




Extruded snacks enriched with açai berry: physicochemical properties and bioactive constituents

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Abstract

This work aimed to develop extrudates enriched with açai and evaluate the effect of this fruit on their physicochemical properties and bioactive constituents of these foods. Rice/corn (2 : 1) extrudates containing 0, 2, 4, and 6% of freeze-dried açai were prepared using a twin-screw extruder and characterized towards proximate composition, the concentration of anthocyanin and carotenoids, and typical process-related extrudate characteristics. The addition of açai increased the total anthocyanins (from 0 to 20.1 mg 100 g⁻¹) and total carotenoid content (from 1.6 to 6.2 µg g⁻¹). Açai enrichment elevated the protein and mineral content by 6.3% and 32.2%, respectively. There was no significant difference between the samples regarding the expansion index. Higher incorporation of açai resulted in crispier snacks extrudates and high total color difference (ΔE). Therefore, açai (up to 6%) can be regarded as stable in the extrusion conditions applied and be used in extrudates to enhance their bioactive and nutritional properties, providing color and suitable physical characteristics. Açai extrudates can serve as an alternative for consumers interested in convenience food with bioactive constituents.

Keywords: açai; açai pulp; anthocyanin; extrudates; extrusion; innovative food.

Practical Application: Açai addition to extrusion result in crispy expanded snacks with anthocyanins and carotenoids.

1 Introduction

Açai (*Euterpe oleracea*) is a fruit with a high concentration of bioactive compounds, such as anthocyanins and carotenoids (Lucas et al., 2018a; Romualdo et al., 2015; Torma et al., 2017). This fruit contains phenolic compounds, flavonoids, tocopherols, minerals, fibers, and polyunsaturated fatty acids, such as linoleic and linolenic acids. Açai has a dark purple color when mature and its palm is found in the low and flooded lands of the estuaries of the Amazon River (Yamaguchi et al., 2015; Lima et al., 2021). This popular fruit is regularly consumed by many people living in the Amazon region; however, due to various bioactive compounds present in its composition, consumers from Europe, Japan, the United States, and China also willing and consume this fruit (Wycoff et al., 2015; Yamaguchi et al., 2015).

Studies have demonstrated the health benefits of açai, and consequently, this fruit is one of the most studied in the world (Peixoto et al., 2016; Romualdo et al., 2015; Yamaguchi et al., 2015). Peixoto et al. (2016) used anthocyanin-rich açai fruit extract and observed antioxidant and neuroprotective activity in the model organism *Caenorhabditis elegans*. Romualdo et al. (2015) observed that açai pulp powder reduced mouse colon carcinogenesis due to the increase in total glutathione and the reduction in DNA damage. Furthermore, research investigating açai as a functional ingredient has shown good sensory acceptance (Fernandes et al., 2016). According to Oliveira et al. (2020) the high concentration of phenolic compounds and anthocyanins found in açai pulp allows functional properties allegations.

The interest in extruded convenience food in the form of snacks has increased worldwide (Dalbhatg et al., 2019). However, most of the formulations available in the market lack nutrients (Potter et al., 2013; Sumargo et al., 2016). In this context, natural ingredients such as fruits containing bioactive compounds can be incorporate into extrudate formulations to improve nutritional properties. Depending on the ingredient added, the sensory properties can be improved, and natural color can be provided (Oliveira et al., 2018). However, the use of such ingredients in cereal-based extrudates can potentially alter their physical properties and result in extrudates less expanded (Kosińska-Cagnazzo et al., 2017; Potter et al., 2013). According to the literature, fractions of fruits (> 6%) incorporated into extrudates can result in differences in diameter and pore size (Basto et al., 2016; Höglund et al., 2018). Thus, such extrudates should be carefully evaluated, as their physical properties are directly related to consumer acceptance (Oliveira et al., 2018).

