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Development of fibre-rich okara-based expanded snack via single screw extrusion

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Abstract

Okara is a by-product of the soymilk and tofu manufacturing industry. Recently, changes in lifestyle and eating patterns led to higher demands for snack foods produced via extrusion technology. Extruded products enriched with okara, which consists of high dietary fibre content, can increase the nutritional quality of extruded snacks with higher commercial values. This study aimed to determine the influence of okara levels; 0, 5, 10, and 15% (w/w) on properties of extrudates in terms of fibre content, water activity, bulk density, expansion ratio, colour, textural (hardness and crispness), and microstructure. The increment of okara level resulted in the reduction of water activity, expansion ratio, lightness, and crispness of extrudates while, soluble and insoluble dietary fibre content, bulk density, and hardness were increased. Extrudate produced at higher levels of okara had a rougher surface, smaller air cells, and thicker walls. A collapse in cell structure was observed at 15% okara. In conclusion, fibre-enriched extrudate with desirable characteristics can be obtained at a 5% okara level. This study provides a promising application in harnessing the nutritional benefits of okara.

1. Introduction

In recent years, there has been a high interest in healthy natural ingredients in food consumption. Many plant by-products resulting from agro-food industries have potential nutritional and functional benefits. Along with the increment of consciousness in the health aspect, there is an increasing trend in utilizing fibre-rich food by-products such as bran and fruit pomace. Fibre-enriched food posed a tremendous economic potential resulting in high-value end products. Okara, an insoluble residue left following the processing of soymilk and tofu, is one of the potential fibre-rich by-products that often being neglected for commercialization in food applications. A considerable amount of okara is generated, in which one kilogram of soybean used for soymilk processing produces 1.2 kg of wet okara (Guimarães *et al*., 2018). This by-product comprises high dietary fibre, consisting of 50.1-55.6% insoluble and 4.2-1.9% soluble fibres, and the remaining is protein (24.5-37.5%) and lipid (9.3-22.3%) (Mateos-Aparicio *et al*., 2010; Schved and Hassidov, 2010; Li *et al*., 2013). Therefore, incorporating okara into food potentially improves the nutritional value of products.

Extrusion is a process to produce a wide range of food products due to its versatility, high productivity, low cost and energy efficiency (Sun *et al*., 2015). It is a method in which food ingredients are subjected to mixing and heating and forced to exit the extruder die at high speed, forming an expanded product (Salata *et al*., 2014). Expansion of extruded snacks is considered a desirable property associated with other characteristics such as hardness and crispness that depend on many process variables such as barrel temperature, screw speed, feed rate, feed moisture and extruder type (Bisharat *et al*., 2013). However, a highly expanded product is challenging to achieve due to the presence of fibre in flour blends. The inclusion of fibre, particularly those containing highly insoluble fibre has been associated with a detrimental effect on extrudate characteristics (Robin *et al*., 2012; Wang *et al*., 2019). Fibre acts as diluent hence reducing the extensibility of the matrix (Yao *et al*., 2011). A similar expansion characteristic has been demonstrated by several authors (Gumul *et al*., 2013; Tomaszewska-Ciosk and Zdybel, 2021), who reported on reduced expansion in products that were enriched with blackcurrant seeds and apple pomace.

A previous study conducted by Kanojia and Singh (2016) on okara-enriched rice-based expanded products demonstrated that increasing okara level in blend ratio

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resulted in higher hardness and lower crispness values. Similar findings were reported by Shi *et al.* (2011) that incorporated different levels of okara in corn-based extruded snacks. It was demonstrated that the increment of okara decreases the radial expansion ratio while increasing the bulk density. In addition, the extrusion process has been demonstrated to modify the characteristics of the fibre. According to Jing and Chi (2013), the extrusion increased the soluble dietary fibre level of okara from 2.05% to 12.65%. Soluble fibre contributes to better expansion and bulk density of extruded products than insoluble fibre fraction (Robin *et al.*, 2012).

