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Physical characteristics of corn extrudates supplemented with red lentil bran

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ABSTRACT

In this study, extruded snacks were produced from corn flour supplemented with red lentil bran (RLB), and effects of exit-die temperature (110, 130 or 150 °C), feed moisture content (19 or 21%), and bran levels (5 or 10%) on the physical and textural properties of extrudates were investigated. A 5% RLB addition level improved the radial expansion index (REI) values of extrudates produced at relatively low exit-die temperature (110 and 130 °C), compared to control samples. Among the bran supplemented samples, the highest REI (4.46) and the lowest extrudate density (ED) (164 kg m^{-3}) results were obtained from 5% RLB blended corn extrudates produced at 150 °C exit-die temperature and 19% feed moisture content. High correlations were determined between extrudates REI and crunchiness ($R^2 = 0.871$) between ED and hardness ($R^2 = 0.890$) and between REI and ED ($R^2 = -0.857$). Whereas REI, ED and colour values of extrudates significantly ($p < 0.001$) influenced by RLB addition to feeding recipe; hardness and crunchiness were not considerably affected. These results show RLB one of the pulse by-products can be used practically in the development of fibre-rich extruded snacks and utilised to provide products with added-value from lentil wastes.

1. Introduction

Snack foods are generally produced by using cereal-based refined flour or starch and many of them are relatively high in sugar, fat and salt, hence being considered energy-dense but nutritionally poor foods. In recent years, with the growth of the market for healthy and sustainable diets, and with increased consumer awareness of diet, health and the environment, there has been the opportunity to develop innovative healthy as well as eco-friendly extruded snacks (Grasso, 2020). Although large amounts of food industry by-products (e.g. cereal brans, vegetable and fruit pomaces, oilseed cakes) were previously discarded or used for animal feed, these residues have more recently been extensively utilised in the extrusion process for re-integration into edible snack foods (Offiah, Kontogiorgos, & Falade, 2019).

Extrusion cooking is a high-temperature, short-time process, which allows the development of a wide range of food products such as fibre-rich products, puffed snacks, breakfast cereals, and various other cereal products. The extruded food products' quality is remarkably dependent upon feed material composition, barrel temperature profile, feed moisture content, screw speed and other extrusion system parameters. Given consumer expectations for the puffed snack foods, high expansion and low density, in addition to crunchy texture and uniform microstructure are desired (Alam, Kaur, Khaira, & Gupta, 2016; Bilgi Boyaci et al., 2012; Meng, Threinen, Hansen, & Driedger, 2010; Trater, Alavi, & Rizvi, 2005). Although dietary fibre-rich cereal brans/vegetable or fruit pomaces in food formulations have adverse effects on expansion and textural, rheological and sensorial properties of end products (Robin, Schuchmann, & Palzer, 2012), these food industry by-products are extensively used to add nutritional value (e.g. antioxidants, minerals, essential fatty acids and dietary fibres) to extruded snacks (Grasso, 2020; Obradović, Babić, Šubarić, Ačkar, & Jozinović, 2014; Offiah et al., 2019).

Grasso (2020) evaluated food industry by-products which are used for producing extruded snacks in mainly four categories: (*i*) pomace and bagasse from fruit and vegetables, (*ii*) bran and spent grains from cereals, (*iii*) oilseed cakes, and (*iv*) whey from the dairy industry. This review outlined the most recent efforts (2014–2018) to include food industry by-products in the production of healthier extruded snacks. While physical and textural properties of extruded snacks supplemented with the aforementioned food industry by-products have been studied

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extensively (Fleischman et al., 2016; Foschia, Peressini, Sensidoni, & Brennan, 2013; Grasso, 2020; Obradović et al., 2014; Offiah et al., 2019), studies on extrusion products incorporating pulse by-products are quite limited.

The objective of this research was to produce fibre-rich extruded snacks by using RLB as a fibre source at different extrusion parameters and thus to introduce a new technique for utilizing lentil waste. It was also sought to investigate the effects of extrusion process variables such as exit-die temperature, feed moisture content and red lentil bran addition level on the physical and textural properties of extruded snacks.

2. Materials and methods

2.1. Materials

Commercial corn flour was obtained from Ankara Metropolitan Municipality Bread Factory (Ankara, Turkey). Red lentil bran (RLB; dark brown in colour) was supplied by Oncu Bakliyat Co. (Mersin, Turkey). RLB was ground by using a LM 3100 laboratory hammer mill (Perten Instruments, Hägersten, Sweden) before sample preparation. The particle size distribution of corn flour and milled RLB was determined according to ASAE Standards Method No. S319.3 (ASAE Standards, 2003), by sifting 100 g of raw material per 10 min through with four sieves with different opening sizes (500, 250, 125 and 75 μm). It was determined that 95.29–98.91 g/100g of the particles in the corn flour fall within the particle size range of 75–500 μm, while 85.16–86.68 g/100g of the RLB particles fall within the same range. The most concentrated particle size distribution was observed in the range of 125–500 μm for both corn flour (71.49–77.4 g/100g) and RLB (82.52–83.05 g/100g).

2.2. Methods

2.2.1. Sample preparation

RLB was supplemented into corn flour at two different levels (5% and 10%; w/w) with the results of a preliminary experiment. Due to the fact that any extrusion product could not be obtained from the blend prepared by adding 15% (w/w) RLB, it was not integrated into the experimental design. First, a 1 kg mixture of RLB with corn flour was achieved in a laboratory−type mixer (KitchenAid, K5SS, St. Joseph, Michigan, USA) in order to prevent concentrated pockets of components. Then, the mixture was transferred to a Hobart mixer (Hobart A-200, Ohio, USA) for bulk blending and mixed for 30 min; hence, a 20 kg blend was prepared in total for each extrusion run.

