Quality evaluation of millet-soy blended extrudates formulated through linear programming

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Abstract Whole pearl millet, finger millet and decorticated soy bean blended (millet soy) extrudates formulations were designed using a linear programming (LP) model to minimize the total cost of the finished product. LP formulated composite flour was extruded through twin screw food extruder at different feed rate (6.5–13.5 kg/h), screw speed (200–350 rpm, constant feed moisture (14% wb), barrel temperature (120 °C) and cutter speed (15 rpm). The physical, functional, textural and pasting characteristics of extrudates were examined and their responses were studied. Expansion index (2.31) and sectional expansion index (5.39) was found to be was found maximum for feed rate and screw speed combination 9.5 kg/h and 250 rpm. However, density (0.25×10^{-3} g/mm³) was maximum for 9.5 kg/h and 300 rpm combination. Maximum color change (10.32) was found for 9.5 kg/h feed rate and 200 rpm screw speed. The lower hardness was obtained for the samples extruded at lowest feed rate (6.5 kg/h) for all screw speed and feed rate at 9.5 kg/h for 300–350 rpm screw speed. Peak viscosity decreases with all screw speed of 9.5 kg/h feed rate.

Keywords Linear programming · Millet · Soy bean · Extrusion · Texture

Introduction

Expanded products like snacks and breakfast cereals are very popular today because of their crunchy texture,

which arises from the honeycomb structure imparted to the material during extrusion (Barrett and Peleg 1992). Ready-To-Eat snacks/Breakfast cereals has dramatically transformed the cereal industry, the key being quality-extruded products offered to consumers at competitive prices (Lin et al. 2002; Yeh and Jaw 1999). Snack foods now comprise an important part of the daily nutrient and calorie intake of many consumers. They can be sweet or savory, light or substantial, and many even are endowed with attributes such as ‘Healthy’ or ‘just for fun’ (Desrumaux et al. 1999). Advantages of extrusion cooking are exhaustively studied by many researchers (Camire et al. 1990; Parker et al. 2000; Eastman et al. 2001). Increasing amount of time spent away from home has led to an increase in snacking (Euromonitor 2001) and now consumers see eating as something to be done while you do something else (Calder 2000). Nutritional features of food are becoming increasingly relevant determinants of consumption patterns for Indian households. Over the last decades, income growth and consequent decrease of food expenditure compared with total consumption, have progressively diverted consumers' attention toward qualitative aspects in the choice of foods. Snacks generally made from corn, wheat, rice and oats, while other cereals such as pearl millet, finger millet, barley, rye, sorghum and triticale have not been used extensively so far (Moore 1994). Pearl millet and finger millet could seek great potential as an ingredient in extruded snacks or breakfast cereals (Riaz 1997) because of its lower cost. Several cereal and soy based food products had been developed so far to enhance protein content (Chemmanur et al. 1992; Adesina et al. 1998). Soybean and legumes contain lectins, trypsin and alpha amylase inhibitors are inactivated and in addition, starch and protein digestibility get increased during extrusion cooking. In the expanded products,

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compact structure resulting from extrusion process can lead to a dense protein network reducing the availability of starch granules to attack by alpha-amylase (Fardet et al. 1999). Peak and final viscosities are important parameters, to have an understanding of product behaviour during and after processing. Liang and King (2003) reported on the pasting effects of lipids and amino acids on rice starch and various reports suggested that pasting characteristics (Lai 2001), rheological properties of paste and gels (Kim et al. 1995; Wiesenborn et al. 1994) and other functional properties (Zobel 1984) of flour and starches vary with species and variants.

Linear programming analysis is an operational research approach that is used to model complex multi factorial problems, including diet-related problems. Product formulation could be done more effectively using a computer-based modeling approach to reduce the errors and biases that can occur when using a consultation process alone. Thus, for any food product development, many factors affect its preference and acceptability. Some factors are intrinsic to the product, such as physical, textural, sensory and other factors are extrinsic, such as social and cultural factors (Deliza et al. 1996). Marketing studies regarding the determinants of food consumption have consistently shown that consumer choices are largely determined by taste (Drewnowski 1997). Thus, keeping in view the commercial potential by underutilized millet crops and highly nutritious soybean, the present study has been planned to optimize the process parameters to develop protein rich low cost extruded snack food using linear programming.