The incorporation of okara as an ingredient in an expanded product can be utilized as a means for the development of a new value-added extruded product. Numerous studies (Wójtowicz *et al.*, 2014; Kaisangsri *et al.*, 2016; Korkerd *et al.*, 2016) have been conducted using extrusion technology to improve the physicochemical properties of the high-fibre extruded product. Nevertheless, there is limited information on the relationship between microstructure and textural properties of okara-enriched extrudates. Therefore, this study aimed to determine the effects of different levels of okara on the properties of extrudates. The physical properties of extrudates were analyzed to determine the most suitable okara level that can be incorporated into ready-to-eat nutritious snack food.

2. Materials and methods

2.1 Materials

Wet okara was obtained from soymilk processing. The okara was dried using a double drum dryer (R. Simon Nip Feed Test Machine, Model 4766, England) at a rotational speed of 1 rpm and steam pressure of 2 bar. Dried flakes were ground and sieved to pass through a 500 µm siever (Endecotts, London). Diacetyl tartaric acid ester of monoglycerides (DATEM) was obtained from Dupont (SouthTower, Singapore). Pre-gelatinized waxy maize starch (PREGEFLO -ROQUETTE) was purchased from Brenntag Sdn Bhd (Shah Alam, Selangor). Glutinous rice flour (Erawan elephant, Thailand) was obtained from a local store (Seri Kembangan, Selangor). Calcium chloride (Chemiz) was purchased from LGC Scientific Sdn Bhd (Balakong, Selangor).

2.2 Sample preparations

A total of 200 g of the okara-flour-starch mixture was prepared by mixing glutinous rice flour: pre-gelatinized waxy maize starch: dried okara at different weight ratios; 70:30:0, 70:25:5, 70:20:10, 70:15:15. These ratios represent different okara levels of 0, 5, 10 and 15%, respectively. Salt (0.1%, w/w) and DATEM (1%, w/w) were added based on the weight of the okara-flour-starch mixture. The moisture content of the mixture ranged from 7.22 to 7.80%. Then, the mixture was pre-hydrated to 10% moisture content according to Equation 1 (Sadik, 2015).

$$W_a = M_s * \left(\frac{m_f - m_i}{100 - m_f}\right) \quad (1)$$

Where W_a = weight of water added (g), M_s = mass of the sample (g), m_i= initial moisture content (%, d.b.), and m_f= final moisture content (%, d.b).

The preconditioning has been performed by spraying water into the flour-okara mixture. The mixture was homogeneously mixed throughout the process manually. The mixture was kept overnight in a hermetically closed container at 4°C to ensure moisture equilibration.

2.3 Extrusion process

The extrusion process was conducted using a single screw extruder (Brabender, Germany) with a barrel diameter of 19 mm and a screw length of 25 D (1 D = 19 mm). The processing parameters used were: screw compression ratio of 3:1, feeder screw speed of 50 rpm, screw speed of 120 rpm, cutter speed of 100 rpm, and die diameter of 5 mm. The barrel is divided into four zones (1, 2, 3 and 4), and the temperature of all heating zones was set to 80, 100, 120 and 140°C, respectively. The flour-okara mixture was manually fed into the extruder. The expanded extrudates were cut at the die exit using rotating knives into a sphere shape. Extrudates were dried overnight in a hot-air dryer at 30°C (Venticell, MMM, Einrichtungen, Germany). Before further analysis, the extrudates were packed in aluminium pouches and stored at room temperature. Three batches of extrusion process have been performed for each level of okara.

2.4 Characterization of extrudates

2.4.1 Determination of fibre content

The fibre content of extrudates was determined according to Association of Official Analytical Chemists (AOAC) methods (AOAC, 2005): Insoluble Dietary Fibre (AOAC Official Methods 991.42), Soluble Dietary Fibre (AOAC Official Methods 993.19) and Total Dietary Fibre (AOAC Official Methods 985.29).

2.4.2 Determination of water activity

The water activity of extrudates was determined using a water activity meter (Aqualab, Model Series 4TE, Decagon Devices, Pullman, Washington DC, USA). Extrudates were grounded in a mortar using a pestle.