2.2.2. Proximate analyses

The moisture contents (g kg^{-1}, wb) of raw materials (corn flour, 5 and 10% RLB supplemented corn flour) were determined according to AACC International Method No. 44–15.02 (AACC International, 2000). The protein ($N \times 6.25$), fat and ash contents (g kg^{-1}, db) of these raw materials were determined according to AACC International Method No. 46–12.01, No. 30–25.01 and No. 08–01.01, respectively (AACC International, 2000). Total dietary fibre contents (g kg^{-1}, db) of raw materials were determined using Megazyme Total Dietary Fibre Kit (Megazyme International Ireland Ltd. Co., Wicklow, Ireland) according to AOAC Approved Method 991.43 (AOAC, 2000). Proximate analyses of raw materials were performed at least in duplicate and the average values were reported.

2.2.3. Extrusion process

Corn flour and corn flour RLB blends (95:5 and 90:10; w/w) were extruded using a laboratory scale twin-screw co-rotating extruder (Feza Makine Ltd Co., Istanbul, Turkey) with a 25:1 screw length to diameter ratio and a die hole diameter of 2.0 mm. Screw configuration was designed as the same following Masatcioglu, Sumer, & Koksel, 2017. The feeder and water pump of the extruder were calibrated to perform a feed rate of 3 kg h^{-1} and feed moisture contents of 19 and 21%. The screw speed was kept constant at 175 rpm for all extrusion runs. The four barrel zones of the barrel were set depending on the exit-die temperatures. Extrusion temperature profiles (from feeder to die zone) were 60/80/100/110 °C, 60/90/110/130 °C, and 60/100/130/150 °C when the temperatures of the exit-die were adjusted to 110, 130 and 150 °C, respectively. Torque and die pressure values of each run were recorded during extrusion and specific mechanical energy (SME) was calculated according to Koksel and Masatcioglu (2018). When the extrusion system parameters (torque, pressure, temperature, feed moisture content and screw speed) reached the steady state, the extrusion products were collected. All extrusion samples collected were oven-dried at 50 °C overnight to achieve a moisture content less than 7% and stored in air- and light-tight plastic bags until further analyses. Each extruded sample was produced in two replicates at two different times.

2.2.4. Image acquisition of extrudates

The images of extrusion products were taken from an image acquisition system consisting of a Pentax K-r digital camera (Japan) and an illumination apparatus. The digital camera was placed vertically at a distance of 20 cm from the sample. The sources of illumination (two fluorescent lamps, Natural Daylight 18 W, colour temperature of 6500 K) were placed at an angle of 45° to the axes of the camera. Images were captured against the same scaled background without automatic zoom.

2.2.5. Radial expansion index and extrudate density

The radial expansion index (REI) was calculated by taking the ratio of extrusion products diameter to extruder exit–die hole diameter (2.0 mm). After drying the extruded samples overnight, 10 randomly selected pieces of extrudate diameters were measured by using digital callipers (with 0.01 mm sensitivity) five times (50 measurements in total) for each run. Extrudate density (ED) was determined according to Koksel and Masatcioglu (2018) and Luo et al. (2020). ED was calculated by a canola seed displacement technique using Eq. (1):

$$\rho_{ext} = \frac{W_{ext}\ (kg)}{V_c\left(m^3\right) x \left(1 - \frac{W_{ext+cs}\ (kg)}{W_{cs}\ (kg)}\right)} \quad (1)$$

where ρ_{ext}, W_{ext}, V_c, W_{ext+cs} and W_{cs} demonstrate density of extrudates, extrudates mass (weighed on a balance), the volume of the cylindrical container, the combined weight of extrudates and canola seeds in constant volume, and canola seeds weight in constant volume respectively. Five measurements were conducted for each treatment.

2.2.6. Texture analysis

The texture characteristics of extrusion products were determined using a texture analyser (Stable Micro Systems TA.XT *plusC*, Guildford, UK) according to the procedure described by Masatcioglu, Gokmen, Ng, & Koksel, 2014. The texture analyser was fitted with a 5 kg load cell and a shear blade probe (1.22 mm thick) with a shear angle of 90°. A trigger force was set to 5.0 g and as pre-test, test and post-test speeds were adjusted by 1.00, 1.00 and 10.00 mm s^{-1}, respectively. Before the texture analysis, all extrusion products were dried with a fan assisted oven dryer (BINDER, FD 115, Tuttlingen, Germany) at 50 °C overnight to ensure approximately equal moisture content. The approximately 5 cm-long extrudates were placed in the centre of the analyser plate. A shear blade probe was lowered to cut the sample up to 50% of its original thickness. Exponent Connect software (Version 6, Stable Micro System, Godalming, UK) was used to plot a time vs. force graph from which textural properties were extracted. During texture analysis, hardness and crunchiness values were measured as maximum peak force (g) and as the total number of positive peaks from the force vs. time plot, respectively. Twenty randomly selected sub-samples were taken from each extrudate sample and results were presented as the average of measurements taken from the sub-samples.

