Functional and physical properties of sorghum-based extruded product supplemented with soy meal flour

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Functional and physical properties of sorghum-based extruded product supplemented with soy meal flour

Solomon Abebaw Tadesse¹,²*, Geremew Bultosa³ and Solomon Abera⁴

Abstract: Effects of soy meal flour (0, 10, and 20%), barrel temperature (135, 150, and 165°C) and feed moisture content (15, 18, and 21%) on functional properties [water absorption index (WAI), water solubility index (WSI) and water holding capacity (WHC)] and physical properties [specific length (SL), diametric expansion (DE), bulk density (BD), and hardness (H)] of sorghum based extruded product were studied using factorial design. Increasing the level of soy meal flour resulted in increase in WAI, WSI, WHC, BD and H from 6.05 to 7.27 g/g, 7.51 to 8.62%, 7.82 to 8.51 g/g, 0.24 to 0.36 g/cm³, and 96.48 to 112.77N, respectively, while DE and SL were decreased from 2.16 to 1.76 and 1.23 to 1.16 cm/g, respectively. A significant higher WSI (8.07 and 8.04%) and DE (2.14 and 2.17), and lower WAI (6.26 and 6.50 g/g), BD (0.24 and 0.26 g/cm³) and H (93.14 and 100.11N) were observed at the lower feed moisture content (15%) and higher barrel temperature (165°C), respectively. Generally, extrudate made from lower

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level of soy flour at low feed moisture and high barrel temperature had better functional and physical properties.

Subjects: Food Engineering; Processing; Product Development;
Keywords: extrusion; functional properties; physical properties; sorghum flour and soy meal flour

1. Introduction
In the continuous search for solution to the problem of malnutrition and its various forms, mainly among the people of the developing countries including Ethiopia, views have been expressed of the need to improve the nutritive quality of foods of the respective countries through better processing and enrichment.

Sorghum (Sorghum bicolor (L.) Moench) is an important cereal crop grown in the semi-arid tropics of Africa and Asia due to its drought tolerance. It is a staple food crop cultivated on a subsistence level by farmers in these areas for human consumption and plays an important role in food security (Taylor, Schober, & Bean, 2006). Starch is the main component of sorghum grain, followed by proteins, non-starch polysaccharides and fat (Dicko, Gruppen, Traoré, Voragen, & Van Berkel, 2006). While sorghum starch provides all the features for production of highly acceptable extruded products (Devi et al., 2013), its nutritional quality is far from satisfying the needs of consumers (Belton & Taylor, 2004). For this reason, several attempts have been done to improve the nutritional quality of sorghum based products using legume flours as a compliments (Anuonye, Onuh, Egwim, & Adeyemo, 2010; Gbenyi, Nkama, & Badau, 2016; Hegazy, El-bedawey, Rahma, & Gaafar, 2017; Kumar, Samuel, Jha, & Sinha, 2015; Pelembe, Erasmus, & Taylor, 2002; Suksomboon, Limroongreungrat, Sangnark, & Thititumjariya, 2011).

Compared with most other protein sources, soy meal flour is a cheap source of protein, as it is a by-product of solvent extraction of soybean oil (Ströher, Stenzel, Pereira, & Zanin, 2012), and contains high concentration of essential amino acids such as lysine and tryptophan (Odebode et al., 2018). As regards, it has been considered as a candidate material to complement the protein and amino acid profile of sorghum flour. Several research works have been done on extrusion cooking of sorghum and soybean flours and reported that addition of soybean flour could be used to improve the nutritional profile of sorghum based extruded products without affecting the physicochemical and sensory quality of the products (Adedeji, Suhr, Bhadriraju, & Alavi, 2016; Basediya, Pandey, Shrivastava, Khan, & Nema, 2013; Kumar et al., 2015). Very recent study by
Tadesse, Bultosa, and Abera (2019) reported that incorporation of soy meal flour to sorghum flour can improve the nutritional profile without affecting the sensory quality of extruded product.

However, the suitability of extruded products for a particular use depends not only on the nutritional and sensory qualities. The functional properties and physical properties also play a significant role in the food application of extrudates (Hernandez-Diaz, Quintero-Ramos, Barnard, & Balandran-Quintana, 2007). Addition of high protein alternate ingredients to starch has been demonstrated to have a significant effect on the functional and physical properties of extruded snacks (Lazou & Krokida, 2010; Matthey & Hanna, 1997). Moreover, functional and physical properties of an extruded product vary considerably depending on operating conditions such as barrel temperature and feed moisture content (Ding, Ainsworth, Plunkett, Tucker, & Marson, 2006; Suksomboon et al., 2011). Even though, the effect of extrusion conditions on the functional and physical properties of various cereal and legume blend products has been investigated (Asare, Sefa-Dedeh, Afoko, Sakyi-Dawson, & Budu, 2010; Gopirajah & Muthukumarappan, 2017; Suksomboon et al., 2011), there is no information available on the functional and physical properties of extruded product made from sorghum and soy meal flour blend. Therefore, the aim of this study was to investigate the effect of soy meal flour, barrel temperature and feed moisture content on water absorption index, water solubility index, water holding capacity, expansion ratio, specific length, bulk density and instrumental hardness of sorghum based extruded product.

2. Materials and methods

2.1. Experimental materials
Sorghum (Sorghum bicolor (L.) Moench) was obtained from Haramaya University research center, Dire Dawa, Ethiopia. Sorghum grain variety (Muyera I) was selected based on its bulk production in the country. Soy (Glycine max) meal was obtained from Health Care Food Manufacturer PLC, Addis Ababa, Ethiopia.

2.2. Material preparation
Before milling, the sorghum grains were cleaned for physical impurities. About 20% water was added to temper the grains to a moisture content of 16% (Taylor & Dewar, 2001) to toughen the pericarp and soften the endosperm. Then, the sorghum grain was decorticated by mechanical abrasive decorticator, and milled using a stone mill. The soy meal was cleaned and oven dried at 70°C for 2 h, and milled using stone mill. Finally, both the flours were sifted to pass through 480 μm mesh sieve (Perez et al., 2008), packed in plastic bags and stored at room temperature

2.3. Extrusion operation
Samples prepared as described in the above section were subjected to extrusion test at all combinations of the operating conditions (feed moisture content, barrel temperature and soy meal flour level). Real values for barrel temperature (135–165°C), feed moisture content (15–21%) and amount of soy meal flour (0–20%) were used (Table 1). These values of the parameters were set based on preliminary test.

| Table 1. Experimental levels of the variables |
|---------------------------------------------|
| Variables          | Levels |
|                   | −1     | 0   | 1 |
| S (%)             | 0      | 10  | 20 |
| FM (%)            | 15     | 18  | 21 |
| BT(°C)            | 135    | 150 | 165 |

S = soy meal flour (%); FM = feed moisture content (%); BT = barrel temperature (°C)
Extrusion was performed using a pilot scale co-rotating twin-screw food extruder (model Clextral, BC-21 No 124, Firminy, France). The barrel has 300 mm useful length and consists of three modules each 100 mm long fitted with 25 mm diameter screws. The temperature of the modules is regulated by electrical heating and water cooling system, and the temperature at each zone was controlled by a Eurotherm controller (Eurotherm Ltd., Worthing, U.K.). For this experiment, the barrel temperatures in zone 1 and 2 were fixed at 25°C (ambient temperature) and 70°C, respectively, and in zone 3 (nearest to the die) varied to the desire temperature of 135, 150 and 165°C. Feed rate, screw speed and die diameter was kept constant at 9 kg/hr (Solomon, 2007), 150 rpm and 0.5 mm (Perez et al., 2008), respectively throughout the experiment. The pump was adjusted to give the amount of water required to bring the moisture to 15%, 18% and 21% in the mixes at constant material feed rate by using hydration Equation (Eq. 1) (Golob, Farrell, & Orchard, 2002).

\[ W_a = S_w \left( \frac{m - m_o}{100} \right) \]  

Where; \( W_a \) = weight of water added (g), \( S_w \) = is sample flour weight (g); \( m_o \) = original flour moisture content (% wwb), and \( m \) = required dough moisture level in (% wwb).

Samples were extruded as straight rope (rod) for a time interval of 10 s (Mason & Hoseney, 1986). The extruded products were placed on a Table and allowed to cool for 30 min at room temperature (25°C) and sealed in moisture proof plastic bags after equilibration for 24 h at ambient condition (25°C).

