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Nutritional Value and Antioxidant Capacity of Mexican Varieties of Sweet Potato (*Ipomoea batatas* L.) and Physicochemical and Sensory Properties of Extrudates

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The objective of the study was to perform a nutritional analysis and antioxidant capacity of three varieties of sweet potatoes, *Ipomoea batatas* L., from Mexico, classified by color as: purple, yellow and white. In addition, sweet potato extrudates were produced and evaluated for their nutritional, antioxidant, sensory and texture properties. The average content of macronutrients for the three varieties was 77.92 g of carbohydrate, 10.51 g of dietary fiber, 8.25 g of protein, and 0.53 g of lipid *per* 100 g tuber on a dry matter (DM) basis. The purple variety exhibited the highest content of fiber as well as zinc and sodium, and the white one displayed the highest content of protein. In turn, contents of calcium, iron, and magnesium were the highest in yellow potatoes. Ascorbic acid content ranged from 60.6 to 106.0 mg/100 g DM, being higher in the yellow potatoes, and the total phenolic content ranged from 216 to 581 mg GAE/100 g DM, being higher in the purple potatoes. The average antioxidant capacity was 40.7 and 23.4 µmol TE/g DM in DPPH and ABTS assays. A lower total phenolic content and antioxidant capacity of extruded sweet potatoes were found with respect to the fresh ones. Among the extrudates, the purple ones had the highest total phenolic content (307 mg GAE/100 g DM) and exhibited the highest antiradical activity in the ABTS assay (15.5 µmol TE/g DM). They were also scored the highest in the sensory analysis, although the instrumental texture analysis showed their greater hardness (64.4 N) compared to the yellow and white extrudates (46.9 and 30.5 N, respectively). Extrudates of the three potato varieties exhibited a sweet taste and, thus, can be considered as sweetener substitutes in snacks with increased nutritional and bioactive potential.

Keywords: colored potatoes, extrusion, potato tuber, proximate analysis, texture parameters

ABBREVIATIONS

SP, sweet potato, *Ipomoea batatas*; RH, relative humidity; DM, dry matter; WM, wet matter; %DRI, percentages of the dietary reference intakes; GAE, gallic acid equivalent; TE, Trolox equivalent.

INTRODUCTION

The sweet potato (SP), *Ipomoea batatas* L., is the second most important tuber crop globally and is harvested in over 110 countries. It is native to and domesticated in tropical America, between Mexico and Peru. Sweet potato is a globally important vegetable, ranking among the six most important food crops after rice, wheat, potato, corn and manioc [Grüneberg *et al*., 2017; Leonel *et al*., 2023]. As reported by the Food and Agriculture Organization of the United Nations (FAO), its global production in 2022 reached 86.4 million tons, with Mexico contributing 81,095 tons [Ritchie *et al*., 2023]. According to this report, China accounted for most of the global production at 53.9%, followed by Malawi (9.3%), Tanzania (4.9%), and Nigeria (4.6%). A diversity

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of varieties is observed, displaying a range of colors, including orange, red, purple, yellow, brown, cream and white, and each variety possesses a distinct chemical and nutritional composition [Oloniyo *et al*., 2021]. Sweet potato composition includes carbohydrates, dietary fibers, vitamins, minerals, and several bioactive metabolites. The purple variety is characterized by its significant content of anthocyanins, while the yellow and orange varieties contain carotenoids and are dense in provitamin A [Tang *et al*., 2015]. In addition to their high water-soluble dietary fiber content, sweet potato tips are also a rich source of protein when compared to other vegetables, as well as iron, potassium, vitamins B_2, C, and E [Hong *et al*., 2022]. The main carbohydrate of sweet potato is starch; however, the tubers contain also significant amount of sucrose, glucose and fructose, which are responsible for their sweet taste [Leonel *et al*., 2023]. Also, during storage and cooking, the presence of maltose is observed due to the hydrolysis of starch by α- and β-amylases.

Several biological activities of sweet potatoes have been reported, both in leaves and root tubers, including antioxidant, anti-inflammatory, antimicrobial, antifungal, antiviral, antidiabetic, antimutagenic, hepatoprotective, anticoagulant, and anticarcinogenic ones [Murnihati *et al*., 2020; Vergun *et al*., 2020]. These activities vary depending on the part of the tuber and the color. Bioactive compounds of sweet potatoes, including phenolic acids, flavonoids, anthocyanins, ascorbic acid, and carotenoids enable these effects to occur [Hossain *et al*., 2022; Makori *et al*., 2020].