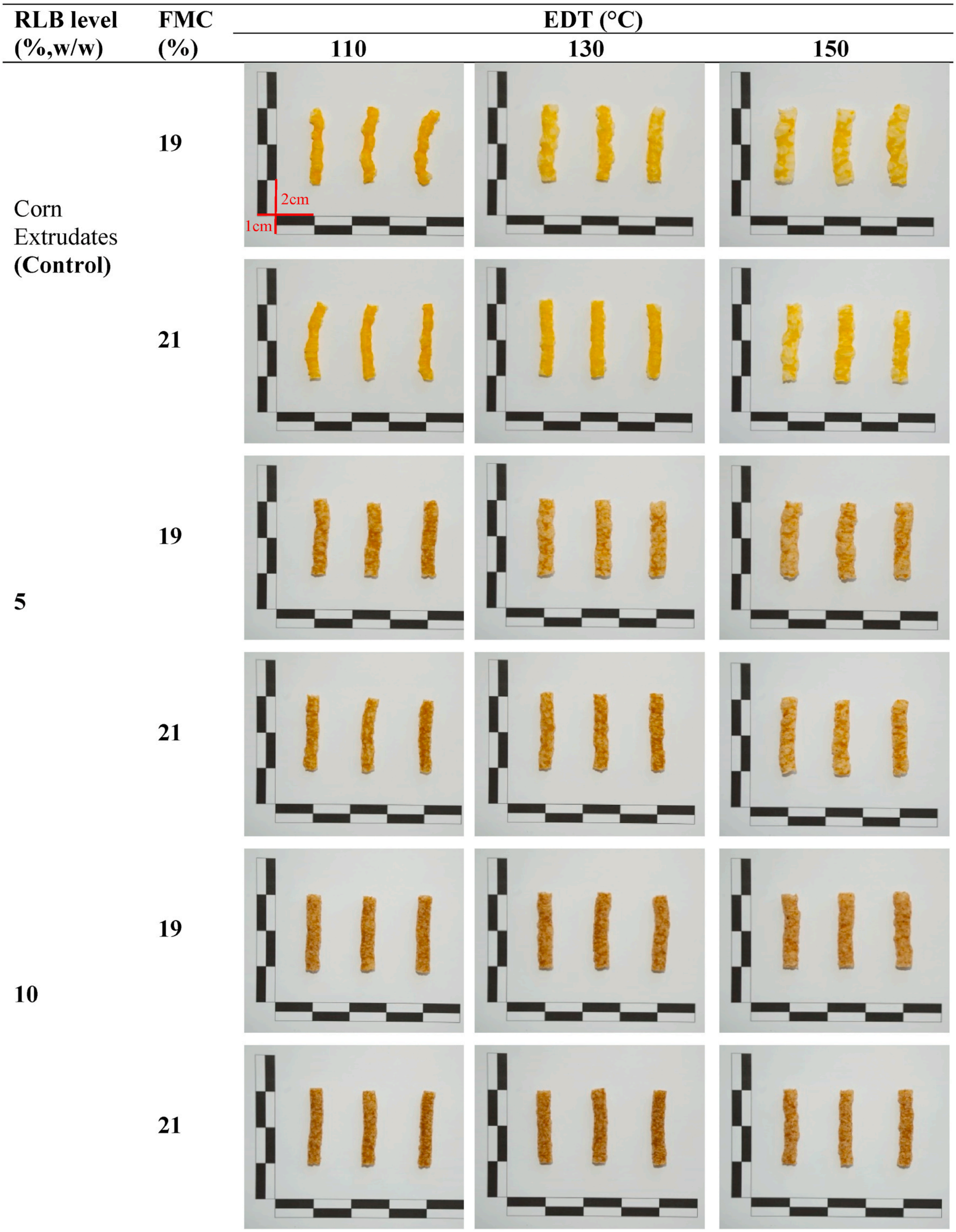

Fig. 1. The images of corn flour and RLB corn flour blend extrudates produced by different extrusion conditions. (*) *The scale (short edge:* 1 cm *& long edge:* 2 cm*) is given in the first picture (left-bottom).*

2.2.7. Colour measurement

Colour values of the extrudates produced by different extrusion conditions were measured by a colourmeter (CR-400, Minolta, Osaka, Japan), using the CIE (L^*, a^*, b^*) system. In the CIE colour space, L^* is for lightness, a^* is for greenness/redness, and b^* is for blueness/yellowness of extrudates. The overall colour difference (ΔE) between an extrudate and the reference ($L_{ref}^* = 0$; $a_{ref}^* = 0$; $b_{ref}^* = 0$, i.e., black) was calculated using Eq. (2):

$$\Delta E = \sqrt{\left(L^* - L_{ref}^*\right)^2 + \left(a^* - a_{ref}^*\right)^2 + \left(b^* - b_{ref}^*\right)^2} \quad (2)$$

The Chroma value, which represents the intensity of the colour, was calculated using Eq. (3):

$$Chroma = \sqrt{a^2 + b^2} \quad (3)$$

The results were reported as the mean of three measurements for each extrusion run.

Table 1
Dependent extrusion process variables[†].

RLB level (%, w/w)	EDT (°C)	FMC (%)	Torque (Nm)	Die pressure (kPa)	SME (Wh kg^{-1})
Corn flour extrudates (Control)	110	19	20.33 ± 0.49^{c}	5470 ± 109^{a}	124.16 ± 2.97^{c}
		21	17.29 ± 0.19^{g}	4660 ± 65^{c}	105.61 ± 1.17^{g}
	130	19	18.57 ± 0.58^{e}	4240 ± 45^{ef}	113.46 ± 3.54^{e}
		21	15.42 ± 0.42^{j}	3760 ± 24^{g}	94.19 ± 2.54^{j}
	150	19	16.30 ± 0.41^{hi}	3225 ± 46^{ij}	99.54 ± 2.51^{hi}
		21	13.20 ± 0.21^{l}	2730 ± 32^{k}	80.63 ± 1.30^{l}
5	110	19	20.91 ± 0.63^{c}	5380 ± 41^{ab}	127.73 ± 3.82^{c}
		21	16.94 ± 0.70^{gh}	4450 ± 131^{d}	103.47 ± 4.28^{gh}
	130	19	18.22 ± 0.88^{ef}	4500 ± 143^{d}	111.31 ± 5.37^{ef}
		21	14.60 ± 0.49^{k}	3520 ± 107^{h}	89.19 ± 2.97^{k}
	150	19	15.54 ± 0.29^{ij}	3300 ± 42^{i}	94.90 ± 1.75^{ij}
		21	12.73 ± 0.66^{l}	2720 ± 70^{k}	77.78 ± 4.04^{l}
10	110	19	24.65 ± 0.55^{a}	5305 ± 104^{b}	150.56 ± 3.35^{a}
		21	19.39 ± 0.76^{d}	4370 ± 61^{de}	118.45 ± 4.62^{d}
	130	19	21.85 ± 0.62^{b}	4220 ± 83^{f}	133.44 ± 3.78^{b}
		21	17.64 ± 0.45^{fg}	3880 ± 98^{g}	107.75 ± 2.73^{fg}
	150	19	17.76 ± 0.39^{efg}	3150 ± 140^{j}	108.46 ± 2.40^{efg}
		21	17.17 ± 0.94^{g}	2575 ± 168^{l}	104.89 ± 5.74^{g}

([†]) *RLB*: red lentil bran; *EDT*: exit-die temperature; *FMC*: feed moisture content; *SME*: specific mechanical energy ($n = 2$ for extrusion runs).
Values were presented by average ± standard deviations.
Values followed by different superscripts in the same column are significantly different ($p < 0.05$).