2.4. Experimental design
A factorial design was used to study the main, combined, and overall effects of soy meal flour level, barrel temperature and feed moisture contents on water absorption index, water solubility index, water holding capacity, expansion ratio, specific length, bulk density and instrumental hardness of sorghum-based extruded product. Generally, there were 27 treatment combinations: 3 (soy meal flour levels) × 3(barrel temperatures) × 3(feed moisture contents). Experiment was conducted in duplicates.

2.5. Determination of water absorption index, water solubility index, and water holding capacity
The water absorption index (WAI) and water solubility index (WSI) were determined by the method described by (Anderson, Conway, & Peplinski, 1970). Ground product passing through a 60 mesh screen was suspended in 30 mL of water at 30°C for 30 min, and then centrifuged at 3000 × g for 10 min. The supernatant was decanted into an evaporating dish of known weight. The WAI was calculated as the total moisture absorbed divided by the dry weight of sample (Eq. 2).

\[ WAI = \frac{W_s}{W_o} \]  

Where: \( W_s \) - weight of sediment (g) and \( W_o \) - weight of sample (g)

The WSI was determined by dividing the amount of solids recovered from evaporation of the supernatant by the weight of the original sample, expressed as a percentage (Eq. 3).

\[ WSI = \frac{W_r}{W_o} \times 100 \]  

Where: \( W_r \) is the weight (g) of residual supernatant after evaporation and \( W_o \) weight of sample (g)

The water holding capacity (WHC) of the extrudates was estimated according to AACC (2000) method 56–20. Centrifuge tube (100 mL) were prepared and weighed as “\( w_i \)”. Sample of extrudate flour (2.0 g) was measured into a tube and 40 mL water was added and shook vigorously to thoroughly suspend the flour. Then the sample was left for 10 min and centrifuged at 1000 × g for 15 min. The clear supernatant was drained out and the residue and the tube was weighed and recorded as “\( w_{sat} \)”. The hydration capacity was calculated according to Eq (4).
Where: WHC is water-holding capacity, \( w_t \) is weight of tube (g), \( w_{sat} \) is weight of sediment and tube (g) and \( w_o \) is sample weight (g, db)

2.6. **Determination of specific length, degree of expansion (diametric expansion) and bulk density**

The average length, diameter, and weight of five randomly selected extrudates were used to calculate expansion ratio, bulk density and specific length. The diameter of the extrudates were measured by a vernier caliper (CДЕЛАНО, cccp, Russia) having 0.05 mm accuracy. The length of the extrudate samples were measured by a pocket size steel tape of 1mm accuracy and the weight were measured by a digital balance (ADAM, AFP1200, South Africa) of 0.01g sensitivity. Degree of expansion, bulk density, and specific length of extrudates samples were calculated as follows (Eqs. 5–7) (Mason & Hoseney, 1986):

\[
DE = \frac{D}{d}
\]

(5)

\[
BD = \frac{4W}{\pi D^2 L}
\]

(6)

\[
SL = \frac{L}{W}
\]

(7)

Where: \( DE \) is expansion ratio (cm/cm), \( BD \) is bulk density (g/cm\(^3\)), \( SL \) is specific length (cm/g), \( D \) is diameter of extrudate (cm), \( L \) is length (cm), \( W \) is weight of extrudate (g) and \( d \) is diameter of die hole (cm).

2.7. **Instrumental texture test**

Ten pieces of extrudate having length of 5 cm were selected randomly from each treatment and placed on the loading cell of a TA-XT2 texture analyzer (Ametek, Lloyd Instruments, UK). General purpose compression test was conducted radially on the extrudates. The charges in the force required to break the sample during compression were recorded in the form of peak and the texture was expressed as hardness, peak force (N) of the first compression required for sample's breakage (Veronica, Olusola, & Adebowale, 2006).

2.8. **Data analysis**

Analysis of variance (ANOVA) was carried out to investigate the effect of soy meal flour, barrel temperature and feed moisture content on functional and physical properties of sorghum-based extruded products using SAS software (SAS Institute and Cary, NC). Duncan Multiple Range Test (DMRT) was used for multiple mean separations at 5% probability level.

3. **Results and discussion**

3.1. **Proximate composition and functional properties of raw sorghum and soy meal flours**

Proximate compositions and functional properties of sorghum and soy meal flours used in this study are presented in Table 2. Figure 1 shows selected pictures of extrudates processed from sorghum and soy meal flour at different processing conditions.

3.2. **Effect of soy meal flour proportion, barrel temperature and feed moisture content on water absorption index**

Table 3 summarizes the effect of soy meal flour proportion, barrel temperature, and feed moisture content on functional properties of the extrudates. Increasing the level of soy meal flour from 0 to 20% resulted in a significant increase (\( P < 0.05 \)) in WA1 of extrudates from 6.05 to 7.27g/g. Pelembe et al. (2002) also found that addition of cowpea to sorghum caused a significant increase
in WAI of extrudates due to the higher amylose/amylopectin ratio of the cowpeas. Filli, Nkama, 
Abubakar, and Jideani (2010) reported a contradictory result and observed decrease in WAI of 
eextrudate with increase in the level of soybean flour because of oil in soybean, which interfered 
with water uptake. The type and amount of proteins, degree of protein denaturation, and amount 
of fiber present are among other reported factors that affecting the WAI of extruded products 
(Duarte, Majewska, & Doetkott, 1998).

Table 2. Proximate composition and functional properties of sorghum and soy meal flour

| Components       | *Sorghum flour (debranned) | *Soy meal flour |
|------------------|-----------------------------|-----------------|
| Moisture (%)     | 7.1 ± 0.06                  | 7.84 ± 0.04     |
| Protein (%)      | 12.14 ± 0.11                | 49.08 ± 0.26    |
| Fat (%)          | 3.25 ± 0.09                 | 6.74 ± 0.01     |
| Ash (%)          | 1.60 ± 0.17                 | 6.46 ± 0.21     |
| Fiber (%)        | 0.85 ± 0.02                 | 5.30 ± 0.05     |
| \(^1\)CHO (%)    | 74.06 ± 0.53                | 23.58 ± 0.02    |
| WAI (g/g)        | 2.55 ± 0.04                 | 2.71 ± 0.24     |
| WSI (%)          | 2.76 ± 0.08                 | 3.01 ± 0.18     |
| WHC (g/g)        | 2.98 ± 0.11                 | 3.26 ± 0.09     |

\(^1\) = Obtained by difference; CHO = carbohydrate (%); WAI = water absorption index (g/g); WSI = water solubility index (%); WHC = water holding capacity (g/g)

Figure 1. Extrudates processed from sorghum and soy meal flour at different processing conditions.

(A) 0% soy meal flour, 15% feed moisture and 165°C barrel temperature; (B) 0% soy meal flour, 15% feed moisture and 150°C barrel temperature; (C) 0% soy meal flour, 18% feed moisture and 165°C barrel temperature; (D) 10% soy meal flour, 15% feed moisture, 165°C barrel temperature; (E) 10% soy meal flour, 18% feed moisture, 165°C barrel temperature; (F) 10% soy meal flour, 18% feed moisture, 165°C barrel temperature; (G) 20% soy meal flour, 15% feed moisture and 165°C barrel temperature; (H) 20% soy meal flour, 18% feed moisture and 150°C barrel temperature; (I) 20% soy meal flour, 21% feed moisture and 150°C barrel temperature.
The WAI of extrudates were significantly increased (P < 0.05) with increase in feed moisture content (Table 3). Increasing the feed moisture content from 15 to 21% resulted in increase the WAI of extrudates from 6.25 to 7.02 g/g. Similarly, effect of moisture content on WAI has been reported for lentil and banana blend (Hernandez-Nava, Bello-Perez, Martin-Martinez, Hernandez-Sanchez, & Mora-Escobedo, 2011) and stated that at high moisture content the viscosity of the starch decrease that allows extensive internal mixing and uniform heating, which intern accounts for enhanced starch gelatinization that might lead to increased water absorption. Similarly, Ding, Ainsworth, Tucker, and Marson (2005) observed that increase in feed moisture content caused a significant increase in the WAI of rice extrudate.

Increasing barrel temperature initially from 135 to 150°C had no significant effect (p ≥ 0.05) on WAI of extrudates (Table 3). However, further increasing the barrel temperature to 165°C resulted in significant decrease (P < 0.05) in WAI to 6.5 g/g. Decrease in WAI with increase in barrel temperature could be due to macromolecular degradation, which increases the solubility of starch (Kebede, Solomon, Bultosa, & Yetneberek, 2010).