The root pulp of sweet potatoes can be cooked, fried, roasted, or used as an ingredient in stews. It is widely used in the food industry, including in baby food, cakes, pastries, frozen vegetables, ice cream, ready-to-eat meals, chips, syrups, starches, snacks, as well as beverages such as juices and teas, and in confectionery products due to the distinctive colors offered by its different varieties. On an industrial level, starch, sugar, alcohol and natural dyes are also extracted. In addition, public awareness of the health risks associated with wheat gluten is opening a new market niche [Escobar-Puentes *et al*., 2022; Hong *et al*., 2022].

The objective of this study was to compare the nutritional composition and antioxidant capacity of three varieties of sweet potatoes native to Mexico, namely purple, yellow, and white, as well as extruded products obtained from these potatoes. The sensory and texture properties of extruded sweet potatoes were also analyzed in the study.

MATERIALS AND METHODS

Raw material

Tubers of three types of sweet potato (SP), *Ipomoea batatas* L., were used in this study based on their color: purple, yellow, and white (**Figure 1**). The SP are indigenous to the Mexican state of Michoacán and were procured from a market in the city of Morelia. For analysis, they were washed with distilled water and sliced into approximately 5-cm thick pieces, including the peel, and dehydrated at 50°C for 48 h in an oven (model 9023A, Ecoshel, Pharr, TX, USA). Subsequently, the samples were ground and passed through a 60-mesh sieve, resulting in a flour with a particle size of less than 260 µm. The dry matter (DM) content of the samples was calculated by the difference in weight before and after drying.

Preparation of extrudates

The fresh SP were blanched for 10 min at boiling temperature, the peel was removed, and they were cut into 5-cm thick pieces. Subsequently, they were dehydrated in a gas oven at 55±5°C for up to 2 h at separate intervals to obtain varying levels of humidity. The final humidity levels achieved were 15–20% in 30 min, 10–15% in 60 min, and 5–10% in 120 min. The extruder equipment was assembled in a laboratory within the Universidad Michoacana de San Nicolás de Hidalgo, México. The screw-type extruder used had a helical worm of circular panel with a 1-cm diameter, and a blade and a die made of stainless steel which allowed to produce 1-cm diameter filament. It was powered by a 1 HP Marver model 10012 series 1009 motor (Crompton, Mumbai, India). The extrusion of SP was conducted without any additives. After extrusion, the products were placed in a gas oven set to 90±5°C for 1 h to remove excess moisture and achieve the desired texture.

Analysis of proximate composition, dietary fiber content and mineral contents

The proximate composition analysis of potatoes and extrudates was conducted according to AOAC International methods [AOAC, 2000]; moisture (method no. 934.01), protein (method no. 960.52), lipids (method no. 920.85), ash (method no. 942.05), and crude fiber (962.09) were determined. The content of dietary fiber (total, soluble and insoluble fractions) was assessed using the method of Prosky *et al*. [1988], with a total dietary fiber assay kit (Sigma-Aldrich, Saint Louis, MO, USA). The analyses were conducted in triplicate. The content of carbohydrates was calculated by difference from the data on moisture, protein, lipid, ash, and dietary fiber. The roots' metabolizable energy was estimated using conversion factors of 4 kcal/g for proteins and carbohydrates, 9 kcal/g for lipids, and a value of 2 kcal/g for dietary fiber, as indicated in the data provided by the FAO [2003].

The determination of SP starch was conducted in accordance with the stipulations of the Mexican standard NOM-F321-S1978 [1978], which represents a modified iteration of the Lane-Eynon procedure. A quantity of 5 g of the sweet potato powder was placed in a container with 150 mL of water and 25 mL of concentrated HCl, and the contents were mixed thoroughly. The solution was heated for 75 min, cooled and neutralized with $NaOH/H_2O$ (1:1, *w/v*) solution. Subsequently, the hydrolysate, after filling the volume to 250 mL was filtered. Then, the 10-fold diluted filtrate was transferred to a burette and was added dropwise to the flask containing a mixture of $CuSO_4{\times}5H_2O$ solution and $NaKC_4H_4O_6{\times}4H_2O$ solution. Just prior to the complete reduction of the copper, 1 mL of the 0.2% aqueous solution of methylene blue was added. The titration was completed until the indicator lost its coloration. Starch content in the sample (g/100 g DM) was calculated utilizing a glucose-to-starch conversion factor of 0.9.