2.2.8. Statistical analysis

The experimental data were analysed statistically by means of one–way analysis of variance (ANOVA). Before ANOVA, the normality assumption and homogeneity of the variances were checked using the Shapiro–Wilk and Levene tests. When the difference between the samples was statistically significant ($p < 0.05$), the Duncan test was used to determine the differences among the means. In addition, three-way interaction amongst extrusion system parameters and correlation between physical properties of samples were determined by ANOVA.

3. Results and discussion

3.1. Proximate composition of raw materials

The moisture content of corn flour and RLB was determined as 102.7 ± 0.51 g kg^{-1} (wb) and 86.8 ± 1.03 g kg^{-1} (wb), respectively. The protein, fat, ash and total dietary fibre content of corn flour was 57.5 ± 2.42 g kg^{-1} (db), 12.4 ± 1.20 g kg^{-1} (db), 5.9 ± 0.16 g kg^{-1} (db) and 53.1 ± 3.89 g kg^{-1} (db), respectively, whereas their content in RLB was 146.4 ± 1.71 g kg^{-1} (db), 9.1 ± 0.29 g kg^{-1} (db), 30.5 ± 0.09 g kg^{-1} (db) and 797.8 ± 6.93 g kg^{-1} (db), respectively. Corn flour demonstrated typical proximate composition values, similar to those reported by Carvalho, Takeiti, Onwulata, and Pordesimo (2010) and da Silva, Ascheri, de Carvalho, Takeiti, and Berrios (2014). Wang and Toews (2011) have investigated the fibre fractions of cotyledons from different pulse varieties; according to their results, lentil fibre fractions had 113.3–116.2 g kg^{-1} protein, 3.6–5.3 g kg^{-1} fat, 15.4–16.8 g kg^{-1} ash and 663.2–727.5 g kg^{-1} total dietary fibre. Our results were found to be relatively higher than Wang and Toews' findings. This might stem from their fibre extraction method. In other words, the relatively higher protein content of RLB in our study could be explained by cotyledon contamination or by the protein attached to the inner seed coat.

3.2. Images of extrusion products

Colour and texture are important quality factors directly related to the acceptability of extrusion products (Tan, Gao, & Hsieh, 1994). It is evident that the colour and textural properties of extrudates will change through the incorporation of food industry by-products such as cereal brans or dietary fibres from different vegetable sources into formulations. Moreover, both attributes of extrudates are remarkably affected by processing conditions during extrusion (Lue, Hsieh, & Huff, 1991; Masatcioglu et al., 2017).

The images of corn flour extrudates and RLB-incorporated corn flour extrudates produced by different exit-die temperatures and feed moisture contents are presented in Fig. 1. These images were provided for visual comparison and given a preliminary insight into the physical quality properties of the extrusion products such as expansion index and colour values.

Although an irregular shape was observed in the image of corn flour extrudate produced at 19% feed moisture content and 110 °C exit-die temperature, the increase in exit-die temperature gave rise to expansion and change in the structure of air cells. This was more evident at the low feed moisture content (Fig. 1). The effects of system parameters on the formation of air cells and improving the expansion ratio are discussed in detail in Section 3.4 and 3.5. Furthermore, digital images have also indicated the differences among the colour values of the extrudates. Qualitative analysis results of colour values (L^*, a^*, b^*, Chroma and ΔE) are given in Section 3.6.

3.3. Dependent extrusion variables

Dependent extrusion process variables, namely torque, die pressure and specific mechanical energy (SME) are shown in Table 1. Torque, die pressure and SME values of corn-based extrudates produced by different extrusion conditions varied between 12.73–24.65 Nm, 2720–5470 kPa and 77.78–150.56 Wh kg^{-1}, respectively. For all extrusion treatments, torque values significantly decreased ($p < 0.05$) as feed moisture content increased, except those produced by using 10% RLB corn flour blend extrudates at 150 °C exit-die temperature. Likewise, the torque values of the extruder significantly decreased ($p < 0.05$) with increasing exit-die temperature at each feed moisture content (19 and 21%) in both RLB added extrudates and control samples. Similar significant decreasing trends ($p < 0.05$) were also observed in die pressure and SME values (Table 1). The decreases in the torque and SME values with the increase in the feed moisture contents are probably due to water's plasticising effect; it can be attributed to the reduction in melt viscosity (Selani et al., 2014). Viscosity is temperature-dependent and decreasing die-temperature can decrease the degree of starch gelatinisation, leading to increased viscosity (Karkle, Keller, Dogan, & Alavi, 2012). In other words, increasing die-temperature causes a decrease in viscosity resulting in decreases in the torque and SME values.

The torque and SME values of 10% RLB corn flour blend extrudates were significantly higher ($p < 0.05$) than control samples' (corn flour extrudates). This finding is in agreement with the results from the study of Singha, Muthukumarappan, and Krishnan (2018), in which the torque and SME values increase with increases the in fibre (distillers dried grains processed for food application; FDDG) addition level. This is because of two main reasons: the high fibre content could be due to (*i*) diluting the starch concentration in the mixture (Singha et al., 2018), or (*ii*) binding more water (Mir, Bosco, Shah, Santhalakshmy, & Mir,

Table 2
Three-way analysis of variance on the effects of RLB level, exit-die temperature, and feed moisture content on physical properties of corn flour and RLB corn flour blend extrudates†.