The interaction between barrel temperature and feed moisture showed a significant effect (P < 0.0001) on WAI of the extrudates (Table 4). Sample extruded at 150°C and 21% feed moisture content had the maximum WAI while the minimum WAI (6.13 g/g) was found at 150°C and 15% feed moisture content. The lower WAI at lower feed moisture content was most likely owing to excessive dextrinization of starch (Valencia, Cruz, de La, Alvarez, & Kallio, 2009).

The WAI of extrudates also significantly affected (P < 0.0001) by interaction of soy meal flour proportion and barrel temperature (Table 4). Extrudate made from 20% soy meal flour and extruded at 135°C barrel temperature had relatively the highest WAI whereas extrudate made from sorghum flour alone and extruded at 165°C had relatively the lowest WAI compared to the rest of conditions. The interaction between blending ratio and moisture content had also

### Table 3. Main effects of extrusion variables on product functional properties

| Variable | n   | * Functional properties          |
|----------|-----|----------------------------------|
|          |     | WAI (g/g) | WSI (%) | WHC (g/g) |
| S (%)    |     |           |         |           |
| 0        | 18  | 6.05 ± 0.30  | 7.51 ± 0.07 | 7.82 ± 0.36 |
| 10       | 18  | 6.48 ± 0.40  | 7.90 ± 0.05 | 7.97 ± 0.18 |
| 20       | 18  | 7.27 ± 0.43  | 8.62 ± 0.09 | 8.51 ± 0.38 |
| F.M (%)  |     |           |         |           |
| 15       | 18  | 6.26 ± 0.51  | 8.07 ± 0.49 | 8.05 ± 0.43 |
| 18       | 18  | 6.53 ± 0.55  | 8.01 ± 0.47 | 8.13 ± 0.37 |
| 21       | 18  | 7.02 ± 0.61  | 7.95 ± 0.47 | 8.13 ± 0.51 |
| BT (ºC)  |     |           |         |           |
| 135      | 18  | 6.66 ± 0.63  | 7.97 ± 0.47 | 7.98 ± 0.34 |
| 150      | 18  | 6.65 ± 0.65  | 8.02 ± 0.48 | 7.94 ± 0.36 |
| 165      | 18  | 6.50 ± 0.65  | 8.04 ± 0.49 | 8.38 ± 0.47 |
| Mean     | 54  | 6.60        | 8.01     | 8.10     |
| CV       |     | 0.98        | 0.30     | 2.13     |

Values followed by the different letters within each variable in a column indicate significant difference (P < 0.05); S = soy flour (%); BT = barrel temperature (ºC); FM = feed moisture content (%); * mean±SD; n = number of observations; WAI = water absorption index (g/g); WSI = water solubility index (%); WHC = water holding capacity; CV = coefficient of variation
a significant effect (P < 0.0002) on WAI of extrudates (Table 4). Extrudate made from 20% soy meal flour proportion at feed moisture content of 21% had relatively higher WAI while sample extruded at 0% soy meal flour level and 15% feed moisture content showed the minimum WAI. The lower WAI at the lowest feed moisture content and soy meal flour proportion is probably due to starch dextrinization caused by enhanced friction and energy dissipation to the starch during extrusion cooking at low moisture content (Valencia et al., 2009).

### Table 4. Two way interaction effects of extrusion variables on functional properties of extrudates

| S   | BT  | N  | WAI (g/g)   | WSI (%)    | WHC (g/g)   |
|-----|-----|----|-------------|------------|-------------|
| 0   | 135 | 6  | 6.10 ± 0.16 | 7.47 ± 0.03 | 7.88 ± 0.47 |
| 0   | 150 | 6  | 6.05 ± 0.39 | 7.51 ± 0.06 | 7.59 ± 0.28 |
| 0   | 165 | 6  | 5.99 ± 0.35 | 7.56 ± 0.08 | 8.00 ± 0.18 |
| 10  | 135 | 6  | 6.49 ± 0.48 | 7.89 ± 0.04 | 7.82 ± 0.09 |
| 10  | 150 | 6  | 6.66 ± 0.44 | 7.92 ± 0.04 | 7.93 ± 0.16 |
| 10  | 165 | 6  | 6.30 ± 0.21 | 7.89 ± 0.07 | 8.15 ± 0.12 |
| 20  | 135 | 6  | 7.39 ± 0.19 | 8.56 ± 0.06 | 8.24 ± 0.19 |
| 20  | 150 | 6  | 7.22 ± 0.52 | 8.63 ± 0.08 | 8.31 ± 0.13 |
| 20  | 165 | 6  | 7.21 ± 0.56 | 8.68 ± 0.08 | 8.99 ± 0.16 |

DMRT (P value) <0.0001*** <0.0001*** 0.0007**

Values followed by the different letters within a column indicate significant difference (P < 0.05); DMRT = Duncan’s Multiple Range Test; ns = not significant (P > 0.05); *, ** = significant at 5% and 1% probability level, respectively; Tt = treatment number; S = defatted soy flour (%); BT = barrel temperature (°C); FM = feed moisture content (%); n = number of observations; WAI = water absorption index (g/g); WSI = water solubility index; WHC = water holding capacity.
The interactions between all independent variable combination were significantly affected (P < 0.0001) the WAI of extrudates (Table 5). Generally, sample extruded at 20% soy flour level, 165°C barrel temperature and 21% feed moisture had the greatest WAI (7.89g/g) and sample extruded at 0% soy flour level (sorghum alone), 150°C barrel temperature and 15% feed moisture content had the least WAI (5.62) compared to the rest of conditions (Table 5). The values of the WAI for extrudates are reflective of undamaged polymer chains and the availability of hydrophilic groups, which can bind water molecules (Kurt, Muthumarappan, & Kannadhason, 2009).