2.4.3 Determination of bulk density

Bulk density was determined according to the seed displacement method (Nissar *et al*., 2017). A 100 mL cylinder was filled with ten grams of extrudates (W_{ex}). Mustard seeds were added until the 100 mL line of the cylinder. The extrudates were removed from the cylinder, and the volume of the seeds was recorded (V_{ms}). Bulk density was calculated according to Equation (2):

$$Bulk\ density\ \left(\frac{g}{cm^3}\right) = \frac{W_{ex}\ (g)}{100 - V_{ms}\ (cm^3)} \tag{2}$$

2.4.4 Determination of expansion ratio

The cross-sectional diameter of the extrudates was measured using a digital Vernier calliper (Starrett, US). The expansion ratio was calculated according to Equation 3 (Meng *et al*., 2010). A total of 6 randomly collected samples from each batch of extrudates were calculated using Equation (3):

$$Expansion\ ratio = \frac{cross-sectional\ diameter\ of\ the\ extrudate\ (mm)}{diameter\ of\ the\ die\ opening\ (mm)} \tag{3}$$

Where the diameter of the die opening is equal to 5 mm.

2.4.5 Determination of colour

The colour of the extrudate was measured using a colour analyzer (Chroma Meter CR-410, Konica Minolta, Inc., Osaka, Japan). The colour parameters were determined using CIE L^* a^* b^* scale. Results were expressed as L^*= lightness (0 = black, 100 = white), a^* ($-a^*$ = greenness, $+a^*$ = redness) and b^* ($-b^*$ = blueness, $+b^*$ = yellowness). The total colour difference (ΔE) of extrudates was calculated as follows:

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \tag{4}$$

Where the subscript “0” represents the colour of extrudate with 0% okara.

2.4.6 Determination of textural properties

Textural properties of the extrudate were measured using a texture analyzer (TA-XT.plus, Stable Micro System, UK). Prior to the analysis, extrudates were placed in a desiccator containing saturated calcium chloride solution for 48 hrs, intended to equilibrate the moisture content of the samples. A one-cycle compression test was performed using an aluminium cylinder plate (P/35) equipped with a 30 kg load cell. Testing conditions were; compression 80%, pre-test speed of 1.0 mm/s, test speed of 2 mm/s, post-test speed of 2 mm/s. Ten extrudates were analyzed for each sample from different batches. Hardness and crispiness were analyzed using Texture Exponent 32 software as the maximum peak force (kg) and initial slope from the force-distance curve (kg.s), respectively. The lower the slope, the crispier the extrudate obtained (Altan and Maskan, 2012).

2.4.7 Determination of microstructure of extrudate

The microstructure of extrudate was examined using LEO 1455 variable pressure scanning electron microscope (VP SEM) (Cambridge, United Kingdom). The extrudate was cut into thin slices and mounted on stubs with double-backed carbon tape. The sample was coated with gold sputter under vacuum conditions and examined at the intensity of 10 kV. The image was viewed at 9× and 30× magnifications.

2.5 Statistical analysis

Statistical analysis was performed using Minitab Statistical Software (Version 16, Minitab Inc., PA, USA). The difference between means was tested using one-way ANOVA. Tukey's test was used to compare the means at a 95% significance level ($p<0.05$).

3. Results and discussion

3.1 Dietary fibre and water activity of extrudates

Table 1 shows the dietary fibre content of the extrudates. Extrudate without okara substitution has 0.8 g/100 g total dietary fibre (TDF), perhaps primarily contributed by glutinous rice flour. The incorporation of 5 to 15% (w/w) okara significantly enhanced the total dietary fibre content of the extrudates, ranging from 22.3 to 24.4 g/100 g. The okara-enriched extrudates contain significantly higher insoluble fibre (IDF) than soluble fibre (SDF), with values ranging from 21.4 to 23.2 g/100 g and 0.9 to 1.2 g/100 g, respectively. The high level of insoluble fibre in the expanded product was in agreement with Wu *et al*. (2020), who reported that okara is high in insoluble but low in soluble dietary fibre. Previous authors demonstrated an increase in TDF, IDF, and SDF of extrudate enriched with blackcurrant seeds (Gumul *et al*., 2013) and apple pomace (Karkle *et al*., 2012).