Effect	DF	*p* value								
		REI	ED	Hardness	Crunchiness	*L**	*a**	*b**	Chroma	ΔE
RLB	2	***	***	NS	NS	***	***	***	***	***
EDT	2	***	***	***	***	***	***	***	***	***
FMC	1	***	***	***	***	***	***	***	***	***
RLB × EDT	4	***	***	*	NS	***	***	***	***	***
RLB × FMC	2	*	***	NS	NS	***	***	***	***	***
EDT × FMC	2	NS	NS	NS	NS	***	**	***	***	***
RLB × EDT × FMC	4	**	NS	NS	NS	***	***	***	***	***

(†) *RLB*: red lentil bran level; *EDT*: exit-die temperature; *FMC*: feed moisture content; *REI*: radial expansion index; *ED*: extrudate density; *L**: lightness; *a**: greenness/redness; *b**: blueness/yellowness; *ΔE*: total colour difference; *DF*: degrees of freedom *NS*: non-significant.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

Table 3
Pearson's correlation for physical properties of corn flour and RLB corn flour blend extrudates†.

	ED	Hardness	Crunchiness	*L**	*a**	*b**	Chroma	ΔE
REI	−0.857**	−0.880**	0.871**	0.058	0.032	0.013	0.010	0.049
ED	1	0.890**	−0.843**	0.359	−0433	0.384	0.385	0.365
Hardness		1	−0.922**	0.137	−0216	0.122	0.124	0.135
Crunchiness			1	−0.127	0.187	−0.101	−0.104	−0.124
*L**				1	−0.987**	0.976**	0.976**	0.999**
*a**					1	−0.987**	−0.987**	−0.990**
*b**						1	1.000**	0.984**
Chroma							1	0.984**
ΔE								1

(†) *REI*: radial expansion index; *ED*: extrudate density; *L**: lightness; *a**: greenness/redness; *b**: blueness/yellowness; *ΔE*: total colour difference.
** Correlation is significant at the 0.01 level.

2017). Both are related to an increase in the melt viscosity inside the extruder, leading to an increase in torque and SME values.

3.4. Radial expansion index and extrudate density

The effects of extrusion system variables (RLB addition level, exit-die temperature and feed moisture content) on physical properties of corn-based extrudates and Pearson's correlation of outputs are given in Table 2 and Table 3, respectively. Radial expansion index (REI) and extrudate density (ED) values of corn-based extrudates were significantly affected by almost all extrusion system variables studied, in either alone or in interactions among them. RLB addition level, exit-die temperature, feed moisture content and RLB addition level × exit-die temperature interactions were highly significant ($p < 0.001$) for both REI and ED, while RLB addition level × exit-die temperature × feed moisture content interactions were significant ($p < 0.01$) only for the REI value (Table 2).

REI values of corn flour extrudates and different ratios of RLB corn flour blended extrudates are presented in Table 4. REI values of extruded samples produced by different system parameters varied between 2.92 and 4.87. The highest REI value was obtained from corn flour extrudate produced by 150 °C exit-die temperature and 19% feed moisture content (Table 4, Fig. 1). REI values were significantly decreased ($p < 0.05$) with increasing feed moisture content in all extrusion process conditions, except for the corn flour extrudates produced at 110 °C exit-die temperature. This might be since the increased water content in the melt would soften the amylopectin molecular structure and reduce its elastic characteristics, therefore decreasing radial expansion (Alvarez-Martinez, Kondury, & Harper, 1988). On the other hand, fibres are also able to bind some of the moisture presents in the matrix, thus reducing its availability for expansion (Moraru & Kokini, 2003).

In extrusion samples produced by blending 5% RLB with corn flour and corn flour at each feed moisture content, the REI values significantly ($p < 0.05$) increased as the exit-die temperature was increased (Table 4). A similarly increasing trend was also observed in the 10% RLB supplemented samples; however, the increases were not significant ($p > 0.05$) at high exit-die temperature (150 °C). At low exit-die temperature (110 °C and 130 °C) and low feed moisture content (19%) extrusion process conditions, REI values of extrudates significantly increased ($p < 0.05$) with 5% RLB supplementation level, and adversely decreased ($p < 0.05$) with 10% addition level when compared with control samples. The REI values of all RLB supplemented extrudates produced at 150 °C exit-die temperature and both feed moisture contents (19% and 21%) significantly decreased ($p < 0.05$) as compared to the corresponding corn flour extrudates (Table 4). Moraru and Kokini (2003) and Hernández-Díaz, Quintero-Ramos, Barnard, and Balandrán-Quintana (2007) reported that their concentration highly affects the expansion ratio of extrudates, regardless of the source of fibre. Grenus, Hsieh, and Huff (1993) stated that both radial and axial expansion increased at 10% rice bran supplemented rice flour extrudates compared with control samples and decreased at higher levels (20 and 30%). The authors indicated that with the presence of a low concentration of rice bran (e.g. 10%) in the extrusion barrel, bran served as the additional nucleation sites for water evaporation as the sample left from the die-exit, and thus both expansion values (radial and axial) were higher than the control sample (0% rice bran). This phenomenon is also explained by Moraru and Kokini (2003) as strict and long fibre molecules in small quantities aligning themselves in the barrel in the flow direction, reinforcing the expanding matrix and increasing its mechanical resistance longitudinally; in turn, the fibre molecules disrupt the continuous structure of the starch melt when above the threshold level, restraining its elastic deformation during expansion.

ED values of corn- and RLB-supplemented extrudates are also presented in Table 4. ED values of extruded samples produced by different system parameters varied between 162 and 691 kg m^{-3}. The corn flour extrudate produced by 150 °C exit-die temperature and 19% feed

Table 4
Radial expansion index, extrudate density, hardness and crunchiness values of corn flour and RLB corn flour blend extrudates[†].