Table 5. Effect of extrusion variables on product functional properties

| Processing conditions | Functional properties |
|-----------------------|-----------------------|
| Tt | S (%) | BT (°C) | FM (%) | n | WAI (g/g) | WSI (%) | WHC (g/g) |
| 1 | 0 | 135 | 15 | 2 | 5.94 ± 0.06<sup>ab</sup> | 7.50 ± 0.02<sup>mn</sup> | 8.13 ± 0.05<sup>bcdef</sup> |
| 2 | 0 | 135 | 18 | 2 | 6.06 ± 0.05<sup>nm</sup> | 7.48 ± 0.01<sup>io</sup> | 8.06 ± 0.17<sup>defg</sup> |
| 3 | 0 | 135 | 21 | 2 | 6.29 ± 0.03<sup>ah</sup> | 7.43 ± 0.01<sup>j</sup> | 7.47 ± 0.75<sup>h</sup> |
| 4 | 0 | 150 | 15 | 2 | 5.62 ± 0.06<sup>a</sup> | 7.57 ± 0.03<sup>kh</sup> | 7.31 ± 0.37<sup>h</sup> |
| 5 | 0 | 150 | 18 | 2 | 6.06 ± 0.02<sup>km</sup> | 7.52 ± 0.02<sup>mh</sup> | 7.65 ± 0.09<sup>g</sup> |
| 6 | 0 | 150 | 21 | 2 | 6.49 ± 0.02<sup>hi</sup> | 7.45 ± 0.01<sup>h</sup> | 7.80 ± 0.02<sup>gh</sup> |
| 7 | 0 | 165 | 15 | 2 | 5.65 ± 0.05<sup>a</sup> | 7.62 ± 0.01<sup>j</sup> | 7.83 ± 0.04<sup>gh</sup> |
| 8 | 0 | 165 | 18 | 2 | 5.92 ± 0.05<sup>k</sup> | 7.59 ± 0.03<sup>h</sup> | 8.00 ± 0.19<sup>defg</sup> |
| 9 | 0 | 165 | 21 | 2 | 6.41 ± 0.12<sup>b</sup> | 7.46 ± 0.01<sup>kh</sup> | 8.17 ± 0.04<sup>defg</sup> |
| 10 | 10 | 135 | 15 | 2 | 6.18 ± 0.11<sup>mn</sup> | 7.92 ± 0.03<sup>gh</sup> | 7.91 ± 0.06<sup>defg</sup> |
| 11 | 10 | 135 | 18 | 2 | 6.18 ± 0.04<sup>km</sup> | 7.89 ± 0.05<sup>h</sup> | 7.84 ± 0.02<sup>gh</sup> |
| 12 | 10 | 135 | 21 | 2 | 7.10 ± 0.11<sup>bc</sup> | 7.85 ± 0.04<sup>h</sup> | 7.73 ± 0.00<sup>gh</sup> |
| 13 | 10 | 150 | 15 | 2 | 6.10 ± 0.05<sup>km</sup> | 7.96 ± 0.01<sup>gh</sup> | 7.78 ± 0.01<sup>gh</sup> |
| 14 | 10 | 150 | 18 | 2 | 6.93 ± 0.08<sup>b</sup> | 7.92 ± 0.04<sup>gh</sup> | 7.89 ± 0.03<sup>gh</sup> |
| 15 | 10 | 150 | 21 | 2 | 6.95 ± 0.08<sup>b</sup> | 7.89 ± 0.02<sup>gh</sup> | 8.12 ± 0.04<sup>defg</sup> |
| 16 | 10 | 165 | 15 | 2 | 6.12 ± 0.05<sup>ia</sup> | 7.98 ± 0.01<sup>h</sup> | 8.00 ± 0.00<sup>defg</sup> |
| 17 | 10 | 165 | 18 | 2 | 6.57 ± 0.01<sup>im</sup> | 7.85 ± 0.01<sup>h</sup> | 8.19 ± 0.06<sup>defg</sup> |
| 18 | 10 | 165 | 21 | 2 | 6.22 ± 0.10<sup>gh</sup> | 7.84 ± 0.01<sup>h</sup> | 8.26 ± 0.03<sup>defg</sup> |
| 19 | 20 | 135 | 15 | 2 | 7.24 ± 0.03<sup>cd</sup> | 8.63 ± 0.01<sup>c</sup> | 8.45 ± 0.06<sup>b</sup> |
| 20 | 20 | 135 | 18 | 2 | 7.30 ± 0.07<sup>e</sup> | 8.56 ± 0.02<sup>c</sup> | 8.25 ± 0.02<sup>b</sup> |
| 21 | 20 | 135 | 21 | 2 | 7.62 ± 0.06<sup>bc</sup> | 8.50 ± 0.01<sup>bc</sup> | 8.03 ± 0.01<sup>defg</sup> |
| 22 | 20 | 150 | 15 | 2 | 6.67 ± 0.04<sup>g</sup> | 8.72 ± 0.00<sup>b</sup> | 8.17 ± 0.05<sup>defg</sup> |
| 23 | 20 | 150 | 18 | 2 | 7.16 ± 0.08<sup>da</sup> | 8.61 ± 0.03<sup>c</sup> | 8.32 ± 0.10<sup>b</sup> |
| 24 | 20 | 150 | 21 | 2 | 7.82 ± 0.02<sup>ga</sup> | 8.56 ± 0.03<sup>c</sup> | 8.43 ± 0.04<sup>ga</sup> |
| 25 | 20 | 165 | 15 | 2 | 6.69 ± 0.04<sup>g</sup> | 8.77 ± 0.04<sup>bc</sup> | 8.84 ± 0.01<sup>a</sup> |
| 26 | 20 | 165 | 18 | 2 | 7.04 ± 0.05<sup>bc</sup> | 8.68 ± 0.02<sup>c</sup> | 8.94 ± 0.00<sup>a</sup> |
| 27 | 20 | 165 | 21 | 2 | 7.89 ± 0.05<sup>ga</sup> | 8.60 ± 0.05<sup>cd</sup> | 9.18 ± 0.00<sup>a</sup> |

Mean: 6.60
CV: 0.98
P value: <0.0001

Values followed by the different letters within a column indicate significant difference (P < 0.05); Tt = treatment number; S = soy flour (%); BT = barrel temperature (°C); FM = feed moisture content (%); n = number of replications; WAI = water absorption index (g/g); WSI = water solubility index; WHC = water holding capacity; CV = coefficient of variation.
3.3. Effect of soy meal flour proportion, barrel temperature and feed moisture content on water solubility index

Water solubility index (WSI) of extrudates, an indicator of macromolecular degradation, was significantly affected (P < 0.05) by level of soy meal flour proportion, feed moisture content and barrel temperature (Table 3). WSI of extrudates increased significantly (P < 0.05) from 7.51 to 8.62% and 7.97 to 8.04% with increase in level of soy meal flour addition and barrel temperature from 0 to 20% and 135 to 165°C, respectively. However, WSI significantly decreased (P < 0.05) from 8.07 to 7.95% as feed moisture content increased from 15 to 21% (Table 3). Kebede et al. (2010) reported similar results when extruding teff. Hagenimana, Ding, and Fang (2006) reported that WSI of extruded rice flour decreased with increase in feed moisture from 16 to 22%. Low moisture content enhances the friction and mechanical shear involved in the extruder that causes starch dextrinization (Anderson et al., 1970; Valencia et al., 2009).

The interaction between soy meal flour level and feed moisture content showed a significant effect (P < 0.0048) on WSI (Table 4). The maximum WSI (8.71%) was observed at 20% soy meal flour proportion and 15% feed moisture content while the lowest value of 7.45% was observed at 0% soy flour level (sorghum alone) and 21% feed moisture content. The interaction between soy flour proportion and barrel temperature also showed a significant effect (P < 0.0001) on WSI (Table 4). The maximum WSI value of 8.68% was observed at 20% soy flour level and 165°C barrel temperature while the lowest value of 7.47% was observed at 0% soy flour level and 135°C barrel temperature. Moreover, there was a significant interaction effect (P < 0.0197) of barrel temperature and feed moisture content on WSI (Table 4). The highest WSI value of 8.12% was observed at a processing condition of 165°C barrel temperature and 15% feed moisture content while the lowest value of 7.93% was observed at 135°C and 21% feed moisture content. Similarly, Suksomboon et al. (2011) observed that extruding purple rice (Hom Nil) and soybean flour blend at 15% feed moisture content and 190°C temperature resulted in higher WSI. Increase in WSI with decrease in feed moisture and increased in barrel temperature may be attributed to higher degradation of starch which produces more soluble lower chain starch aggregates (Anderson et al., 1970).

Although the interaction of the three variables did not show a significant (p ≥ 0.05) effect on WSI (Table 5), the highest WSI (8.77%) was observed from 20% soy meal flour level, 165°C barrel temperature and 15% feed moisture content, and the lowest WSI (7.43%) was found from 0% soy meal flour, 135°C barrel temperature and 21% feed moisture content (Table 5).

3.4. Effect of soy meal flour proportion, barrel temperature and feed moisture content on water holding capacity

Water holding capacity (WHC), an indicator of the reconstitution and textural ability of extrudates, were significantly affected (P < 0.05) by soy meal flour proportion and barrel temperature whereas feed moisture content had no significant effect (P ≥ 0.05) on WHC (Table 3). WHC significantly increased (P < 0.05) from 7.82 to 8.51 and 7.98 to 8.38 g/g with increase in level of soy flour addition from 0 to 20% and barrel temperature from 135 to 165°C, respectively. Abioye, Ade-Omowaye, Babarinde, and Adesigbin (2011) reported that WHC of plantain-based flour increased with soy flour substitution. Addition of soy flour to plantain flour increases the water binding capacity to plantain flour because of the increase in protein content of the flour. Similarly, Crowe and Johnson (2001) testified that WHC of texturized soy proteins increased with increase in barrel temperature.

The interaction of soy flour proportion and barrel temperature was significantly (P < 0.0007) affected the WHC of the resulting extrudates (Table 4). Relatively, the higher WHC (8.99 g/g) was observed at the highest level of soy meal flour (20%) and barrel temperature (165°C), and the lower WHC (7.59 g/g) was found at 0% soy meal flour level and 150°C barrel temperature. The interaction of barrel temperature and feed moisture content also showed a significant (P < 0.0001) effect on WHC of the resulting extrudates. Relatively, the higher WHC (8.54 g/g) was found at 165°C barrel temperature and 21% feed moisture content, and the lower WHC (7.74g/g) was observed at 135°C barrel temperature and 21% feed moisture content (Table 4). As it can be seen in Table 3, feed moisture content did
not affect the WHC of the extrudates. Therefore, it is obvious that the interaction effect of barrel temperature and feed moisture is come from the barrel temperature effect. Heating disrupts the quaternary structure of soy proteins and subsequently separates the subunits that allow active amino acid R-groups expose to bind water (Crowe & Johnson, 2001). Although, the interaction of the three variables did not show a significant ($P \geq 0.05$) effect on WHC of the extrudates, it was found in the range of 7.31–9.18g/g (Table 5).