Studies have already examined the effects of the chokeberry (Hirth et al., 2015), bilberry (Hirth et al., 2014), peach palm (Basto et al., 2016), apple, banana, strawberry, and tangerine (Potter et al., 2013) on extrudates. Potter et al. (2013) applied fruit powders in extruded snacks to improve nutritional quality and obtained snacks high in fiber content. Hirth et al. (2014) investigated the effect of extrusion in bilberry anthocyanins of extruded samples. The authors reported retention of anthocyanins (up to 90%) on extrudates depending on barrel temperature and

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moisture content applied in the process. In another research, the influence of the extrusion process parameters on the retention of chokeberry polyphenols was evaluated and up to 65% of anthocyanin retention was observed (Hirth et al., 2015). However, to the best of our knowledge, no studies have analyzed açai concerning its use for the development of extruded snacks. Therefore, this work aimed to develop extrudates enriched with açai and evaluate the effect of this fruit on the physicochemical properties and bioactive constituents.

2 Materials and methods

2.1 Materials

Rice flour (moisture content of 10.7% and a dry basis composition based on the following: 9.3% of protein, 0.6% of lipids, 0.5% of ash, and 89.6% of carbohydrates; anthocyanin and carotenoids were not detected) and corn flour (moisture content of 10.4% and a dry basis composition based on the following: 8.5% of protein, 3.7% of lipids, 1.1% of ash, and 86.7% of carbohydrates; anthocyanin was not detected, and the total carotenoids were $10.3 \pm 0.04 \mu\text{g/g}$) were purchased from Zwicky (Müllheim-Wigoltingen, Switzerland). The açai pulp was obtained from Amazonbai (Macapá, Amapá, Brazil); it was frozen at -80°C in an ultrafreezer (Indrel, model IULT 90-D, Brazil) and then freeze-dried (Liobras, model L108, Brazil). The freeze-dried açai (moisture content of 3.6%, and a dry basis composition based on the following: 11.8% of protein, 54.2% of lipids, 3.3% of ash, and 30.7% of carbohydrates) was vacuum packed (Model Supervac 400, Sulpack, Brazil) and stored at -18°C in laminated bags. The proximate composition was performed following the procedures described by the Association of Official Analytical Chemists (1995). Carbohydrates and fibers were estimated by difference. Total anthocyanins and total carotenoids for the flours were analyzed according to the procedures described below. The bioactive compounds in freeze-dried açai had been previously investigated, and $38.28 \mu\text{g/g}$ for total carotenoids and 5.87 mg/g for total anthocyanins were found (Lucas et al., 2018a).

2.2 Sample preparation

The control sample (C) was prepared using a 2 : 1 ratio of rice flour and corn flour. It was observed that this concentration of rice and corn flour results in extrudates with acceptable physicochemical and sensory properties (Lucas et al., 2018b).

The samples A2, A4, and A6 were produced by adding 2, 4, and 6% of açai pulp powder in the control sample, respectively. The maximum of 6% of açai was chosen by checking previous studies on fruit added to extrudates development (Basto et al., 2016; Kosińska-Cagnazzo et al., 2017). The ingredients were homogenized using a powder mixer (Model HMP 135L, Altrad, Germany).

2.3 Extrusion cooking

Extrusion cooking was performed using a co-rotating twin-screw extruder (Model DNDL-44, Bühler, Uzwil, Switzerland) with a 900 mm length and $L/D = 20.45$. The raw material was fed to the extruder by a K-Tron powder feeder (Coperion

K-Tron, Niederlenz, Switzerland). Mass balance was used to perform corrections in moisture content and distilled water was added to maintain 16.2% of moisture during the process. The extrusion parameters used were a feed rate (12.6 kg/h), screw speed (250 rpm), and temperature of 143°C in the last zone (Lucas et al., 2018b). All of the extrusion parameters were monitored during the process.

The configuration of the screw was composed for conveying, mixing and kneading elements, as follows: 3 elements 67/28; 1 element 44/19; 1 element kneading block 60/4/20; 1 element 44/20; 1 element kneading block 60/4/20; 3 elements 44/20; 4 elements 44/19; 1 element 67/28; 1 element 34/15; 3 elements 15/15; 2 elements 34/15; 1 element 15/15; and 1 element 34/15. In the end, a circular die (3.6 mm) was used and the extruded products were cut using a single rotary knife at a constant speed of 275 rpm.