RLB level (%, w/w)	EDT (°C)	FMC (%)	REI	ED (kg m^{-3})	Hardness (g)	Crunchiness (peak count)
Corn flour extrudates (Control)	110	19	2.99 ± 0.13^{h}	660 ± 94^{a}	1318.70 ± 60.54^{c}	5.65 ± 2.22^{hi}
		21	2.92 ± 0.12^{h}	691 ± 84^{a}	1430.9 ± 79.48^{b}	4.65 ± 1.43^{i}
	130	19	3.92 ± 0.23^{de}	328 ± 31de	817.13 ± 68.69^{hi}	10.00 ± 1.41^{de}
		21	3.49 ± 0.10^{f}	349 ± 46^{cd}	974.16 ± 164.94^{fg}	7.75 ± 0.82^{f}
	150	19	4.87 ± 0.23^{a}	162 ± 7^{h}	492.89 ± 27.62^{kl}	16.20 ± 0.75^{a}
		21	4.43 ± 0.28^{b}	226 ± 6^{g}	732.99 ± 119.15^{ij}	11.55 ± 1.12^{c}
5	110	19	3.77 ± 0.11^{e}	338 ± 19$^{c\text{-}e}$	1054.10 ± 63.49^{ef}	7.05 ± 1.14^{fg}
		21	3.23 ± 0.04^{g}	459 ± 23^{b}	1525.40 ± 241.40^{a}	6.40 ± 0.94^{gh}
	130	19	4.11 ± 0.06^{c}	236 ± 8^{g}	779.11 ± 22.02$^{h\text{-}j}$	10.80 ± 0.75^{cd}
		21	3.56 ± 0.05^{f}	390 ± 28^{c}	1087.20 ± 33.40^{e}	6.20 ± 2.00^{gh}
	150	19	4.46 ± 0.16^{b}	164 ± 7^{h}	574.69 ± 44.41^{k}	13.50 ± 1.13^{b}
		21	4.10 ± 0.06^{c}	251 ± 7^{fg}	718.74 ± 80.70^{j}	10.20 ± 1.11^{de}
10	110	19	3.58 ± 0.01^{f}	291 ± 8^{ef}	956.18 ± 70.76^{g}	9.20 ± 0.48^{e}
		21	3.28 ± 0.05^{g}	391 ± 17^{c}	1199.30 ± 43.60^{d}	6.20 ± 0.78^{gh}
	130	19	3.84 ± 0.05^{de}	264 ± 57^{fg}	796.08 ± 44.61$^{h\text{-}j}$	9.80 ± 0.95^{de}
		21	3.50 ± 0.05^{f}	355 ± 26^{cd}	1056.90 ± 112.84^{ef}	9.50 ± 0.41^{e}
	150	19	3.99 ± 0.09^{cd}	175 ± 9^{h}	471.95 ± 22.86^{l}	15.40 ± 1.10^{a}
		21	3.50 ± 0.05^{f}	272 ± 6^{fg}	860.77 ± 105.44^{h}	9.80 ± 0.67^{de}

([†]) *RLB*: red lentil bran; *EDT*: exit-die temperature; *FMC*: feed moisture content: *REI*: radial expansion index; *ED*: extrudate density ($n = 2$ for extrusion runs; $n = 50$ for REI; $n = 5$ for ED; $n = 20$ for texture measurements).
Values were presented by average ± standard deviations.
Values followed by different superscripts in the same column are significantly different ($p < 0.05$).

moisture content extrusion conditions resulted in the lowest ED value (Table 4). In general, ED values of control and fibre rich extrudates increased as feed moisture content increased. This increasing trend was found to be significant ($p < 0.05$) in the RLB blended samples produced at each exit-die temperature (Table 4). Asare, Sefa-Dedeh, Sakyi--Dawson, and Afoakwa (2004) reported increases in bulk density with increasing feed moisture content because the extrusion cooking was not enough to vaporize whole moisture from the die nozzle, this leading to retention of some moisture, and hence the reduced puffing of the product, the results of which were denser.

ED values of corn- and RLB-supplemented extrudates decreased with increasing exit-die temperature at each feed moisture content and most of these decreases were significant ($p < 0.05$). This is probably due to the higher barrel temperatures increasing the extent of gelatinisation and also the content of superheated steam giving rise to more expansion, this resulting in low bulk density products (Guha & Ali, 2006). According to another study, under higher barrel temperature conditions, the extrudates leaving the barrel lose more moisture and become lighter in weight, thus decreasing density values of samples (Samray, Masatcioglu, & Koksel, 2019).

As indicated in Table 3, ED values were strongly and negatively correlated to the REI values ($R^2 = -0.857$). In the current study, the inverse relation between ED and REI values are consistent with the literature (Alam et al., 2016; Samray et al., 2019).

3.5. *Textural properties of extrudates*

Hardness and crunchiness values of extrudates were significantly ($p < 0.001$) affected by exit-die temperatures and feed moisture contents; however, exit-die temperature × feed moisture content interactions were not found to be significant ($p > 0.05$) in both values (Table 2).

To better explain the hardness and crunchiness values of the extrudates, typical force-time curves of two selected samples (the hardest and softest among the extrudates studied) produced by different extrusion conditions are given in Fig. 2. The hardness and crunchiness values of 5% RLB blended corn extrudates produced at 21% feed moisture content and the exit-die temperature of 110 °C were found to be 1373.0 g and 6, respectively (Fig. 2a). The counterpart values were determined as 426.2 g and 17 for 10% RLB blended corn extrudates produced at 19% feed moisture content at an exit-die temperature of 150 °C, respectively (Fig. 2b).

The effects of RLB level, exit-die temperature and feed moisture content on textural properties of extruded samples are given in Table 4. Hardness values of control and RLB supplemented extrudates significantly increased ($p < 0.05$) with increasing feed moisture content at each exit-die temperature (Table 4). This might be due to the water acting as plasticiser of the amorphous regions of starch granules and leading to starch gelatinisation, this consequently reducing the viscosity and the capacity for mechanical energy dissipation in the extruder. Thus, the final product becomes denser and harder with restricted cell growth (Ding, Ainsworth, Plunkett, Tucker, & Marson, 2006; Oliveira, Schmiele, & Steel, 2017). In the present study, the hardness values of extrudates were strongly linear correlated to the ED values ($R^2 = 0.890$); this finding is in agreement with the results was reported by Ding et al., 2006 and Samray et al., 2019.

For all extrusion samples, as the exit-die temperature increased, the hardness values decreased significantly ($p < 0.05$) at each feed moisture content (Table 4). Yao, Jannink, Alavi, and White (2006) reported that the hardness of extruded cereal displayed an inverse relationship with its expansion. This is mainly because of the fact that a more expanded extrusion product has longer but thinner cell walls, this leading to ease in crushing of the product under compression (Yao et al., 2006). As indicated in Table 3, the present study confirmed the results of the earlier studies that also reported strong and negative correlation between REI and hardness values (Koksel & Masatcioglu, 2018; Yao et al., 2006).