3.5. The effect of soy meal flour proportion, barrel temperature and feed moisture on expansion ratio of extrudate

Table 6 illustrates the main effects of soy meal flour proportion, barrel temperature, and feed moisture content on physical properties of sorghum extrudates. Soy meal flour level, barrel temperature and feed moisture content showed significant ($P \leq 0.05$) effect on diametric expansion of extrudates. Increasing the level of soy meal flour (0 to 20%) and feed moisture content (15–21%) significantly ($P \leq 0.05$) decreased the expansion of the resulting extrudates, whereas increasing of barrel temperature from 135–165°C resulted in a significant ($P \leq 0.05$) increase in expansion of the extrudates.

The ER, measured as diameter expansion, decreased from 2.16 to 1.76 as the level of soy meal flour increased from 0 to 20% in the composites at the same extrusion temperatures and feed moisture content (Table 6). It could be due to the increment of protein as a result of soy meal flour. Pelembe et al. (2002) reported that increasing protein content in the mixture decreases ER of extrudates. According to Pelembe et al. (2002), the lower ER in the mixtures of higher legume content could be related to the lower amylose/amylopectin ratio in sorghum. Amylopectin exerts a positive and amylose a negative influence on radial ER.

Extrudates produced using the highest barrel temperature (165°C) at the same soy meal flour proportion and feed moisture content had significantly ($P \leq 0.05$) higher ER (2.17) than the other which was processed at 135 and 150°C barrel temperature (Table 6). As the barrel temperature

| Variable      | n  | ER     | SL(cm/g) | BD(g/cm$^3$) | H (N)  |
|---------------|----|--------|----------|--------------|--------|
| S (%)         | 0  | 2.16 ± 0.29$^a$ | 1.23 ± 0.22$^a$ | 0.24 ± 0.05$^a$ | 96.48 ± 16.64$^b$ |
|               | 10 | 2.08 ± 0.22$^b$  | 1.27 ± 0.23$^b$ | 0.25 ± 0.07$^b$  | 101.77 ± 13.09$^b$ |
|               | 20 | 1.76 ± 0.11$^c$  | 1.16 ± 0.07$^c$ | 0.36 ± 0.03$^c$  | 112.77 ± 11.86$^c$ |
| F.M (%)       | 15 | 2.14 ± 0.30$^a$  | 1.26 ± 0.15$^a$ | 0.24 ± 0.08$^a$  | 93.14 ± 16.72$^a$ |
|               | 18 | 1.99 ± 0.26$^b$  | 1.28 ± 0.22$^b$ | 0.27 ± 0.07$^b$  | 103.61 ± 10.17$^b$ |
|               | 21 | 1.87 ± 0.20$^c$  | 1.12 ± 0.16$^c$ | 0.33 ± 0.04$^c$  | 114.28 ± 10.77$^c$ |
| Temp (ºC)     | 135| 1.87 ± 0.20$^b$  | 1.26 ± 0.15$^b$ | 0.30 ± 0.07$^b$  | 109.67 ± 12.97$^b$ |
|               | 150| 1.96 ± 0.23$^c$  | 1.31 ± 0.21$^c$ | 0.27 ± 0.09$^c$  | 101.25 ± 13.50$^c$ |
|               | 165| 2.17 ± 0.30$^c$  | 1.09 ± 0.12$^c$ | 0.26 ± 0.07$^c$  | 100.11 ± 18.09$^c$ |
| Mean          | 54 | 2.00    | 1.22     | 0.28          | 103.68 |
| CV            |    | 4.20   | 8.85     | 8.29          | 8.44   |

Values followed by the different letters within each variable in a column indicate significant difference ($P < 0.05$); S = soy meal flour (%); BT = barrel temperature (ºC); FM = feed moisture content (%); n = number of observation; $\bar{x}$ = mean±SD; SL = specific length (cm/g); ER = expansion ratio; BD = bulk density (g/cm$^3$); H = hardness (N); CV = coefficient of variation.
increased the viscosity of the feed material decreased, which resulting in better expansion ratio (Ding et al., 2005; Kebede et al., 2010). High temperature provides more thermal input that leads to complete gelatinization of starch resulting in higher ERs (Majumdar, Venkateshwarlu, & Roy, 2011).

ER of extrudates were significantly (P ≤ 0.05) decreased from 2.14 to 1.87 when the feed moisture content increased from 15 to 21% at the same barrel temperature and soy meal flour addition (Table 6). Low moisture content in feed may restrict flow of the material and increase shearing rate and residence time, which might increase the degree of gelatinization and expansion (Gopirajah & Muthukumarappan, 2017).

### Table 7. Two way interaction effects of extrusion variables on product physical properties

| S  | BT  | n  | SL (cm/g)     | ER (cm/cm) | BD (g/cm³) | H (N)       |
|----|-----|----|---------------|------------|------------|-------------|
|    |     |    | 0.13 ± 0.14^ab | 1.98 ± 0.23 | 0.26 ± 0.04 | 103.10 ± 15.88 |
|    |     |    | 0.136 ± 0.16^ab | 2.06 ± 0.23 | 0.23 ± 0.05 | 100.02 ± 15.85 |
|    |     |    | 1.03 ± 0.19    | 2.44 ± 0.15 | 0.22 ± 0.06 | 86.33 ± 15.72 |
|    |     |    | 1.26 ± 0.22^ab | 1.96 ± 0.09 | 0.27 ± 0.06 | 108.11 ± 8.28 |
|    |     |    | 1.43 ± 0.25^a  | 2.06 ± 0.22 | 0.23 ± 0.09 | 100.13 ± 15.35 |
|    |     |    | 1.11 ± 0.08    | 2.23 ± 0.24 | 0.24 ± 0.07 | 97.07 ± 14.16 |
|    |     |    | 1.20 ± 0.05^ab | 1.67 ± 0.06 | 0.38 ± 0.01 | 117.79 ± 10.83 |
|    |     |    | 1.14 ± 0.08^ab | 1.78 ± 0.11 | 0.36 ± 0.03 | 103.60 ± 11.08 |
|    |     |    | 1.13 ± 0.03^ab | 1.84 ± 0.10 | 0.33 ± 0.04 | 116.93 ± 9.29 |
|    |     |    |               |            |            |             |
| DMRT (P value) |    |    | 0.0035^**     | 0.0008^**  | 0.4888 ns  | 0.0169*     |

| S  | BT  | n  | SL (cm/g)     | ER (cm/cm) | BD (g/cm³) | H (N)       |
|----|-----|----|---------------|------------|------------|-------------|
|    |     |    | 1.28 ± 0.10^ab | 2.38 ± 0.18 | 0.18 ± 0.02 | 80.10 ± 10.89 |
|    |     |    | 1.28 ± 0.27^ab | 2.09 ± 0.31 | 0.24 ± 0.03 | 98.75 ± 11.14 |
|    |     |    | 1.14 ± 0.25^ab | 2.00 ± 0.24 | 0.29 ± 0.02 | 110.61 ± 11.46 |
|    |     |    | 1.35 ± 0.20^ab | 2.22 ± 0.24 | 0.20 ± 0.05 | 92.02 ± 13.29 |
|    |     |    | 1.39 ± 0.23^ab | 2.11 ± 0.18 | 0.21 ± 0.03 | 100.91 ± 8.70 |
|    |     |    | 1.06 ± 0.08    | 1.92 ± 0.13 | 0.33 ± 0.03 | 112.39 ± 8.96 |
|    |     |    | 1.15 ± 0.08^ab | 1.82 ± 0.13 | 0.34 ± 0.04 | 107.31 ± 14.44 |
|    |     |    | 1.15 ± 0.05^ab | 1.78 ± 0.12 | 0.35 ± 0.03 | 111.18 ± 6.72 |
|    |     |    | 1.17 ± 0.08^ab | 1.69 ± 0.06 | 0.38 ± 0.01 | 119.84 ± 11.18 |
|    |     |    |               |            |            |             |
| DMRT (P value) |    |    | 0.0004^**     | 0.0033^**  | <0.0001^**  | 0.1516 ns   |