Materials and methods

Preparation of composite flour The raw materials viz., pearl millet (*Pennisetum typhoides*), finger millet (*Eleusine coracana*), and soybean (*Glycine max*) were procured from local market and were cleaned to remove all foreign matter, broken and immature grains, if any. Soybean was decorticated using multi grain pearler. All the grains were ground in burr mill separately to get fine flour (0.589 mm) sieve. Then composite flour was obtained in desired proportion by mixing in flour mixer. Flour samples were then extruded through twin screw extruder.

Linear programming formulation A linear programming model was developed to formulate low cost composite flour mixture based on pearl millet, finger millet and soybean to fulfill Recommended Dietary Allowance (RDA) the protein, energy and calcium requirement profile (ICMR 1989). Formulation was designed with varying quantities of the ingredients as shown in Table 1. Three types of restrictions were set upon the variables: 1) minimum and maximum quantities of ingredients to be included; 2) protein, calcium and energy supply of each ingredient; and 3) material balance. The objective function established was:

$$\text{Min } Z = C_i X_i \quad (1)$$

where, Z is the cost per kilogram of formulation; C_i is the cost of ingredient; and X_i is the proportion in which ingredient are used in the formulation. Based on the data given in Table 1, food formulation was developed by using linear programming software (Arsham 2003). Following assumptions were made (i) Serving size: 150 g, (ii) LPP was performed for 100 g sample and (iii) 1/3 of RDA for sedentary workers was taken.

The low cost composite flour (Rs 12/kg) obtained using linear programming is pearl millet (81.68%), finger millet (7.02%) and decorticated soybean (11.29%) (Table 2).

Experimental design The effects of extrusion cooking conditions on millet-soy based extrudates properties were studied. Results from preliminary trials were used to select suitable extrusion cooking conditions including screw configuration and die size, and to reduce the number of variables in the experimental design. Linear programming formulated composite flour was extruded through twin screw food extruder at different feed rate (6.5, 9.5, 11.5 and 13.5 kg/h), screw speed (200, 250, 300 and 350 rpm) at constant feed moisture (14% wb), barrel temperature (120 °C) and cutter speed (15 rpm). The extrudates prepared from millet-soy blended extrudates using twin screw extruder are shown in Fig. 1.

Extrusion cooking condition The raw grains were conditioned to moisture level of 14% (wb) and kept for overnight to equilibrate the moisture (Singh et al. 2000) and mixed with ribbon blender. Extrusion cooking was performed on a twin screw food extruder (BTPL lab model, India), driven by 10 hp AC motor. The feeder and cutter were controlled

Table 1 List of variables, ingredients, and cost for LPP food formulation

Variable	Ingredient	Cost ^a (Rs/kg)	Protein (%)	Energy (Kcal)	Calcium (mg)
X ₁	Pearl millet	07.00	11.6	361	42
X ₂	Finger millet	08.00	7.3	328	344
X ₃	Decorticated soybean	20.00	43.2	432	240

^a Prices as of December 2009

Table 2 Formulation through linear programming

Objective function MIN Z : $0.7 X_1 + 2X_2 + 0.8X_3$		
Constraints	Equation	Test results
Protein (g/d)	$11.6X_1 + 43.2X_2 + 7.3X_3 = 20 = 20$	True (20=20)
Calorific value (kcal/d)	$361 X_1 + 432X_2 + 328X_3 \geq 800$	True (843 $\geq$ 800)
Calcium (mg/d)	$42 X_1 + 240 X_2 + 344 X_3 = 135$	True (135=135)
Ingredient (serving size)	$1 X_1 + 1X_2 + 1 X_3 = 1.5$	True (1.5=1.5)
Limitation	$0 X_1 + 1X_2 + 0X_3 = 0.15$	True (0.1053 $\geq$ 0.15)
Status: Optimal		MIN Z: 1.2039
Degeneracy: No		$X_1=1.2253$
Test to constraints: Ok		$X_2=0.1053$
		$X_3=0.1694$