Certain minerals including calcium, copper, iron, potassium, magnesium, sodium, and zinc of SP were quantified using atomic absorption spectrometry. Digestion was performed using nitric acid, according to the procedure described by Uddin *et al*. [2016]. A quantity of 0.5 g of the sample was weighed, and 5 mL of 65% HNO_3 was added. The resulting mixture was then boiled gently over a water bath maintained at 90°C for a period of 1–2 h until a clear, fully digested solution was obtained. The solution was then filtered using Whatman 42 filter paper (2.5 µm). Enough deionized water was then added to the final sample's volume to 50 mL. The analysis was conducted in triplicate using an atomic absorption spectrometer model AAnalyst 200 (Perkin Elmer, Waltham, MA, USA). The results were reported as mg/100 g DM.

Determination of ascorbic acid and total xanthophyll contents

Ascorbic acid in potatoes was quantified using the titrimetric method with 2,6-dichloroindophenol according to the AOAC International procedure (967.21) [AOAC, 2000] and its content was expressed as mg/100 g DM.

The total xanthophyll content was determined in accordance with the AOAC International method no. 970.64 [AOAC, 2000]. A sample weighing 50 mg was mixed with 3 mL of a solution composed of hexane, ethanol, acetone and toluene (10:6:7:7, *v/v/v/v*), and then 2 mL of 40% KOH in 80% methanol was added. The mixture was then incubated at 20°C for 16 h, brought to a volume of 10 mL with 10% $NaSO_4$ and shaken for 2 min in a vortex mixer. It was then allowed to stand for 1 h until the epiphase had clarified in the dark. Subsequently, the solution was transferred to a centrifuge tube and centrifuged at 3,000×g for 5 min. The absorbance was determined at a wavelength of 474 nm using a spectrophotometer, with hexane used as the blank. The total xanthophyll content was calculated using extinction coefficient for *trans*-lutein (236 L/(g×cm)) and expressed in µg/g potato sample.

Determination of total phenolic content, total flavonoid content, and antioxidant capacity

An extraction of each of the three SPs and three extrudates was conducted in order to determine the content of total phenolics, total flavonoids (only extrudates), and antioxidant capacity *via* assays with 2,2-diphenyl-1-picrylhydrazyl (DPPH) radicals and with 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radical cations. The powdered samples were treated as follows: 10 mL of ethanol (75%) was added to 1 g of each sample and stirred for 24 h in the dark. The samples were then centrifuged at 3,910×g for 10 min, after which the supernatants were collected and kept at 4°C until used for analyses.

The total phenolic content was determined using the colorimetric method with the Folin-Ciocalteau reagent, following the procedure established by Singleton *et al*. [1999] with minor modifications suggested by Treviño-Gómez *et al*. [2017]. A 250 µL aliquot of the extract was combined with 250 µL of 2 N Folin-Ciocalteu reagent and 250 µL of 20% Na_2CO_3, agitated, and incubated at 40°C for 30 min. Subsequently, 2 mL of distilled water were added to the mixture, which was then vortexed. The samples were subjected to absorbance measurement at 750 nm using a spectrophotometer (Genesys 20, Thermo Fisher Scientific Inc.). Gallic acid was used as a standard and the results were reported as mg gallic acid equivalent (GAE)/100 g DM.

The total flavonoid content of the extrudates was evaluated in accordance with the methodology described by Zhishen *et al*. [1999]. A 150 µL aliquot of each extract was combined with 150 µL of 5% $NaNO_2$, 150 µL of 10% $AlCl_3$, and 1 mL of 0.1 M NaOH. Subsequently, the samples were analyzed using a spectrophotometer (Genesys 20, Thermo Fisher Scientific Inc.) at an absorbance of 510 nm. The standard used was quercetin, and the results were expressed as mg quercetin equivalent (QE)/100 g DM.

The determination of DPPH radical scavenging activity was conducted according to the method developed by Brand-Williams *et al*. [1995] with modifications proposed by Ru *et al*. [2019]. In summary, 200 µL of each extract was added to 3 mL of the DPPH radical solution in methanol (100 µM). The samples were homogenized for 10 s, then the reaction mixture was incubated in the dark at room temperature for 30 min, after which its absorbance was measured at 517 nm using a spectrophotometer (Genesys 20, Thermo Fisher Scientific Inc.). The results were expressed as µmol Trolox equivalent (TE)/g DM using a standard curve of Trolox.