Moisture loss (%) during the extrusion was calculated considering the difference between the initial moisture (16.2%) and the moisture of the extrudates at the end of the die. For these measurements, a moisture analyzer (HC103 Moisture analyzer, Mettler Toledo, Switzerland) was used. The results were $50.5 \pm 2.3\%$, $51.5 \pm 0.9\%$, $47.6 \pm 0.5\%$, and $51.4 \pm 2.1\%$ for the samples C, A2, A4, and A6, respectively, without significant differences between the samples. According to Azzollini et al. (2018), the easier the moisture evaporates in the die of the extruder, the more expanded and porous the extrudates.

Afterward, the extrudates were dried in an oven (Model AE, MIWE, Arnstein, Germany) at 80°C for 20 min to a moisture content of below 6%. The extrudates were cooled to ambient temperature and stored in sealed metalized bags for further analyses.

2.4 Analyses of extrudates

Anthocyanins

The extrudates were first crushed with a mortar and pestle and then hydrated with distilled water for 30 min in the dark. The extraction of total anthocyanins was performed using the methodology adapted from Hirth et al. (2014) with methanol: water mixture (ratio 80 : 20) followed by homogenization at 12,000 rpm for 15 s (Polytron PT 3100 D, Tool 3020/2 S, Kinematica AG, Switzerland) and then centrifugation at $10,000 \times g$ for 15 min (Sigma 6-16K, Germany). The supernatant was recovered, and the extraction procedure was repeated until the residue (pellet) was colorless.

Total anthocyanin was quantified by the spectrophotometric pH differential method (Giusti & Wrolstad, 2001). A coefficient (ϵ) of $26,900 \text{ L/cm mol}$ and a molecular weight of 449.2 g/mol were used. Results were expressed as mg cyanidin-3-glucoside.

Carotenoids

Total carotenoids were extracted and quantified as described by Rodriguez-Amaya & Kimura (2004). The total carotenoids concentration was determined at 450 nm using a spectrophotometer (UviLine 9400, Schott Instruments). Equation 1 was used to

quantify total carotenoids content. The whole analysis was performed in the dark to minimize carotenoid degradation.

$$\text{Carotenoids } (\mu\text{g/g}) = \frac{A \times V \times 10^4}{A_{1\text{cm}}^{1\%} \times m} \quad (1)$$

Where A is the absorbance, V is the volume of the extract (mL), $A_{1\text{cm}}^{1\%}$ is the absorption coefficient of 2592 and m is the sample weight (g).

Proximate composition and protein digestibility

Moisture content was determined gravimetrically in the oven at 105 °C; protein content was determined using the Kjeldahl method with a conversion factor of 6.25, lipid content utilizing the Soxhlet method, and ash employing a muffle furnace at 550 °C, following AOAC Official Methods (Association of Official Analytical Chemists, 1995). Carbohydrates were quantified by difference. In vitro protein digestibility was determined according to Rathod & Annature (2016).

Color

The color of the extrudates was measured with a colorimeter (Spectrophotometer CM-700d, Konica Minolta, Japan). The color was represented by L^* (lightness), a^* (greenness-/redness+) and b^* (blueness-/yellowness+). Chroma (C^*), hue angle (h_{ab}), and total color difference (ΔE) were calculated according to Equations 2, 3, and 4, respectively. L^*_0 , a^*_0 , and b^*_0 represent the values obtained in the control sample (C).

$$C^* = (a^{*2} + b^{*2})^{1/2} \quad (2)$$

$$h_{ab} = \tan^{-1} \left(\frac{b^*}{a^*} \right) \quad (3)$$

$$\Delta E = \sqrt{(L^* - L^*_0)^2 + (a^* - a^*_0)^2 + (b^* - b^*_0)^2} \quad (4)$$

Expansion index

The expansion index (EI) was determined according to Gujska & Khan (1990) (Equation 5), in which D_E is the diameter of the extrudate (cm) and D_D is the die diameter (cm).

$$EI = \frac{D_E}{D_D} \quad (5)$$

Bulk density

The bulk density (BD) of the extrudates was measured as described by Alvarez-Martinez et al. (1988). BD was calculated according to Equation 6, in which m is the weight of the sample (g), D is the diameter (cm) and L is the extrudate length (cm).