with 0.5 hp DC motor, separately. The length to diameter (L/D) ratio of the extruder was 5:1. The composite flour was fed into the extruder with a pre-calibrated twin-screw volumetric feeder. The screws were heated or cooled at two sections by a separate water circulation system. Barrel wall temperatures were measured by thermocouples. Steady-state conditions were assumed to have been reached when there were no visible drifts in percent torque, pressure and product temperature at the die for at least 5 min. Extruded rods through 3 mm circular die were cut through a constant cutter speed (15 rpm). Extruded samples were collected, cooled to room temperature under natural convection conditions and stored in low density polyethylene (LDPE) bags for further analyses.

Determination of products The extrudates produced were dried at 105 °C for 3 min before further analysis. The expansion index and sectional expansion index (SEI) was calculated using Eqs. 2 and 3 (Balasubramanian and Singh 2007).

$$\text{Expansion index} = \frac{\text{Diameter of extrudate}}{\text{Diameter of die}} \quad (2)$$

$$\text{Sectional expansion index} = \frac{(\text{Diameter of extrudate})^2}{(\text{Diameter of die})^2} \quad (3)$$

Fig. 1 View of extrudates with experimental design layout for constant feed moisture (14% wb) and cutter speed (15 rpm) at barrel temperature of 120 °C

Feed Rate (kg/h)	Main Screw speed (rpm)			
	200	250	300	350
6.5
9.5
11.5
13.5

Constant feed moisture (14% wb), Cutter speed (15 rpm)

Table 3 Textural analysis test conditions

Testing conditions	Textural attributes		
	Hardness	Puncture force	Breaking strength
Probe	P-75	P-5	HDP/BS
Strain/displacement	40%	40%	30 mm
Constant Load cell (kg)	5	5	5
Constant cross- head speed (mm/s)	1	1	1

Fig. 2 Response surface plot for **a** expansion index **b** sectional expansion index **c** specific length **d** product density of extrudates

Fig. 3 Response surface plots for **a** total colour change **b** water absorption index **c** water solubility index of extrudates

Specific length was calculated as the ratio of weight of extrudates to unit length of extrudates as shown in Eq. 4 (Fan et al. 1996).

$$\text{Specific length (g/cm)} = \frac{\text{Weight of extrudates}}{\text{Length of extrudates}} \quad (4)$$

Product density of the extrudate was calculated as the ratio of weight of extrudates to the volume of extrudates assuming a cylindrical shape of extrudate as given in Eq. 5.

$$\text{Density (g/mm}^3\text{)} = \frac{\text{Weight of extrudates}}{\text{Volume of extrudates}} \quad (5)$$

The color values of ground extrudates samples in terms of L, a and b were measured using HunterLab LabScan XE (Hunter Associates Laboratory Inc., Reston, Virginia, USA) (NR-3000; 10°/D65). Color values were recorded as L= lightness (0=black, 100=white), a (−a=greenness, +a = redness), and b (−b=blueness, +b = yellowness). Total color change was calculated using Eq. 6

Total color change

$$= \sqrt{(L - L_0)^2 + (b - b_0)^2 + (a - a_0)^2} \quad (6)$$

Where, the subscript '0' indicates initial color values of the raw material. For measuring water absorption index (WAI) (Eq. 7) and water solubility index (WSI) (Eq. 8) the extrudates were milled to a mean particle size (180–250 μm) (Singh and Smith 1997).

Water absorption index(%)

$$= \frac{\text{Weight of sediment}}{\text{Weight of dry solids}} \times 100 \quad (7)$$

Water solubility index(%)

$$= \frac{\text{Weight of dissolved solids in supernatant, g}}{\text{Weight of dry solids, g}} \times 100 \quad (8)$$

Textural evaluation of the extrudates was performed with texture analyzer (TA-HDi, Stable Micro Systems Ltd., UK) and settings are given in Table 3. Hardness, puncture force and breaking strength of extrudates was determined as the maximum force offered by extrudates during compression and three point cutter test, respectively (Onwulata et al. 2001). The breaking strength was calculated using Eq. 9.