The water activity of the extrudates varied from 0.46 to 0.48 at 0 to 15% of okara (Table 1). Increasing the level of okara in the matrix significantly reduced the values of water activity. A previous study by Vadukapuram *et al*. (2014) reported water activity ranged between 0.48 - 0.69 and 0.52 - 0.57 for the combination of navy-corn-flaxseed and pinto-corn-flaxseed of the extrudate, respectively. The lower water activity with an increment of okara content is attributed to the presence of fibre that is able to bind water. Higher dietary fibre content leads to a greater amount of bound water, reducing the available water.

Table 1. Total, soluble, and insoluble dietary fibre contents and water activity of extrudates enriched at different levels of okara.

Percentage of okara (%)	Dietary fibre in extrudate (%) Total dietary fibre	Insoluble dietary fibre	Soluble dietary fibre	Water activity
0	0.8±0.0^{d}	0.5±0.0^{d}	0.3±0.0^{d}	0.480±0.002^{a}
5	22.3±0.0^{c}	21.4±0.0^{c}	0.9±0.0^{c}	0.479±0.005^{a}
10	23.7±0.0^{b}	22.6±0.0^{b}	1.1±0.0^{b}	0.466±0.002^{b}
15	24.4±0.0^{a}	23.2±0.0^{a}	1.2±0.0^{a}	0.463±0.001^{b}

Values are presented as mean±SD of three replications, on a dry basis. Values with different superscripts within the same column are statistically significantly different (p<0.05).

3.2 Colour of extrudates

Colour is a critical quality factor determining the consumer acceptability of extruded products. Enrichment of okara into the food matrix significantly affects the colour of end products. Table 2 and Figure 1 show the colour properties of the extrudates. Increasing the okara level significantly decreased the sample's *L** value (lightness) as indicated by a value of 77.99±0.25 in 15% okara compared to 82.84±0.25 in the Control sample. In contrast, a higher addition of okara resulted in a significant increase in both *a** and *b** values, in which the sample incorporated with 15% okara showed the highest *a** (6.57±0.39) and *b** (21.25±0.31) values, indicative a darker and more brownish okara-enriched extrudate. Total colour difference (Δ*E*) indicates the magnitude of colour difference between extrudates incorporated with and without okara (Control). A significant increase in total colour difference was observed with an increment in the okara level. Similar colour changes were reported by previous authors (Altan and Maskan, 2012) in grape pomace-enriched extrudates.

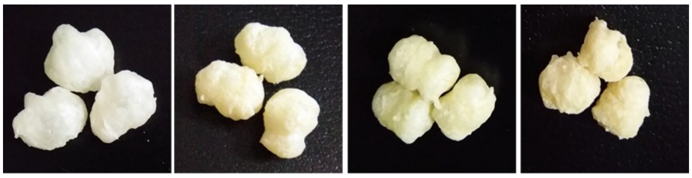

Figure 1. Extrudates made with and without substitution of okara.

The colour changes in okara-enriched samples could be attributed to non-enzymatic browning that occurred during the extrusion process. The addition of okara appears to increase the degree of Maillard reaction, perhaps attributed to the increase in protein and reducing sugar contents of the raw material. This finding was in agreement with previous authors (Alam, Pathania and Sharma 2016) who reported enhanced Maillard reactions with the incorporation of fibre-rich ingredients during extrusion. The greater *a** value (higher redness) of okara-enriched extrudates could be associated with protein aggregation and the formation of disulphide bonds (Kristiawan *et al*., 2018). The combined effect of high extrusion temperature and increased protein content of okara-flour blends perhaps caused greater protein aggregation, hence a higher *a** value. It can be concluded that both protein and carbohydrate of okara play an essential role in regulating the colour of extrudates.