$$BD \text{ (g/cm}^3\text{)} = \frac{4 \times m}{\pi \times D^2 \times L} \quad (6)$$

Textural properties

The hardness and crispness of the extrudates were analyzed using a TA-XTplus Texture Analyzer (Stable micro systems, Surrey, UK), equipped with a 50 kg load cell and a cylinder probe with 25 mm diameter, operating with a test speed of 1 mm/s. The hardness was obtained by the maximum force required for compression of the extrudates by 50%, whereas the crispness was obtained from the total number of peaks of the curve (Oliveira et al., 2017).

Water Absorption Index (WAI) and Water Solubility Index (WSI)

The samples were previously ground and sieved (Centrifugal Mill Retsch ZM 200, Retsch, Germany). WAI and WSI were determined following the methodology described by Anderson et al. (1969).

Water activity (A_w)

Extruded samples were ground and A_w -value was evaluated using Novasina Lab Master- A_w (Novasina, Switzerland) with a temperature setting of 25 °C.

Sample structure

Extrudates had cross-sections cut to a thickness of between 4 and 5 mm. The internal radial structures of the extrudates were examined using a 3D Digital Microscope VHX 5000 from Keyence (USA).

Statistical analyses

The analyses of results were carried out by analysis of variance (ANOVA), and the means were compared by Tukey's test at $p < 0.05$.

3 Results and discussion

3.1 Proximate composition, protein digestibility, and bioactive compounds

The proximate composition of the extrudates is presented in Table 1. By increasing the açai pulp powder incorporated into the product, the protein concentration significantly increased ($p < 0.05$), being 6.25% higher in the A6 sample as compared to the control sample (C). The improved protein levels in enriched extrudates have been described in the literature (Azzollini et al., 2018; Lucas et al., 2018b).

According to Table 1, all snacks' samples presented high protein digestibility (> 80%). Extrusion has been reported to improve protein digestibility (Table 1) due to the protein denaturation and inactivation of antinutritional factors. This is due to the mechanical shear that can change the protein molecules structures and due to the high temperatures, that reduce or eliminate antinutritional factors (Dalbhagat et al., 2019; Rathod & Annature, 2016). Similar results were reported by Azzollini et al. (2018). Furthermore, the results are in line with Sumargo et al. (2016) and with Rathod & Annature (2016).

Table 1. Proximate composition and bioactive constituents of control snacks (C) and snacks enriched with 2% (A2), 4% (A4), and 6% (A6) of açai pulp powder.

	C	A2	A4	A6
<i>Bioactive compounds</i>				
Total anthocyanins (mg/100g)	n.d.	8.29 ± 0.44 ^c	12.67 ± 0.39 ^b	20.10 ± 0.20 ^a
Total carotenoids (µg/g)	1.60 ± 0.10 ^d	2.77 ± 0.01 ^c	4.50 ± 0.05 ^b	6.20 ± 0.02 ^a
<i>Proximate composition</i>				
Protein (g/100g)	8.80 ± 0.01 ^d	8.97 ± 0.10 ^c	9.20 ± 0.03 ^b	9.35 ± 0.01 ^a
Lipids (g/100g)	0.10 ± 0.02 ^d	0.24 ± 0.00 ^c	0.51 ± 0.06 ^b	0.86 ± 0.08 ^a
Ashes (g/100g)	0.59 ± 0.01 ^d	0.65 ± 0.00 ^c	0.71 ± 0.02 ^b	0.78 ± 0.01 ^a
Carbohydrates (g/100g)	90.51	90.14	89.58	89.01
Protein digestibility (%)	83.69 ± 3.34 ^a	87.72 ± 2.77 ^a	82.11 ± 5.65 ^a	87.05 ± 1.77 ^a

n.d. = not detected. Means ± standard deviation ($n = 3$); different letters in the same line indicate significant differences between samples ($p < 0.05$); all of the results were expressed on a dry basis.