| BT  | FM  | n  | SL (cm/g)     | ER (cm/cm) | BD (g/cm³) | H (N)       |
|-----|-----|----|---------------|------------|------------|-------------|
| 135 |     |    | 1.27 ± 0.08^ab | 1.97 ± 0.24 | 0.28 ± 0.08 | 102.73 ± 12.40 |
| 135 |     |    | 1.33 ± 0.18^ab | 1.83 ± 0.19 | 0.30 ± 0.07 | 107.14 ± 8.72 |
| 135 |     |    | 1.18 ± 0.16^ab | 1.81 ± 0.16 | 0.34 ± 0.05 | 119.13 ± 12.97 |
| 150 |     |    | 1.33 ± 0.23^ab | 2.14 ± 0.25 | 0.23 ± 0.09 | 87.25 ± 4.84 |
| 150 |     |    | 1.42 ± 0.24^ab | 1.95 ± 0.17 | 0.25 ± 0.08 | 102.25 ± 10.31 |
| 150 |     |    | 1.18 ± 0.09^ab | 1.80 ± 0.11 | 0.34 ± 0.04 | 114.25 ± 7.14 |
| 165 |     |    | 1.18 ± 0.09^ab | 2.31 ± 0.33 | 0.22 ± 0.08 | 89.44 ± 24.59 |
| 165 |     |    | 1.08 ± 0.06^ab | 2.19 ± 0.28 | 0.25 ± 0.06 | 101.44 ± 12.06 |
| 165 |     |    | 1.01 ± 0.15^ab | 2.01 ± 0.26 | 0.32 ± 0.04 | 109.45 ± 10.89 |
|    |     |    |               |            |            |             |
| DMRT (P value) |    |    | 0.2210 ns     | 0.0063 ns  | 0.0659 ns  | 0.5141 ns   |

Values followed by the different letters with in a column indicate significant difference (P < 0.05); DMRT = Duncan’s Multiple Range Test; ns = non-significant (P > 0.05); ^ = significant at 5% probability level, respectively; S = soy meal flour (%); BT = barrel temperature (°C); FM = feed moisture content (%); n = number of replication; 1 = mean±SD; SL = specific length (cm/g); ER = expansion ratio; BD = bulk density (g/cm³); H = hardness (N); Tt = treatment number
The interaction between soy meal flour and barrel temperature showed significant \((P < 0.05)\) effect on ER of the resulting extrudates (Table 7). Relatively, higher ER was observed for extrudates produced with 0% soy meal flour proportion (sorghum alone) at 165°C barrel temperature than the other. It may be because of the feed materials become hard as protein increased and denatured (Basediya et al., 2013). Soy meal flour proportion and feed moisture content also showed significant \((P < 0.05)\) effect on ER of the resulting extrudates. Extrudates produced at 100% sorghum flour and 15% feed moisture content had relatively higher ER than the rest of processing conditions.

Generally, the highest ER (2.60) was observed at 0% level of soy meal flour (sorghum alone) and feed moisture content (15%), and highest barrel temperature (165°C). Extrusions using low barrel temperature (135°C), high feed moisture content (21%) and soy meal flour level (20%) resulted in lower expansion (1.66) (Table 8). Leonel, Freitas, and Mischan (2009) reported similar result for extrudate of cassava starch and observed that, under low moisture conditions, an increase in barrel temperature led to increased expansion. Expansion is related to the starch gelatinization degree so that low moisture content in the material may restrain its flow inside the extruder, increasing shear and residence time, could increase the gelatinization degree (Leonel et al., 2009).

### 3.6. The effect of soy meal flour proportion, barrel temperature and feed moisture on specific length

Specific length (SL) of extruded product measures the axial expansion of the extrudate and related to the expansion volume. Soy meal flour proportion, barrel temperature and feed moisture content showed significant \((P < 0.05)\) effect on the SL of extrudates (Table 6). Although the changes in SL as the level of soy meal flour increased from 0 to 10% were not statistically significant \((P < 0.05)\), there was a slightly increase in SL from 1.23 to 1.27 cm/g. A further increase in soy meal flour level from 10 to 20% resulted in a significant \((P < 0.05)\) decrease in SL from 1.27 to 1.16 cm/g. This might be due to the increase in the bulk density with the increase in the protein content of the mixture.

Increasing the feed moisture content from 15 to 18% and barrel temperature from 135 to 150°C did not affect \((P \geq 0.05)\) the SL of extrudates (Table 6). However, further increasing the feed moisture content to 21% and barrel temperature to 165°C resulted in a significant \((P < 0.05)\) decrease in SL from 1.28 to 1.12 cm/g and 1.31 to 1.09 cm/g, respectively (Table 6). Ozer, Ibanoglu, Ainsworth, and Yagmur (2004) reported that the axial expansion of extrudates decreased as the feed moisture content increased. This may be due to the lower degree of gelatinization of starch at higher feed moisture content which, in turn, resulted in the higher bulk density. At higher feed moisture content, extrudates become heavier due to higher density, indicating a general strengthening of structures or filled in structure. As cell size decreased extrudates become less porous and cell walls become thicker resulting into harder extrudates with lower SL because this is inversely related with the extrudates mass.

Generally, the highest SL (1.62 cm/g) was observed at a combination of process conditions of 10% soy meal flour proportion, 18% feed moisture content and 150°C barrel temperature. On the other hand, the lowest SL (0.85cm/g) was found at a combination of 0% soy meal flour (sorghum alone), 165°C temperature and 21% feed moisture content (Table 8).

### 3.7. The effect of soy meal flour proportion, barrel temperature and feed moisture on bulk density

The bulk density (BD) is an index of extent of puffing. The extrudates having lower expansion showed higher density and vice versa (Table 6). In this study, it was found that soy meal flour proportion, barrel temperature, and feed moisture had significant \((P < 0.05)\) effect on the bulk density of the extrudate (Table 6). As the level of soy meal flour increased from 0 to 10%, the BD did not show significant change \((P \geq 0.05)\). Further increasing soy meal flour level to 20% resulted in a significant \((P < 0.05)\) increase in BD to 0.36g/cm³. Starch-protein interactions probably played
| Processing condition | Product physical property | Tt | S (%) | BT(°C) | FM (%) | *SR (cm/100g) | *SL(cm/g) | *BD(g/cm³) | *H(N) |
|----------------------|--------------------------|----|-------|--------|--------|----------------|-----------|------------|--------|
| 1                    |                          | 1  | 0     | 135    | 15     | 2.22 ± 0.00    |          | 0.21 ± 0.01 | 90.22 ± 4.25 |
| 2                    |                          | 2  | 0     | 135    | 18     | 1.28 ± 0.05    | cdefg    | 2.22 ± 0.00 | 120.74 ± 15.7 |
| 3                    |                          | 3  | 0     | 135    | 21     | 1.34 ± 0.13    | bcdef    | 0.21 ± 0.01 | 98.36 ± 0.91  |
| 4                    |                          | 4  | 0     | 150    | 15     | 1.34 ± 0.02    |          | 2.33 ± 0.05 | 82.90 ± 3.13  |
| 5                    |                          | 5  | 0     | 150    | 18     | 1.36 ± 0.09    |          | 1.96 ± 0.03 | 106.99 ± 18.2 |
| 6                    |                          | 6  | 0     | 150    | 21     | 1.25 ± 0.06    |          | 1.89 ± 0.09 | 115.08 ± 3.54 |
| 7                    |                          | 7  | 0     | 165    | 15     | 1.23 ± 0.08    |          | 2.60 ± 0.05 | 67.09 ± 2.27  |
| 8                    |                          | 8  | 0     | 165    | 18     | 1.34 ± 0.13    |          | 2.43 ± 0.09 | 90.91 ± 2.55  |
| 9                    |                          | 9  | 0     | 165    | 21     | 1.32 ± 0.01    |          | 2.93 ± 0.10 | 104.99 ± 1.32 |
| 10                   |                          | 10 | 10    | 135    | 15     | 0.85 ± 0.17    |          | 2.79 ± 0.10 | 105.78 ± 9.62 |
| 11                   |                          | 11 | 10    | 135    | 18     | 1.44 ± 0.14    |          | 1.95 ± 0.04 | 109.84 ± 9.97 |
| 12                   |                          | 12 | 10    | 135    | 21     | 1.00 ± 0.06    |          | 1.95 ± 0.04 | 108.71 ± 11.5 |
| 13                   |                          | 13 | 10    | 150    | 15     | 1.00 ± 0.06    |          | 2.45 ± 0.09 | 87.63 ± 6.59  |
| 14                   |                          | 14 | 10    | 150    | 18     | 1.54 ± 0.20    |          | 2.25 ± 0.21 | 87.63 ± 6.59  |
| 15                   |                          | 15 | 10    | 150    | 21     | 1.64 ± 0.04    |          | 2.10 ± 0.04 | 95.47 ± 5.25  |
| 16                   |                          | 16 | 10    | 165    | 15     | 1.11 ± 0.13    |          | 1.11 ± 0.13 | 114.71 ± 13.6 |
| 17                   |                          | 17 | 10    | 165    | 18     | 1.11 ± 0.13    |          | 2.42 ± 0.22 | 97.41 ± 2.83  |
| 18                   |                          | 18 | 10    | 165    | 21     | 1.11 ± 0.13    |          | 2.28 ± 0.23 | 113.23 ± 6.42 |
| 19                   |                          | 19 | 20    | 135    | 15     | 1.34 ± 0.02    |          | 1.96 ± 0.03 | 90.79 ± 0.04  |
| 20                   |                          | 20 | 20    | 135    | 18     | 1.25 ± 0.06    |          | 2.79 ± 0.10 | 95.47 ± 5.25  |
| 21                   |                          | 21 | 20    | 135    | 21     | 1.22 ± 0.05    |          | 1.96 ± 0.03 | 115.57 ± 1.41 |
| 22                   |                          | 22 | 20    | 150    | 15     | 1.10 ± 0.04    |          | 1.96 ± 0.03 | 115.57 ± 1.41 |
| 23                   |                          | 23 | 20    | 150    | 18     | 1.95 ± 0.04    |          | 1.96 ± 0.03 | 115.57 ± 1.41 |
| 24                   |                          | 24 | 20    | 150    | 21     | 1.22 ± 0.05    |          | 1.96 ± 0.03 | 115.57 ± 1.41 |