$$\text{Breaking strength (N/m}^2\text{)} = \frac{\text{Peak breaking force}}{\text{Cross sectional area}} \quad (9)$$

Fig. 4 Response surface plot for textural parameters **a** Hardness **b** Puncture force **c** Breaking strength of extrudates

Rheological parameters The paste viscosity of extrudates powder was evaluated by Rapid Visco Analyser (RVA™), operated with Themocline 3.0 for Windows (TCW) software. In RVA, the short temperature profile (13 min) was used and the mixture was stirred at 960 rpm for 10 s and then at 160 rpm for the remainder of the test. A mixture of 3.0 g extrudate powder and 30.0 ml water was held at 50 °C for 1 min and subsequently, heated to 95 °C at 12.2 °C/min. Holding time at 95 °C was 2.5 min, subsequently the sample was cooled to 50 °C at 1.2 °C/min, where it was kept for 2.1 min. (Deffenbaugh and Walker 1990) All the experimentation was replicated five times and data was analyzed using Statistica (99 edition, kernel release 5.5, Statsoft Inc, USA).

Results and discussion

Pictorial view of extrudates Figure 1 illustrates the view of extrudates with experimental design layout for constant feed moisture (14% wb) and cutter speed (15 rpm) at barrel temperature of 120 °C of different extrudates. The extrudates produced at 9.5 kg/h feed rate and 250 rpm screw speed has maximum expansion index showing smooth surface of extrudates with uniform expansion diameter as compared to other combinations. The extrudates produced at 6.5 kg/h and 350 rpm expanded less yielding maximum density and rough extrudate surface.

Expansion index, sectional expansion index, specific length and density of extrudates Figure 2 shows the effects of independent variables on the expansion index, sectional expansion index, specific length and density of extrudates. The expansion index, sectional expansion index, specific length and density of extrudates were ranged between 2.05 to 2.31, 4.28 to 5.39, 83.16 to 130.65 g/cm and 0.249 to 0.463×10^{-3} g/mm³, respectively. Expansion index, sectional expansion index increased for feed rate between 6.5 to 9.5 kg/h and 200–300 rpm screw speed while with further increase of feed rate and screw speed showed reduced expansion. In contrast, the extrudate specific length is increasing with the increase of feed rate and screw speed. This was expected as length and diameter expansion are known to be inversely proportional (Launay and Lisch 1984). Also, lower extrudate density was found for the higher expanded extrudates i.e. inversely proportional to expansion index and sectional expansion index. The highest expansion index, sectional expansion index were measured for 9.5 kg/h feed rate and screw speed in the range of 250–300 rpm, whereas these values were found to be lower for highest feed rate and lowest screw speed levels. It was

reported by Chinnaswamy and Bhattacharya (1983) that the expansion index, sectional expansion index of extrudates depends mainly on its degree of gelatinization. Chiang and Johnson (1977), Bhattacharya and Hanna (1987) observed that these characteristics can also be determined by temperature, shear rate and moisture content of the feed material. Low moisture content of the starch may restrict the material flow inside the extruder barrel, increasing the shear rate and residence time, which would perhaps increase the degree of starch gelatinisation, and thus, expansion. However, when the feed moisture content is very low (below 10% wb.), it may create very high shear rates and longer residence times, and thus increase the product temperature. Several authors have cited that lower feed moisture contents and barrel temperature favoured the expansion of materials such as corn grits, corn starch (Gomez and Aguilera 1984), potato starch (Mercier 1977) and corn germ flour (Peri et al. 1983). Expansion generally decreases rapidly when moisture content increases (Guy and Horne 1988). Davidson et al. (1984) explained that when the extent of macromolecular degradation of starch increases, extrudates expansion ratio gets decreased.