The lipid content increased significantly ($p < 0.05$) after 2, 4, and 6% açai addition. Therefore, it is 8-fold higher in the sample with 6% of fruit as compared to the control sample. Lipids (< 1%) are assumed to lubricate and stabilize the extrusion process (Azzollini et al., 2018). However, the lipid concentration obtained in all formulations in the present study was lower than expected, since the açai pulp powder used is 54.2% lipid. According to Obradović et al. (2015), extruded products have complex composition, and the ingredients can interact during the process. Thus, one hypothesis for the result obtained is the formation of complexes between amylose and lipids (Dalbhagat et al., 2019). The ashes contents were 10.17%, 20.34%, and 32.20% higher than the control sample, after the addition of 2, 4, and 6% of açai powder, respectively. The increase in minerals content in enriched snacks has been previously demonstrated (Azzollini et al., 2018; Lucas et al., 2018b).

Total anthocyanins content ranged from 0 (control) to 20.10 mg/100 g (Table 1). Other studies have reported anthocyanins in fruit-added extrudates (Camire et al., 2002; Khanal et al., 2009). Camire et al. (2002) produced breakfast cereals with white cornmeal and blueberry and reported 4.03 mg of anthocyanins/100 g. Retention of total anthocyanins was up to 71%. These results are in line with those of Khanal et al. (2009), who observed retention of total anthocyanins up to 67%, after extrusion of blueberry pomace with decorticated white sorghum flour.

Anthocyanins are known to be heat sensitive and are susceptible to degradation during high-temperature processing (Lucas et al., 2018a). According to Hirth et al. (2014), one possible reason for anthocyanin retention could be attributed to the low residence time of the material under thermal exposure. Furthermore, moisture content used in the process could positively influence anthocyanin retention. Moisture content can decrease the shear stress during the extrusion and results in less destruction of these compounds (Hirth et al., 2014). According to Khanal et al. (2009) process moisture can prevent high anthocyanin losses. Hirth et al. (2015) observed higher retention (65%) of chokeberry anthocyanins in extrudates when using higher water content in the extrusion.

Regarding the total carotenoids concentration in the extrudates, the 2%, 4%, and 6% of açai addition resulted in

increases of these bioactive compounds compared to the control sample (Table 1). The enrichment of extrudates with carotenoids has been previously reported. Obradović et al. (2015) developed extrudates with 8% pumpkin powder and reported lutein and zeaxanthin amounts higher than treatment without pumpkin addition. Similar to our results, Basto et al. (2016) enriched extrudates based on corn with 15 and 25% of yellow peach palm and reported total carotenoids of 5.61 and 6.34 µg/g, respectively. Kosińska-Cagnazzo et al. (2017) found that goji berries could increase zeaxanthin dipalmitate concentration in rice-based extrudates.

Previous studies have shown carotenoids stability, and even their increase, during extrudates development (Basto et al., 2016; Obradović et al., 2015). According to Obradović et al. (2015), the increased carotenoid concentration in extrudates is a consequence of the improved extractability of these compounds (which were previously tightly bound to other molecules) due to high temperature and high-pressure treatment.

3.2 Color characteristics

Anthocyanins are pigments that provide purple, red, and blue colors (Camire et al., 2002), while carotenoids provide yellow, orange, and red colors (Rodriguez-Amaya, 2019). These compounds are often desired in foods not just to increase the bioactive properties but also to act as a natural colorant (Camire et al., 2002; Lucas et al., 2018a).