3.3 Microstructure of extrudates

Figure 2 shows the cross-sections of extrudates made with different percentages of okara. In general, microstructure attributes such as the number and size of air cells, and smoothness and roughness of extrudates were positively correlated with the percentage of okara. The Control sample (0% okara) is made up of a smaller number but larger pore size, suggesting relatively well-expanded air cells when the extrudates exist from the die. In contrast, increasing compactness of extrudate structure was observed with increment in okara level. The compactness of structures is observed as a dense structure with a reduced air cell size of the extrudates. At higher okara levels (10-15%), a greater structural collapse was observed, having a less porous structure with a thicker cell wall. This finding was in agreement with previous authors (Kallu *et al*., 2017; Shirazi *et al*., 2020), who reported a decrease in cell size and total cell area, with an increase in wall thickness with the increment of fibre content in extrudates. In addition, the Control extrudate has a smoother surface (Figure 2a) compared with samples containing 10% and 15% okara.

Table 2. Colour parameters (*L*, a*, b**), and total colour difference (*ΔE*) of extrudates were obtained at different levels of okara.

Percentage of okara (%)	Colour parameters *L**	*a**	*b**	Total colour difference (Δ*E*)
0	82.84±0.25^{a}	-0.13±0.03^{d}	13.48±0.17^{c}	-
5	80.90±0.17^{b}	3.66±0.14^{c}	18.22±0.19^{b}	6.45±0.18^{c}
10	79.53±0.08^{c}	4.78±0.06^{b}	20.57±0.12^{a}	9.28±0.17^{b}
15	77.99±0.25^{d}	6.57±0.39^{a}	21.25±0.31^{a}	11.41±0.52^{a}

Values are presented as mean±SD of three replications, on a dry basis. Values with different superscripts within the same column are statistically significantly different (p<0.05).

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The latter had a rougher surface, indicative of a sign of shrinkage attributed to the collapse of the starch matrix. Similar findings have been reported in extrudate containing a high level (15%) of carrot (Kaisangsri *et al*., 2016) and cherry (Wang *et al*., 2017) pomace.

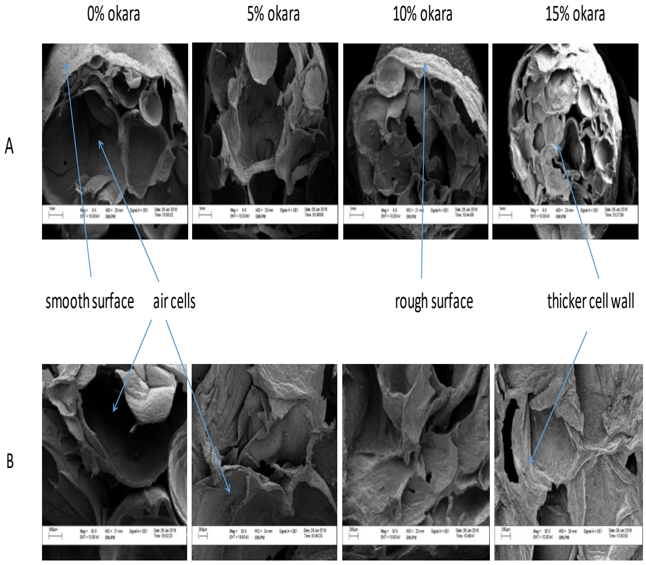

Figure 2. Microstructure of extrudates at different levels of okara observed at (A) 9× (B) 30× magnifications.

The incorporation of okara, a fibre-rich by-product, interferes with the formation of an extrudate structure. Fibre has been associated with retardation of expansion and extensibility of the cell wall. This outcome is associated with the ability of fibre particles to pierce through, hence weakening the starch matrix (cell walls), making it unable to withstand high steam pressure at the die, causing a collapse in structure (Altan and Maskan, 2012; Wang *et al*., 2017). On the contrary, the absence of fibre in the Control sample perhaps allows for proper gelatinization, hence a well-developed starch matrix, leading to extrudate with a good structure. Previous authors (Reyes-Jáquez *et al*., 2012) have demonstrated that protein incorporation in extrudates resulted in both a small air cell and a wrinkled extrudate wall. The high protein content of okara possibly contributed to the poor strength of the starch matrix. Both protein and fibre may compete with starch for water hydration, negatively affecting gelatinization, and limiting the starch expansion.