In general, increasing RLB addition levels caused slight decreases in the hardness values and slight increases in the crunchiness values as compared to respective control samples (Table 4); however, these increases/decreases tendency were not found to be significant at $p > 0.05$ (Table 2). On the other hand, as mentioned above, crunchiness values were significantly ($p < 0.001$) influenced by extrusion system parameters such as exit-die temperature and feed moisture content. Crunchiness values of extrudates had an increasing trend as the exit-die temperature

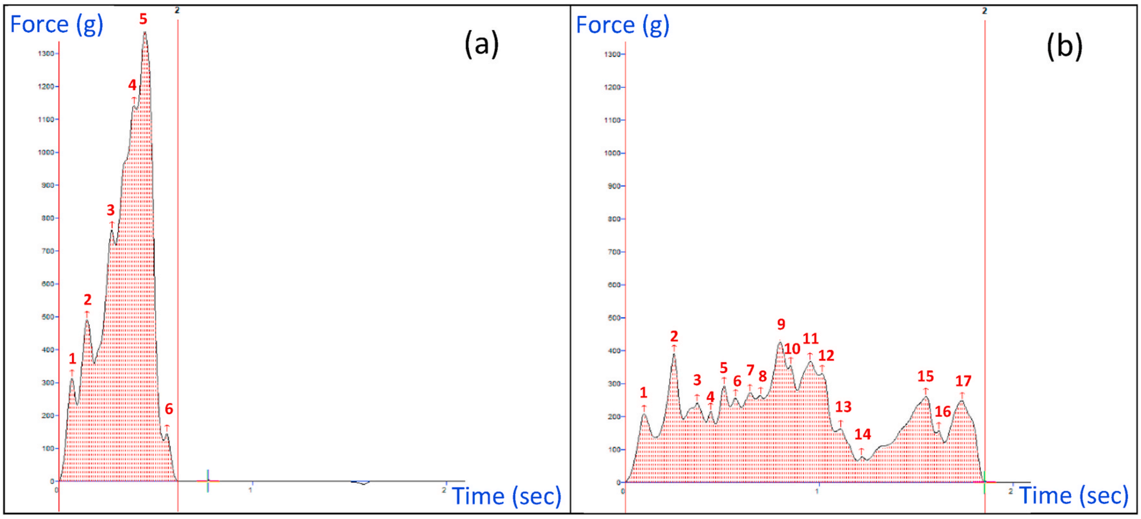

Fig. 2. Typical force-time curves of (a) 5% RLB blended corn extrudates produced at 110 °C exit-die temperature and 21% feed moisture content, (b) 10% RLB blended corn extrudates produced at 150 °C exit-die temperature and 19% feed moisture content.

Table 5
Colour values of corn flour and RLB corn flour blend extrudates†.

RLB level (%, w/w)	EDT (°C)	FMC (%)	L^*	a^*	b^*	Chroma	ΔE
Corn flour extrudates (Control)	110	19	86.59 ± 0.01^{bc}	-3.49 ± 0.02^{s}	30.02 ± 0.09^{b}	30.23 ± 0.09^{a}	91.71 ± 0.03^{b}
		21	86.22 ± 0.03^{d}	-3.20 ± 0.01^{o}	29.31 ± 0.03^{c}	29.48 ± 0.03^{b}	91.12 ± 0.03^{c}
	130	19	86.84 ± 0.03^{ab}	-3.33 ± 0.01^{r}	30.11 ± 0.02^{a}	30.29 ± 0.02^{a}	91.98 ± 0.02^{a}
		21	86.95 ± 0.01^{a}	-3.26 ± 0.01^{p}	28.89 ± 0.03^{e}	29.08 ± 0.03^{d}	91.69 ± 0.01^{b}
	150	19	86.39 ± 0.05^{cd}	-2.90 ± 0.01^{m}	28.89 ± 0.09^{e}	29.04 ± 0.08^{d}	91.14 ± 0.02^{c}
		21	86.24 ± 0.04^{d}	-3.01 ± 0.02^{n}	29.22 ± 0.06^{d}	29.37 ± 0.06^{c}	91.10 ± 0.04^{c}
5	110	19	76.23 ± 0.04^{e}	0.11 ± 0.03^{k}	21.23 ± 0.03^{f}	21.23 ± 0.03^{e}	79.13 ± 0.03^{d}
		21	76.53 ± 0.04^{e}	-0.06 ± 0.03^{l}	21.01 ± 0.06^{g}	21.01 ± 0.06^{f}	79.36 ± 0.03^{d}
	130	19	76.30 ± 0.05^{e}	0.53 ± 0.02^{i}	20.80 ± 0.06^{h}	20.81 ± 0.06^{g}	79.09 ± 0.03^{d}
		21	76.44 ± 0.18^{e}	0.25 ± 0.01^{j}	21.17 ± 0.02^{f}	21.17 ± 0.02^{e}	79.32 ± 0.17^{d}
	150	19	75.88 ± 0.02^{f}	1.28 ± 0.03^{f}	19.97 ± 0.01^{j}	20.01 ± 0.01^{i}	78.48 ± 0.02^{e}
		21	75.79 ± 0.04^{f}	0.98 ± 0.02^{h}	20.36 ± 0.03^{i}	20.38 ± 0.03^{h}	78.49 ± 0.04^{e}
10	110	19	70.94 ± 0.04^{j}	1.78 ± 0.01^{d}	19.28 ± 0.02^{l}	19.36 ± 0.02^{k}	73.53 ± 0.04^{h}
		21	72.14 ± 0.08^{g}	1.22 ± 0.01^{g}	19.41 ± 0.06^{k}	19.45 ± 0.06^{j}	74.71 ± 0.09^{f}
	130	19	71.24 ± 0.65^{hi}	1.99 ± 0.04^{c}	19.38 ± 0.06^{k}	19.48 ± 0.06^{j}	73.86 ± 0.62^{g}
		21	71.07 ± 0.02^{ij}	1.61 ± 0.03^{e}	19.00 ± 0.01^{m}	19.06 ± 0.01^{l}	73.59 ± 0.02^{gh}
	150	19	68.58 ± 0.02^{k}	2.35 ± 0.01^{a}	18.57 ± 0.01^{n}	18.72 ± 0.01^{m}	71.09 ± 0.02^{i}
		21	71.42 ± 0.05^{h}	2.18 ± 0.02^{b}	18.47 ± 0.01^{o}	18.60 ± 0.01^{n}	73.80 ± 0.04^{gh}