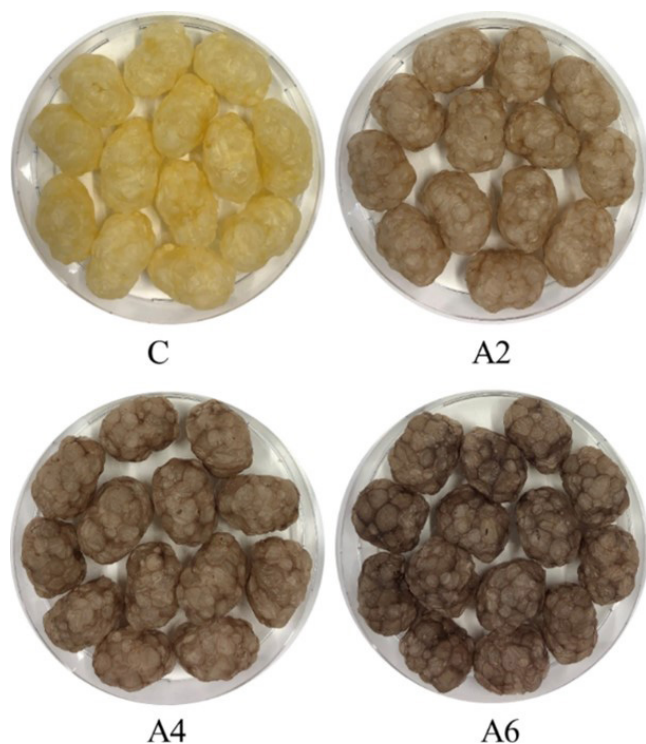
In extrudates, color is one of the most important characteristics that directly relate to their acceptance (Camire et al., 2002; Oliveira et al., 2018). In the present study, the color parameters of the expanded snacks were significantly affected ($p < 0.05$) by açai incorporation (Table 2) due to the presence of the color bioactive compounds (Table 1).

The extrudates are presented in Figure 1. Açai addition resulted in darker, more reddish, and blue snacks with significant ($p < 0.05$) lower L^* , b^* , and C^* , and a higher a^* when compared to the control sample. The extrudates presented a hue angle situated between the red and yellow; in sample C, it appeared closest to 90° (yellow) (Table 2). By observing the total color difference (ΔE), açai pulp powder in all concentrations (2, 4,

Table 2. Color properties of control snacks (C) and snacks enriched with 2% (A2), 4% (A4), and 6% (A6) of açai pulp powder.

Trial	L*	a*	b*	C*	h	ΔE
C	61.32 ± 0.61 ^a	0.65 ± 0.23 ^c	16.81 ± 1.23 ^a	16.83 ± 1.23 ^a	87.81 ± 0.77 ^a	(-)
A2	51.23 ± 0.88 ^b	3.36 ± 0.57 ^b	11.71 ± 1.37 ^b	12.18 ± 1.47 ^b	74.09 ± 0.94 ^b	11.71 ± 0.75 ^c
A4	43.25 ± 0.74 ^c	4.43 ± 0.35 ^a	9.75 ± 0.39 ^c	10.71 ± 0.49 ^{b,c}	65.59 ± 1.00 ^c	19.77 ± 0.71 ^b
A6	38.63 ± 1.36 ^d	4.86 ± 0.41 ^a	8.96 ± 0.64 ^c	10.20 ± 0.72 ^c	61.52 ± 1.34 ^d	24.39 ± 1.11 ^a

L* = lightness; +a* = redness; -a* = greenness; +b* = yellowness; -b* = blueness; C* = chroma; h = hue angle; ΔE = total color difference; (-) = standard values (L*, a*, b*) used in the calculation of ΔE. Means ± standard deviation (n = 5); different letters in the same column indicate significant differences between samples (p < 0.05).

**Figure 1.** Extrudates C, A2, A4, and A6 containing 0, 2, 4, and 6% of açai pulp powder, respectively.

and 6%) showed the potential of being a natural colorant. ΔE-values between 6 and 12 indicate a strong difference between two colors, and values superior to 12 indicated different colors (Limbo & Piergiovanni, 2006; You et al., 2018). Thus, in the present study, extrudates A4 and A6 presented colors different from the control and the A2 sample's color showed a strong difference compared to the control.

These findings are in line with the study of Kosińska-Cagnazzo et al. (2017), who observed a significant reduction in lightness (from 77.9 to 56.1) as well as an increase in a* values (from 6.0 to 21.9) when incorporating goji berries (28.5%) to extrudates. Camire et al. (2002) applied blueberries as a natural colorant in breakfast cereals and observed a significant reduction of L* and b* as well as an increase in a*. Hirth et al. (2014) showed that the incorporation of 2% bilberry extract into extrudates resulted in a red to purple color. Oliveira et al. (2018) developed extruded breakfast cereals with jaboticaba peel powder (10%)

and reported a modification of the color, with a lower L* (40.28) and b* (0.95), which resulted in a better appearance.