(Continued)
Table 8. (Continued)

| Processing condition | Product physical property |
|----------------------|---------------------------|
| Tt | S (%) | BT(°C) | FM (%) | n | *SL (cm/g) | *ER (cm/cm) | *BD (g/cm³) | **H (N) |
| 25 | 20 | 165 | 15 | 2 | 1.14 ± 0.06<sup>efgh</sup> | 1.92 ± 0.10<sup>gfh</sup> | 0.31 ± 0.05<sup>cdef</sup> | 118.77 ± 7.07<sup>abc</sup> |
| 26 | 20 | 165 | 18 | 2 | 1.12 ± 0.01<sup>efgh</sup> | 1.87 ± 0.03<sup>gfh</sup> | 0.33 ± 0.01<sup>abcdef</sup> | 116.01 ± 5.80<sup>abcd</sup> |
| 27 | 20 | 165 | 21 | 2 | 1.14 ± 0.03<sup>efgh</sup> | 1.74 ± 0.01<sup>hij</sup> | 0.37 ± 0.01<sup>abc</sup> | 116.00 ± 18.38<sup>abcd</sup> |
| Mean | | | | 54 | 1.22 | 2.00 | 0.28 | 103.68 |
| CV | | | | | 9.21 | 6.23 | 10.10 | 8.53 |

Values followed by the different letters within a column indicate significant difference (P < 0.05); S = soy meal flour (%); BT = barrel temperature (°C); FM = feed moisture content (%); n = number of replication; * = mean±SD; SL = specific length (cm/g); ER = diametric expansion; BD = bulk density (g/cm³); H = hardness (N); Tt = treatment number; CV = coefficient of variation.
an important role in affecting the density by disrupting the continuous starch matrix and thus reducing the extensibility of cell walls (Shi et al., 2011).

Increasing the FM from 15 to 21% also resulted in a significant (P < 0.05) increase in BD from 0.24 to 0.33 g/cm$^3$ (Table 6), probably due to the reduction in starch gelatinization. Charunuch, Tangkanakul, Lim Sangouan, and Sonted (2008) reported that high feed moisture content during extrusion may reduce the elasticity of the dough through plasticization of the melt resulting in reduced specific mechanical energy (SME) and gelatinization, which decrease the expansion and increase the density of the extrudate. Increasing barrel temperature from 135 to 150°C resulted in a significant decrease in (P < 0.05) BD from 0.30 to 0.27 g/cm$^3$. Further increasing the barrel temperature to 165°C slightly decreased the BD to 0.26 g/cm$^3$ with no significant (P ≥ 0.05) effect (Table 6). Ding et al. (2005) reported that an increase in temperature decreases the melt viscosity at the same time increasing the vapor pressure. This favors the bubble growth that is the driving force for expansion that produces low-density products. Similarly, high bulk density of extrudates, made from sorghum, horse gram and defatted soy flour blends, because of the effect of high temperature on viscosity and starch degradation was reported by Basediya et al. (2013).

The interaction between soy meal flour proportion and feed moisture content showed a significant (P < 0.0001) effect on BD (Table 7). The BD increased with increase in soy meal flour level and feed moisture content. Similar result was reported by Basediya et al. (2013). Generally, the highest BD (0.39 g/cm$^3$) was observed at process conditions of 20% soy meal flour proportion, 21% feed moisture content and 150°C temperature, and 20% soy meal flour level, 18% feed moisture and 135°C temperature (Table 8). On the other hand, the lowest BD (0.16 g/cm$^3$) was found at a process condition of 0% soy meal flour (sorghum alone), 165°C barrel temperature and 15% feed moisture content. Those samples with 20% soy meal flour proportion were found to have high BD values indicating the high influence of soy meal flour on this property. Bulk density (BD) is directly related to the texture of the final product of expanded starch-based snacks extrudates, and it is determined by the combination of growth and subsequent shrinkage or collapse of water vapor bubbles in the extrudates and also by the effect of die swelling due to the elastic property of the melted matrix (Fan, Mitchell, & Blanshard, 1996), since light density means soft structure which is desirable in such product type.

3.8. The effect of soy meal flour proportion, barrel temperature and feed moisture on instrumental texture (hardness)

As it can be seen from Table 6, soy meal flour proportion, barrel temperature and feed moisture content were found to have a significant (P < 0.05) influence on the hardness of resulting extrudate samples. An increase in soy meal flour level from 0 to 20% resulted in a significant (P < 0.05) increase in hardness from 96.48 to 112.77N. An increase in hardness with the level of soy meal flour could be attributed to reduction in expansion due to starch-protein interaction. Pelembe et al. (2002) also reported similar finding.

A significant (P < 0.05) increase in hardness from 93.14 to 103.61 N was observed as the feed moisture content increased from 15 to 18%. Further increase in FM to 21% resulted in a significant (P < 0.05) increase in hardness to 114.278 N (Table 6). Previous studies have also reported that the hardness of extrudate increases as the feed moisture content increases (Brncic et al., 2006). This is because when the moisture content of composite flours is high enough, it may impede rapid gelatinization of starch granules in the extrudates. The incomplete gelatinization eventually leads to incomplete expansion of the extrudates and consequently increases the hardness of the extrudates. Duarte et al. (1998) reported the negative association between expansion and hardness. Accordingly, the higher values of expansion index were associated with lower hardness values indicating a lighter and crispier extrudates, which is a desirable characteristic. Generally, high breaking strength values are related to large cells with thicker walls that create a crunchy texture. On the other hand, low breaking strength values are usually related to large number of small cells per unit area with thinner cell walls, resulting in a crispy texture (Duarte et al., 1998).
Increasing barrel temperature from 135 to 165°C found to reduce the hardness significantly (P < 0.05) from 109.67 to 100.11 N (Table 6). This reduction in hardness might be due to the decrease in bulk density and/or increase in expansion caused by low feed moisture content or high barrel temperature. Ding et al. (2005) reported that an increase in temperature decreases the melt viscosity at the same time increasing the vapor pressure. This favors the bubble growth, which is the driving force for expansion that produces low density products and consequently decreases the hardness of the extrudates.

The interaction between soy meal flour proportion and barrel temperature was found to have a significant (P < 0.05) influence on extrudates (Table 8). However, the interaction between soy meal flour level and feed moisture content, and barrel temperature and feed moisture content had not a significant (P < 0.05) effect on the extrudate samples. Generally, the highest hardness value (127.95N) was recorded for processing condition of 20% soy meal flour level, 135°C barrel temperature and 21% feed moisture content (Table 8). The lowest value of 67.09N was, however, recorded for processing condition of 0% soy meal flour level, 15% feed moisture content and 165°C barrel temperature. Duarte et al. (1998) observed the relationship of breaking parameters with either cell size or density. Obviously, breaking force increased as extrudates density increased, indicating a general strengthening of structures or the structure was “filled in” and less porous with thicker cell walls as cell size decreased, resulting in greater strength and larger forces required to compress the material. For example, the extrudates produced at lower moisture and higher barrel temperature levels, which had the lowest bulk densities, could have inherently weaker cell walls because of a reduction in average molecular weight of the starch (Duarte et al., 1998).