(†) *RLB*: red lentil bran; *EDT*: exit-die temperature; *FMC*: feed moisture content; L^*: lightness; a^*: greenness/redness; b^*: blueness/yellowness; *ΔE*: total colour difference ($n = 2$ for extrusion runs; $n = 3$ for colour measurements).
Values were presented by average ± standard deviations.
Values followed by different superscripts in the same column are significantly different ($p < 0.05$).

increased, while the reverse tendency was observed with feed moisture content increased. The increase of crunchiness values when increasing the exit-die temperature from 110 to 150 °C was more evident for both RLB added extrudates and control samples, produced at both feed moisture contents (Table 4). Earlier studies reported that the increase in temperature is able to increase the extent of gelatinisation (Guha & Ali, 2006) and also increase the degree of superheating of water (Wang, Ganjyal, Jones, Weller, & Hanna, 2005), which might cause more expansion and thinner shell wall and furthermore, improve the crunchiness values of extrudates. The results of the current study are consistent with the literature indicating that the crunchiness of snacks has strong and positive correlations with their expansion.

3.6. Colour

The lightness (L^*), redness (a^*) and yellowness (b^*) values of corn flour were measured as 90.17, −2.80 and 26.22, respectively, where the corresponding values of RLB were 57.55, 3.50 and 15.33, respectively.

The regression analysis and Pearson's correlation for the colour values of the extrudates as a function of the independent variables are given in Tables 2 and 3, respectively. The lightness (L^*), redness (a^*), yellowness (b^*), and Chroma and ΔE values of extrudates were significantly ($p < 0.001$) influenced by all studied variables, either alone (RLB, EDT or FMC) or in interactions among them (RLB × EDT, RLB × FMC, EDT × FMC or RLB × EDT × FMC) (Table 2).

The extrudates' colour values are displayed in Table 5. The L^* value of extruded samples produced by different system parameters was in the range of 68.58–86.95. The lightness value was the most affected by the RLB addition level relative to the other variables (i.e., exit-die temperature and feed moisture content). The L^* values of extrudates were significantly decreased ($p < 0.05$) with an increasing RLB addition level; in other words, RLB blended extrudates were darker compared to control samples (Fig. 1, Table 5). This finding is in agreement with the results of Fleischman et al. (2016) and Olivera et al. (2017), who reported that wheat bran layers such as pericarp and aleurone cells are formed by polysaccharides (cellulose, arabinoxylans, lignin, glucomannans and beta-glucan), which give a brown aspect to the flour. Another parameter that can have an effect on the L^* value is increasing temperature, which may cause the degradation of pigments (mainly carotenoids) during the extrusion operation (Olivera et al., 2017). Nevertheless, no linear relationship could be determined related to the effect of increasing exit-die temperature on the lightness values of extrudates in this study.

The redness (a^*) value of extrudates varied between −3.49 and 2.35 (Table 5). The a^* values of samples increased with increasing RLB supplementation levels at corresponding exit-die temperatures and moisture contents. A similarly increasing trend was also observed in the samples produced by higher exit-die temperatures at corresponding moisture contents. Harsh extrusion conditions (high exit-die temperature and low feed moisture content) resulted in more reddish extrudates (Table 5), which is in agreement with the results reported by Olivera et al. (2017).

The yellowness (b^*) value was negatively affected by RLB; the lowest b^* values were measured in the highest bran blended (10% w/w) extrudates (Table 5, Fig. 1). This is probably related to the replacement of corn flour by RLB leading to a less yellow colour in blended extrusion samples, which contains a relatively low level of carotenoids compared to control samples.

The Chroma value indicates saturation and is directly proportional to the intensity of the colour. The Chroma value of corn flour was calculated as 26.4; the corresponding value was 15.7 for RLB. As expected, the Chroma values were decreased with an increasing RLB level in the recipe of extrudates (Table 5). While the overall colour difference (ΔE) value of corn flour (93.95) was determined as higher than that of the extrudates', the lowest ΔE value (59.66) was observed in RLB. The ΔE value of extrudates produced by different system parameters was in the range of 71.09–91.98 (Table 5). The ΔE value was most influenced by the RLB level, when compared to the exit-die temperature and feed moisture content. Asare et al. (2004) reported that the only significant variable of effect for total colour change was the level of cowpea addition ($p < 0.05$) in the rice-legume blend extrudates. Our finding is hence in agreement with the literature.

4. Conclusion

In this study, the potential of using RLB in the formulation of extrusion products was investigated. The combined effect of increasing exit-die temperature and decreasing feed moisture content resulted in enhanced physical properties such as higher REI and lower ED values of studied extrudates. The developing trend stemming from this combined effect was also observed in the textural characteristics (i.e., lower hardness and higher crunchiness) of the samples. Whereas earlier studies reported that the amount of bran negatively affected the physical and textural attributes of the cereal-based extrudates, in the present study, REI and crunchiness values of extrudates significantly increased with a 5% RLB supplementation level in comparison to control samples.

Overall findings have demonstrated that RLB as one of the pulse by-products can be practically used in the improving of fibre-rich extruded snacks and utilised to provide products with added value from lentil wastes. Further studies are in progress to evaluate the effect of RLB supplementation level and extrusion system parameters on the functional and nutritional properties of fibre-rich extrudates.

Declaration of competing interest

The authors declare no conflicts of interest.

CRediT authorship contribution statement

Cihan Kesre: Methodology, Formal analysis. **M. Tugrul Masatcioglu:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Visualization, Project administration.

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