3.3 Physical-chemical characteristics

Producing extrudates with bioactive constituents and acceptable physical properties is considered a challenge. In the present study, the extrudates retained anthocyanins and carotenoids (Table 1) as well as presented suitable physical properties (Table 3).

The expansion index (EI) is considered an important property of extrudates. In the present study, the expansion index of the extrudates containing açai showed no significant difference (p > 0.05) compared to the control sample (Table 3). These results were similar to those obtained by Lucas et al. (2018b) for snacks enriched with microalga (4.57 cm/cm). This indicates that the reduction of the flour fraction by replacing it with 2, 4, and 6% of açai was not relevant for the radial expansion.

Açai extrudates showed a similar diameter and distribution of air cells compared to the control sample (Figure 2). Previous studies reported that higher fractions of fruits (> 6%) incorporated into extrudates can result in differences in diameter and pore size of the samples (Basto et al., 2016; Höglund et al., 2018). Kosińska-Cagnazzo et al. (2017) observed a reduction of the expansion index in extrudates with goji berry (13, 23, and 28.5%). Basto et al. (2016) observed a smaller diameter and irregular air cells in extrudates with 25% peach palm as compared to the control sample (100% corn).

Bulk density is a physical parameter commonly evaluated in extrudates, which reflects an expansion in all directions (Jeyakumari et al., 2016). The addition of 2% açai pulp powder did not result in significant (p > 0.05) changes in this property. However, samples A4 and A6 showed significantly (p < 0.05) higher bulk density. These results can be related to the increase in proteins in these formulations. Interaction between protein and starch may have occurred, impeding the ability of starch to link to water (Anton et al., 2009; Sumargo et al., 2016;), reducing the gelatinization and increasing bulk density. Similar to our findings, Lucas et al. (2018b) reported a significant increase in bulk density of snacks containing *Spirulina* (from 0.070 in the control sample to 0.077 g/cm³).

In the present study, denser snacks showed harder texture as well. These results are comparable with those found by other studies on expanded snacks (Ding et al., 2005; Lucas et al., 2017). The hardness in A2 and A4 did not differ significantly from the control sample (p > 0.05). However, snacks made with

Table 3. Physical-chemical properties of control snacks (C) and snacks enriched with 2% (A2), 4% (A4), and 6% (A6) of açai pulp powder.

Trial	Expansion index (cm/cm)	Bulk density (g/cm ³)	Texture		WAI (g/g)	WSI (%)
			Hardness (N)	Crispness ¹		
C	4.81 ± 0.03 ^a	0.056 ± 0.002 ^c	20.39 ± 1.37 ^b	100.00 ± 5.29 ^b	5.32 ± 0.10 ^a	44.12 ± 1.47 ^a
A2	4.81 ± 0.08 ^a	0.059 ± 0.001 ^{b,c}	21.42 ± 1.00 ^{a,b}	101.33 ± 5.03 ^b	4.97 ± 0.18 ^b	44.02 ± 1.50 ^a
A4	4.80 ± 0.03 ^a	0.064 ± 0.004 ^{a,b}	23.61 ± 1.45 ^{a,b}	116.67 ± 7.09 ^a	4.86 ± 0.11 ^b	39.52 ± 1.53 ^b
A6	4.77 ± 0.04 ^a	0.066 ± 0.002 ^a	23.85 ± 1.26 ^a	117.33 ± 2.52 ^a	4.91 ± 0.02 ^b	37.10 ± 1.33 ^b

¹ = number of measured force peaks; WAI = water absorption index; WSI = water solubility index. Means ± standard deviation (*n* = 3); different letters in the same column indicate significant differences between samples (*p* < 0.05).