The ABTS assay was conducted in accordance with the methodology outlined by Re *et al*. [1999]. Firstly, a solution consisting of ABTS (7 mM) and potassium persulfate (2.45 mM) was mixed at room temperature in the dark for 20 h to generate $ABTS^{\bullet+}$. Then, methanol was used to dilute the $ABTS^{\bullet+}$ mixture to an absorbance around 0.70 at 734 nm. Subsequently, 0.1 mL of each extract was combined with 3.9 mL of the aforementioned $ABTS^{\bullet+}$ solution. The reaction mixture was kept at room temperature for 6 min, then the absorbance was recorded at 734 nm. The results were calculated based on the calibration curve plotted with Trolox and were expressed as µmol Trolox equivalent (TE)/g DM.

Texture analysis

A texture analysis by compression was conducted on the three extrudates using a Brookfield CT3 texture analyzer with TexturePro CT v1.7 Build 28 software (Brookfield Engineering Lab. Inc, Middleboro, MA, USA). The apparatus was operated with a TA11/1000 probe TA-SB element. The analysis was conducted on a single cycle with the target at 6.0 mm and an activation load of 0.07 N at a speed of 0.5 mm/s and 0.5 mm/s lap speed with a sampling rate of 50 points *per* s. The sample was 16.0 mm in length and 6.0 mm in height. The analysis was performed at room temperature (25±2°C) with 10 samples *per* extrudate.

Sensory analysis

Forty untrained participants were used to perform a sensory analysis of the extruded products using a hedonic test. The acceptability of the extrudates was determined using a 5-point hedonic scale, where 5 corresponded to "I like very much"; 4 to "I like"; 3 to "I neither like nor dislike"; 2 to "I dislike"; and 1 to

Table 1. Proximate composition and metabolized energy value of Mexican sweet potatoes with different tuber colors.

Constituent/Parameter	Purple	Yellow	White
Moisture (g/100 g)	60.80±1.52^{b}	72.44±2.17^{a}	68.54±1.37^{a}
Carbohydrate (g/100 g DM)	75.64±1.72^{b}	80.79±1.16^{a}	77.35±1.38^{ab}
Starch (g/100 g DM)	59.67±3.12^{a}	43.87±2.94^{b}	43.77±3.04^{b}
Dietary fiber (g/100 g DM)	13.56±1.20^{a}	8.33±0.61^{b}	9.65±0.73^{b}
Soluble fiber (g/100 g DM)	1.20±0.10^{b}	1.18±0.09^{b}	1.88±0.13^{a}
Insoluble fiber (g/100 g DM)	12.36±1.10^{a}	7.15±0.52^{b}	7.77±0.60^{b}
Protein (g/100 g DM)	7.97±0.42^{b}	7.03±0.33 ^{b}	9.73±0.48^{a}
Lipid (g/100 g DM)	0.15±0.02^{b}	1.20±0.10^{a}	0.25±0.03^{b}
Ash (g/100 g DM)	2.68±0.09^{b}	2.65±0.12^{b}	3.02± 0.13^{a}
Energy value (kcal/100 g)	363±3^{c}	379±1^{a}	370±2^{b}

Results are shown as mean ± standard deviation. Different letters in the same row indicate the significant differences (p<0.05). DM, dry matter.

"I dislike very much". Color, odor, texture, and taste of the samples were evaluated.

Color parameter analysis

The color was evaluated in fresh, blanched, and extruded sweet potatoes from the three varieties. A Spectro-guide 45/0 colorimeter was employed for this purpose (BYK-Gardner GmbH, Geretsried, Germany). Values were obtained based on the CIELab scale with a brightness of D65, viewing angle of 10° and aperture diameter of 8 mm. The instrument provided darkness/brightness (L*), green/red intensity (a*), and blue/yellow intensity (b*). Three replicates of measurements were conducted for each sample, and the instrument was calibrated with a white ceramic plate standard prior to each procedure.

Statistical analysis

Analyses of nutritional composition, mineral content, bioactive compound content, antioxidant capacity, and color parameters were performed in triplicate. For texture parameters and sensory scores, the number of repetitions were 10 and 40, respectively. Results were subjected to a one-way analysis of variance (ANOVA) using JMP software version 8.0 (JMP Statistical Discovery LLC, Cary, NC, USA). Means were compared using Tukey's test, and differences were considered significant when p<0.05.