4. Conclusions
The proportion of soy meal flour and operating conditions (feed moisture content and barrel temperature) showed a significant effect on functional and physical properties of sorghum-based extrudates. Increasing the level of soy meal flour resulted in a significant increase in WAI, WSI, WHC, BD and hardness of extrudates, whereas the ER and SL of extrudates were decreased. Increasing the feed moisture content caused a significant decrease in WSI, and SL of extrudates, and increase in the WAI, BD and hardness of extrudate. WSI, WHC, BD, SL, and hardness of extrudates were significantly decreased, and WAI and ER of extrudates were significantly increased with increasing the barrel temperature. Generally, extrudate made from lower level of soy meal flour at low feed moisture and high barrel temperature had better physical properties.
and sensory properties of soy-plantain flour. African Journal of Food Science, 5(4), 176–180.

Adedeji, A. A., Suh, E., Bhadriraju, S., & Alavi, S. (2016). Drying characteristics of bean analog – a sorghum based extruded product. Journal of Food Processing and Preservation, 41(2). doi:10.1111/jfpp.12856

Anderson, R. A., Conway, H. F., & Peplinski, A. J. (1970). Gelatinization of corn grits by roll cooking, extrusion cooking and steaming. Starch-Starke, 22(4–5), 2–7. doi:10.1002/star.19700220408

Anuonye, J. C., Onuh, J. O., Egwim, E., & Adeyemo, S. O. (2010). Nutrient and antinutrient composition of extruded acha/soybean blends. Journal of Food Processing and Preservation, 34, 680–691. doi:10.1111/j.1745-4549.2009.00425.x

Asare, E. M., Sefa-Dedeh, S., Afoakwa, E. O., Sakyidawson, E., & Budu, A. S. (2010). Response surface methodology for studying the effects of feed moisture, ingredient variations on the chemical composition and appearance of extruded sorghum-groundnut cowpea blends. International Journal of Food Engineering, 6(6). doi:10.2202/1556-3758.2025

Baseldiyar, A. L., Pandey, S., Shrivastava, S. P., Khan, K. A., & Nema, A. (2013). Effect of process and machine parameters on physical properties of extrudate during extrusion cooking of sorghum, horse gram and defatted soy flour blends. Journal of Food Science and Technology, 50(1), 44–52. doi:10.1007/s13197-011-0319-y

Bellon, P. S., & Taylor, J. R. N. (2004). Sorghum and millets : Protein sources for Africa. Trends in Food Science & Technology, 15, 94–98. doi:10.1016/j.tifs.2003.09.002

Brnic, M., Tripalo, B., Jezek, D., Semenski, D., Drvar, N., & Ukrcincazyk, M. (2006). Effect of twin-screw extrusion parameters on mechanical hardness of direct-expanded extrudates. Sadhana, 31(5), 527–536. doi:10.1007/BF02715911

Charunuch, C., Tangkonakorn, P., Limsangouan, N., & Sonted, V. (2008). Effects of extrusion conditions on the physical and functional properties of instant cereal beverage powders admixed with mulberry (Morus alba L.) leaves. Food Science and Technology Research, 14(5), 421–430. doi:10.3136/fstr.14.421

Crowe, T. W., & Johnson, L. A. (2001). Twin-screw extrusion texturization of extruded-expelled soybean flour. Journal of the American Oil Chemists Society, 78(8), 781–786. doi:10.1177/0003013201075.00432-8

Devi, N. L., Shobho, S., Tang, X., Shaur, S. A., Dogan, H., Alavi, S., & Alavi, S. (2013). Development of protein-rich sorghum-based expanded snacks using extrusion technology. International Journal of Food Properties ISSN, 16(2), 263–276. doi:10.1080/10942912.2011.551865

Dicko, M. H., Gruppen, H., Traoré, A. S., Voragen, A. G. J., & Van Boekel, W. J. H. (2006). Sorghum grain as human food in Africa : Relevance of content of starch and amylase activities. African Journal of Biotechnology, 5(5), 384–395.

Ding, Q., Ainsworth, P., Plunkett, A., Tucker, G., & Manson, H. (2006). The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. Journal of Food Engineering, 73, 142–148. doi:10.1016/j.jfoodeng.2005.01.013

Ding, Q., Ainsworth, P., Tucker, G., & Manson, H. (2005). The effect of extrusion conditions on the physico-chemical properties and sensorial characteristics of rice-based expanded snacks. Journal of Food Engineering, 66, 283–289. doi:10.1016/j.jfoodeng.2004.03.019

Duarte, P. R., Majewksa, K., & Doetkott, C. (1998). Effect of extrusion process parameters on the quality of buckwheat flour mixes. Cereal Chemistry, 75(3), 338–345. doi:10.1094/CHEM.1998.75.3.338

Fan, J., Mitchell, J. R., & Blanshard, J. M. V. (1996). The effect of sugars on the extrusion of maize grits : I. The role of the glass transition in determining product density and shape. International Journal of Food Science and Technology, 31, 55–65. doi:10.1111/jfis.1996.31.issue-1

Filli, K. B., Nkamo, I., Abubakar, U. M., & Jideani, V. A. (2010). Influence of extrusion variables on some functional properties of extruded millet-soybean for the manufacture of ‘Furu’: A Nigerian traditional food. African Journal of Food Science, 4(6), 342–352.

Gbenyi, D. I., Nkamo, I., & Badau, M. H. (2016). Modelling mineral profile of extruded sorghum bambaarana groundnut breakfast cereals. British Journal of Applied Science and Technology, 17(4), 1–14. doi:10.14419/bjast.2016.29700

Golob, P., Farrell, G., & Orchard, J. E. (2002). Crop post-harvest : Science and technology (Vol. 1). Blackwell: Blackwell science Ltd.

Gopinjajraj, R., & Muthukumarappan, K. (2017). Effect of extrusion process conditions on the physical properties of Tef-Oat healthy snack extrudates. Journal of Food Processing and Preservation, e13559, 1–9. doi:10.1007/fpp.13559

Hagenimana, A., Ding, X., & Fang, T. (2006). Evaluation of rice flour modified by extrusion cooking. Journal of Cereal Science, 43, 38–46. doi:10.1016/j.jcs.2005.09.008

Hegazy, H. S., El-bedawy, A. E. A., Rahmo, E. H., & Gasfar, A. M. (2017). Effect of extrusion process on nutritional, functional properties and antioxidant activity of germinated chickpea incorporated corn extrudates. American Journal of Food Science and Nutrition Research, 4(1), 59–66.

Hernandez-Diaz, J. R., Quintero-Ramos, A., Barnard, J., & Balandran-Quintana, R. R. (2007). Functional properties of extrudates prepared with blends of wheat flour/pinto bean meal with added wheat bran. Food Science and Technology International, 13(4), 301–308. doi:10.1177/10820132013070824863

Hernandez-Nova, R. G., Bella-Perez, L. A., Martin-Martinez, E. S., Hernandez-Sanchez, H., & Moro-Escobedo, R. (2011). Effect of extrusion cooking on the functional properties and starch components of lentil/banana blends: Response surface analysis. Revista Mexicana De Ingenieria Quimica, 10(3), 409–419.

Kebede, L., Solomon, W., Bultosa, G., & Vetereberek, S. (2010). Effect of extrusion operating conditions on the physical and sensory properties of tef (Eragrostis tef [Zuc. ] Trotter) flour extrudates. Ethiopian Journal of Applied Science and Technology, 1(1), 27–38.

Kumar, T. V. A., Samuel, D. V. K., Jha, S. K., & Sinha, J. P. (2015). Twin screw extrusion of sorghum and soya blends : A response surface analysis. Journal of Agricultural Science and Technology, 17, 649–662.

Kurt, A. R., Muthumarappan, K., & Kannadhasan, S. (2009). Effects of ingredients and extrusion parameters on properties of Aquafeeds containing DDGS and corn starch. Journal of Aquaculture Feed Science and Nutrition, 1(1), 22–38. joa.sfsu.2009.22.38.

Lazou, A., & Krkouda, M. (2010). Functional properties of corn and corn-lentil extrudates. Food Research International, 43, 609–616. doi:10.1016/j.foodres.2009.09.017

Leone, M., de Freitas, T. S., & Mischan, M. M. (2009). Physical characteristics of extruded cassava starch. Scientia Agricola, 66(4), 486–493. doi:10.1590/S0103-9062009000600009