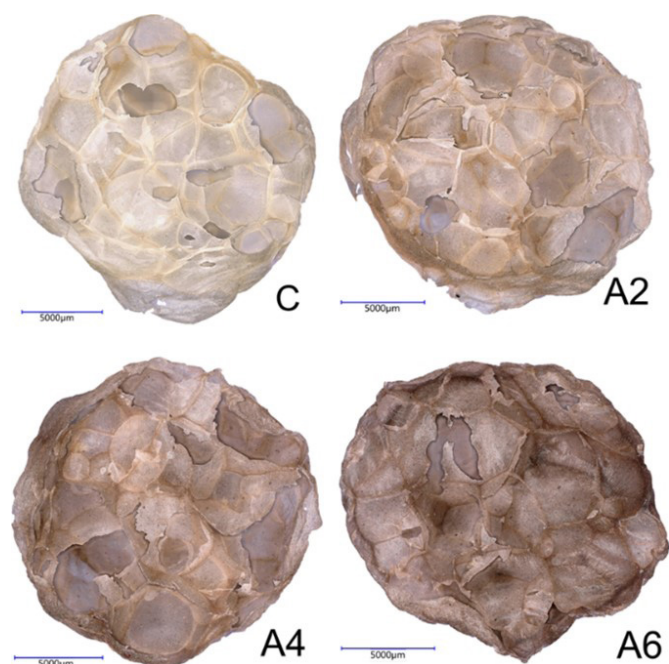


Figure 2. Internal radial structure of extrudates C (0% açai), A2 (2% açai), A4 (4% açai), and A6 (6% açai).

6% of açai showed a significant (*p* < 0.05) increase in hardness compared to the control.

Crispness is a texture attribute directly related to the acceptance of extrudates. The addition of 4% and 6% of açai resulted in crispier snacks. The results are following those reported by Oliveira et al. (2018), who obtained 125.7 ± 9.73 for crispness in sensorially accepted breakfast cereals containing jaboticaba peel powder.

The water absorption index (WAI), which indicates an index of gelatinization (Lazou & Krokida, 2010), was significantly (*p* < 0.05) lower in açai incorporated samples. A plausible reason could be the reduction in starch content, by reducing the flours content, leading to lower overall gelatinization during the extrusion (Sumargo et al., 2016) of açai formulations. Another reason could be due to the increase in protein content (by increasing açai proportion) that may have caused bounds formation with amylose and amylopectin inhibiting the capacity of starch to bind water (Lazou & Krokida, 2010; Sumargo et al., 2016). The water solubility index, which indicates the degraded starch content during the extrusion (Dalbhagat et al., 2019), was significantly lower (*p* < 0.05) in samples A4 and A6. According

to Dalbhagat et al. (2019), the reduced values of the WSI could be due to the formation of an amylose-lipid complex or other interactions. The obtained results are in line with those reported by Sumargo et al. (2016) for rice-bean extrudates.

Water activity (A_w -value) is a measure for the free water available in the material and is directly related to food shelf life, being values lower than 0.6 related to higher stability (Gümüşay et al., 2019). In this work, A_w -values in the extrudates were 0.2 for all treatments, indicating a longer shelf life (Gümüşay et al., 2019).

Despite the differences between the formulations in some parameters evaluated, the results are in line with previous findings for extrudates with high sensory acceptance (Lucas et al., 2018b). Therefore, snacks with bioactive compounds and adequate technological characteristics can be developed using açai berries.

Although the present study found relevant results related to the development of extrudates added with berries, contributing to the existing literature, a limitation should be pointed out: the lack of sensory analyses. Thus, future research might address consumer (adults and children) perception by using verbal and non-verbal approaches (Cruz et al., 2021; Delorme et al., 2021; Lucas et al., 2020; Lucas et al., 2018b).

4 Conclusions

Bioactive constituents (anthocyanins and carotenoids) as well as the main physicochemical properties were preserved in the extrudates elaborated with different concentrations of açai. Furthermore, the addition of 6% açai to cereal-based extrudates increased the protein content by 6.3% and ashes content by 32.2%.

Açai-enriched extrudates presented no differences regarding moisture loss during extrusion process, expansion index, water activity, and protein digestibility, as compared to the control sample. Higher concentrations of açai resulted in denser, harder and crispier snacks. The bioactive pigments from the fruit acted as a natural colorant, resulting in darker, more reddish, and blue colors. Thus, extruded snacks added with açai can be considered an alternative for consumers interested in convenience food with bioactive constituents.

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