, *WAI*, *WSI*, *BD* and *H* were 3.319, 140 Wh kg⁻¹, 27, 4.33 g g⁻¹, 23.45 per cent, 102.2 kg m⁻³, and 42 N, respectively.

CONCLUSIONS

This study analyzed the effect of processing variables on the responses of extrudates manufactured from different blends of sorghum and soybean. The models were found to be statistically valid and provided adequate information regarding the behavior of the responses upon variation in the processing variables. The results showed that various levels of soybean could be



Figure 9. Response surface plot for *WSI* as a function of *SS* and *SL* while other variables are at center point.

incorporated into extruded sorghum based snacks depending on the desired qualities of the product. The products with high ER and C and low BD and H, which are generally good characteristics of extruded snacks, were produced at low FM, high SS, medium to high BT, and medium SL. The study confirms the feasibility of developing nutritious snack food from sorghum-soya by extrusion processing.

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خروجی مخلوط سورگم و سویا از دستگاه روزن ران مضاعف: تجزیه به روش سطح واکنش

ت. و. آرون کومار، د. و. ک. ساموئل، س. ک. جها، و ج. پ. سینها

چکیدہ

برای تولید یک محصول، مخلوط آرد سورگم و سویا در یک دستگاه اکسترودر یا روزن ران مضاعف(SL)، مقدار سویا(SL) و همچرخ فرآوری شد. برای بررسی اثرهای مقدار سویا(SL)، رطوبت خوراک(FM) feed moisture (FM) ، و سرعت پیچ(SS) ، روی پارامترهای دستگاه و ویژگی های مواد خروجی از دستگاه مزبور از تجزیه به روش سطح واکنش (پارامترهای دستگاه و ویژگی های مواد خروجی از دستگاه مزبور از تجزیه به روش سطح واکنش (BD)، محصول(PT)، گشتاور موتور(MT)، انرژی مکانیکی ویژه(SME)، جرم مخصوص (BD) سفتی(H)، تردی و شکنندگی(C)، نمایه جذب آب(WAI)، و نمایه حلالیت در آب(WSI). سپس به منظور تعیین واکنش ها به صورت تابعی از متغیر های فرآیند فرآوری، ازمدل چند جمله ای درجه دوم استفاده شد. نتایج نشان داد که BT،FM ، و SS اثرهای معنی داری روی همه واکنش ها داشتند به اثر گذاشت. همه مدل ها از نظر آماری معنی دار بودند (O.S) مینی می داری روی RT، BD، و استند به اثر گذاشت. همه مدل ها از نظر آماری معنی دار بودند (O.S) ، نایر بودا. بنا بر تاییج، مخلوط سورگم-سویای حاصله از دستگاه روزن ران محصولی قابل تولید بود و مقدار بهینه متغیر های فرایند فرآوری به این قرار مشخص شد:۲۱٪=SL ، مبنای تر ۱۴٪=FM ، حرارت بشکه برابر °C