3.4 Expansion ratio and bulk density of extrudates

Figure 3 shows the expansion ratio and bulk density of extrudates enriched with okara. In general, increasing the okara level negatively affects the extent of puffing of extrudate. It was observed that 0% okara showed 2.60 mm/mm expansion ratio while 15% okara gave 1.87 mm/mm expansion ratio. The results obtained suggested that the expansion ratio significantly decreased ($p<0.05$) as the percentage of okara increased. The incorporation of 5% okara resulted in a 5.03% reduction in expansion, in contrast with a 28.35% reduction observed in extrudate with 15% okara enrichment. Meanwhile, bulk density significantly increased with the percentage of okara. The bulk density ranged from 0.20 to 0.27 g/cm^3, the lowest in 0% of okara and the highest in 15% of okara. A higher density value indicates a less porous structure. A strong negative correlation (r = 0.9339) was observed between bulk density and expansion ratio. These findings correlate with the microscopic observation of the extrudates. Previous authors reported a similar trend of bulk density and expansion with increasing levels of apple pomace (0-20%) (Singha and Muthukumarappan, 2018) and rye bran (15-30%) (Alam *et al*., 2016).

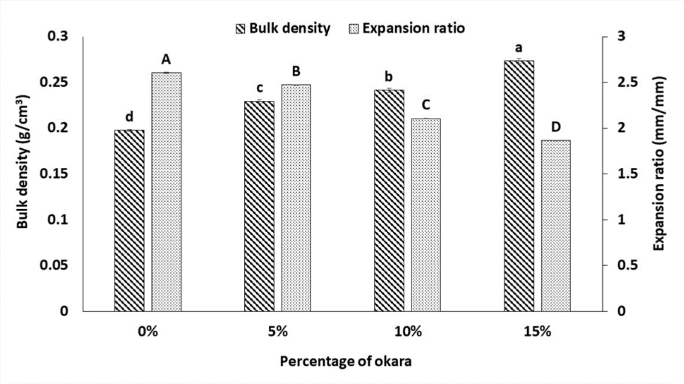

Figure 3. Bulk density and expansion ratio of extrudates made with different levels of okara. Bars with different uppercase and lowercase notations represent statistically significantly difference ($p<0.05$) for expansion ratio and bulk density, respectively.

Okara contains high insoluble fibre (IDF). The presence of high IDF content has been negatively associated with a reduced expansion of extrudate. The IDF such as cellulose not only pierce the cell wall of extrudate (Wang *et al*., 2019), but a high level of fibre causes it to aggregate, leading to discontinuity of starch matrix (Kaisangsri *et al*., 2016; Kallu *et al*., 2017). A positive correlation (r = 0.7437) was observed between the increment of IDF content and the density of extrudates. In addition, the ability of fibres to bind more water perhaps creates a more viscous okara-flour mass in the extruder barrel, hence negatively affecting the expansion. Previous authors (Van der Sman and Broeze, 2013) reported that a high viscosity of polymer matrix caused a greater degree of bubble rupturing in snack food produced via extrusion. In addition, the incorporation of okara increases the protein and lipid contents of the okara-flour blends. The presence of okara lipids possibly promotes the formation of an amylose-lipid complex during the extrusion process. Nevertheless, proteins have been reported to affect water distribution in the matrix and increase intermolecular cross-linking, eventually influencing the stretching of the starch matrix due to reduced interactions between starch

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(Yadav *et al*., 2014). The combined interplay of fibre, protein, and lipids of okara and their effects on starch characteristics eventually limits the expansion of air bubbles, hence producing extrudates with higher density and lower puffing characteristics.