Total color change, water absorption index and water solubility index of extrudates The variation among total color change, water absorption index and water solubility index of extrudates are shown in Fig. 3. Total color change, water absorption index and water solubility index of extrudates ranged from 3.3 to 10.32, 512.35 to 688.40% and 0.9 to 10.97%, respectively. The total color changes showed the effect of independent variables on the cooking

of the composite flour (Fig. 3). Maximum color change was found as 10.32 for 9.5 kg/h feed rate and 200 rpm screw speed. It was found that the extrudates having maximum color values were having maximum expansion index and minimum hardness. Thus, it can be an indicator of degree of cooking. A similar result was reported by Lo et al. (1998) that screw speed had a marked effect on extrudates color values. The light color of extrudates might be caused by the heat decomposition of pearl millet and finger millet pigments. However, the water absorption index and water solubility index for different extrudates were lower for lower feed rate for all the selected screw speed combination range. This is in agreement with Barnes et al. (1990) that the decrease in water absorption index with increasing screw speed and increase of water solubility index with decreasing feed rate indicated the extent of starch damage.

Hardness, puncture force and breaking strength of extrudates Hardness, puncture force and breaking strength of extrudates with respect to independent variables are shown in Fig. 4. The minimum and maximum values of hardness, puncture force and breaking strength of extrudates are 25.32 to 96.81 N, 8.91 to 29.22 N and 7.19 to 16.09 N/m². For constant barrel temperature (120 °C), feed rate and screw speed inversely affected the firmness of the extruded products. The lower hardness or crispy extrudates were obtained for the samples extruded at lowest feed rate (6.5 kg/h) for all screw speed and feed rate at 9.5 kg/h for 300–350 rpm screw speed. As the textural values were associated with the expansion index and extrudates with greatest expansion were softer and crispy. Politz et al.

Fig. 5 Response surface plot for RVA parameters **a** Peak viscosity and **b** Final viscosity of extrudates

(1994) cited that formulations containing high amylopectin levels were most prone to fragmentation. These authors also cited that it seemed that a thinner cell wall was formed in extrudates with greater radial expansion resulting in lower breaking strength. Similar trend was also followed by puncture force and hardness. Obviously, breaking strength does not showed much variation as compared to hardness, puncture force because of the extruder diameter in the denominator in the calculation. The reduction in the textural values may be due to decrease in air cell wall thickness.

Peak and final viscosity of extrudates Peak viscosity and final viscosity of extrudates measured using rapid visco analyzer are presented in Fig. 5. It is obvious that the peak viscosity shows a decreasing trend with the increase of screw speed at 9.5 kg/h feed rate. However the similar trend is not noticed in other feed rate and screw speed combination range. This trend is in corroboration with the expansion index, sectional expansion index and product density of extrudates. This is an expected trend, as extrudate samples are already gelatinized which enable them to hydrate faster than the raw sample. The minimum and maximum peak viscosity and final viscosity 141.67 to 370.67 cp and 2 to 69.33 cp, respectively for different feed rate and screw speed. It was noticed that the PV decreases with all screw speed of 9.5 kg/h feed rate. Heating slurries of completely gelatinized materials is known to cause a decrease in the viscosity leading to the ‘thinning’ of the slurry (Schweizer et al. 1986). However, during the heating phase, there was a decline in the rate of thinning, which could be ascribed to the counter effect of swelling of the partially gelatinized residual materials. This indicates structural and molecular changes in the starch granules and intensive degradation of the starch during extrusion cooking. Similar results were reported by Guha et al. (1998) that peak viscosity generally decreased with increasing screw speed and barrel temperature for rice extrudates.

Conclusion

Feed rate and screw speed were at constant barrel temperature (120 °C) and feed moisture (14%) shown to have a little effect on the expansion behaviour of pearl millet (81.68%), finger millet (7.02%) and decorticated soy bean (11.29%) composite flour as obtained through LPP. The maximum expansion index (2.31), sectional expansion index (5.39), specific length (130 g/mm) and density (0.25×10^{-3} g/mm³) were obtained for feed rate and screw speed combination 9.5 kg/h and 250 rpm, 9.5 kg/h and 250 rpm, 6.5 kg/h and 350 rpm, 9.5 kg/h and 300 rpm, respectively. Thus, it is understood that the process

variables affects the various product quality and organoleptic qualities of extrudates. Hence, the pearl millet based expanded snacks using twin screw extruder shows promising features for the production of low cost of extrudates.

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