3.5 Textural properties of extrudates

Increasing the okara level affects the textural properties of the extrudates. The hardness of the extruded products ranged from 9.74 to 25.71 kg. Minimum hardness was recorded in Control (0% okara), whereas maximum hardness was observed in the sample containing 15% okara. An increment in okara substitution significantly increased ($p<0.05$) the hardness (Figure 4). These findings agreed with Shirazi *et al*. (2020) who demonstrated greater hardness with increasing carrot pomace in expanded barley-carrot pomace snacks. The hardness of the extrudates is inversely proportional to the expansion ratio ($r = 0.6865$) implying that harder extrudates tend to expand less. Crispness was measured as the positive slope of the force -distance curve, in which a lower slope indicates the higher value of crispness, thus a crispier product. Increasing the level of okara negatively affects the crispiness of extrudates, ranging from 87.00 kg.s in Control (0% okara) to 156.34 kg.s in 15% okara. Similarly, Nascimento *et al*. (2012) reported that increased extrudate hardness produced less crispy textured extrudate.

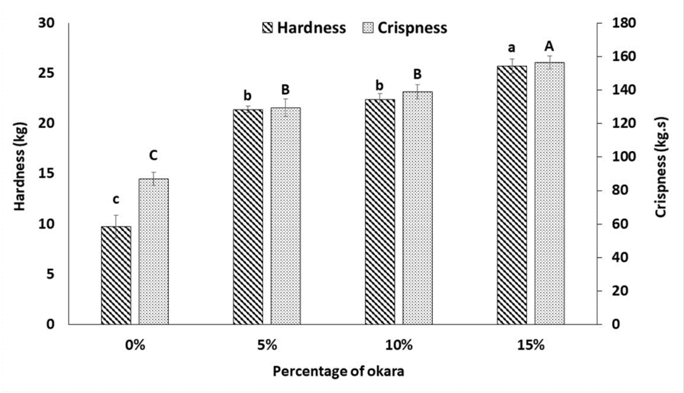

Figure 4. Hardness and crispness of extrudates made with different levels of okara. Bars with different uppercase and lowercase notations represent statistically significantly difference ($p<0.05$) for crispness and hardness, respectively.

The incorporation of fibre has been reported to disrupt the growth of air bubbles, causing reduced average cell size that eventually affects the thickness of air bubbles, leading to premature rupture (Stojceska *et al*., 2008; Altan and Maskan, 2012). Strong positive correlations (r) were observed between both textural parameters and the density of extrudates, with values of 0.8870 and 0.9538 for both hardness and crispness, respectively. The textural properties of okara-enriched extrudate correlate with microscopic observation, in which samples with a higher content of okara demonstrated a limited number of voids and thicker cell walls, thus making a denser, harder and less crispy product.

Dried okara contains 20-30% protein, therefore, incorporation of okara increases the protein content of extrudates. The rearrangement of protein molecules during the extrusion process possibly enhanced the interactions with other components such as starch via polymerization and crosslinking (Day and Swanson, 2013; Vallée *et al*., 2017; Philipp *et al*., 2018), which might be detrimental to textural qualities of the extrudate. In addition, the increment in both fibre and protein contents in okara-enriched flour mixture possibly caused reduced hydration of starch granules, eventually impeding the starch gelatinization. This behavior affects the expansion capacity of starch causing a compact extrudate structure.

4. Conclusion

The incorporation of okara even at a 5% level significantly improved the nutritional value of the expanded snack. Nevertheless, due to its high insoluble dietary fibre content, increment in okara content is detrimental to the extrudate's expansion and textural properties, causing harder, less crispy and denser products. This behavior is well correlated with microscopic observation of the extrudates, in which incorporation of 15% okara resulted in a collapse of the structure. Higher protein content in okara-enriched extrudates resulted in slightly creamy to darker expanded products. Incorporating 5% okara can be proposed as a suitable level to produce expanded products with high nutritional values and acceptable characteristics. Further works on manipulating extrusion conditions may allow for a higher amount of okara incorporation.

Conflicts of interest

All authors declare no conflict of interest.

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