RESULTS AND DISCUSSION

Macronutrients of sweet potatoes

The results of proximate analysis of SP are presented in **Table 1**. Moisture content was 60.80 g/100 g in purple, 72.44 g/100 g in yellow, and 68.54 g/100 g in white potatoes, with an average of 67.26 g/100 g. The moisture content of yellow and white varieties did not differ significantly (p≥0.05).

The three varieties under examination had an average dry matter content of 32.74 g/100 g. Grüneberg *et al*. [2017] conducted a comprehensive study of SP with 1,174 clones analyzed in various environments and determined an average dry matter content of 34.9 g/100 g. They also noted that genotypic factors had a greater impact on variability than environmental factors. Rowena *et al*. [2009] reported a dry matter content of 32.46 g/100 g after analyzing five varieties from the Philippines, while Teow *et al*. [2007] found a value of 30.2 g/100 g after studying nineteen clones from the USA.

Carbohydrates were found to be the most abundant nutrient of SP (**Table 1**), with an average content of 77.92 g/100 g DM. The highest content was found in the yellow variety, while the lowest content was in the purple variety. These findings were statistically significant (p<0.05). Additionally, the white variety did not differ statistically (p≥0.05) from the yellow and purple varieties. Armijos *et al*. [2020] reported an average of 81.66 g/100 g DM in carbohydrate content for seven varieties native to Ecuador with yellow, orange, and purple colors. Nascimento *et al*. [2015] studied three Brazilian SP varieties (white and orange) from organic cultivation and reported that their carbohydrate content was 57.21 g/100 g DM, being higher in the white variety, which is consistent with the results of our study. The content of starch, the main carbohydrate fraction of SP, ranged from 43.87 to 59.67 g/100 g DM (**Table 1**), and a significantly (p<0.05) higher value was noted for the purple variety compared to the other varieties. Armijos *et al*. [2020] reported an average of 60.56 g/100 g DM in starch content of SP with yellow, orange, and purple colors. Grüneberg *et al*. [2017] found that starch content of different clones of *I. batatas* was 66.0 g/100 g DM, while the content of sucrose, glucose, and fructose in DM was 10.3 g/100 g, 2.2 g/100 g, and 1.7 g/100 g, respectively. Nascimento *et al*. [2015] reported a starch content of 29.3 g/100 g DM in Brazilian SP. In turn, Hossain *et al*. [2022] who analyzed eight SP varieties from Bangladesh, reported an average starch content of 52.72 g/100 g in powdered dry roots. It is also noteworthy that the purple varieties exhibit the highest starch content, which is comparable to that determined in the present study.

The lipid content of SP was minimal with an average of 0.53/100 g DM, and the yellow variety had a significantly (p<0.05) higher lipid content (1.20 g/100 g DM) than the other varieties (**Table 1**). Armijos *et al*. [2020] and Hossain *et al*. [2022] reported lipid contents of 1.35 and 1.51 g/100 g DM, respectively. The latter author noted that the highest content of lipids was

Table 2. Mineral content of Mexican sweet potatoes with different tuber colors (mg/100 g dry matter).

Mineral	Purple	Yellow	White	%DRI	
				Men	Women
Calcium	44.4±1.8^{c}	139.8±5.7^{a}	72.8±2.4^{b}	2.6	2.6
Iron	10.5±0.4^{b}	12.8±0.5^{a}	11.4±0.4^{b}	46.8	20.8
Potassium	2,439±119^{b}	2,948±133^{a}	2,948±105^{a}	26.4	34.6
Magnesium	75.3±3.2^{c}	117.4±4.4^{a}	104.0±4.2^{b}	7.7	10.0
Sodium	106.9±4.3^{a}	87.8±3.5^{b}	54.0±2.3^{c}	1.8	1.8
Zinc	1.17±0.04^{a}	0.40±0.01^{b}	0.00±0.0	2.6	3.6

Results are shown as mean ± standard deviation. Different letters in the same row indicate the significant differences (p<0.05). %DRI, percentage of the dietary reference intakes of the minerals by consuming 100 g of fresh sweet potato calculated according to recommendations of the National Institutes of Health in USA [NIH, 2022].

found in the yellow variety, a finding that aligns with the results of our research.

The average protein content was 8.25 g/100 g DM, with the white variety having the highest content (9.73 g/100 g) and differing significantly (p<0.05) in this respect from the other varieties (**Table 1**). Armijos *et al*. [2020] reported a protein content of 6.50 g/100 g DM, while Grüneberg *et al*. [2017] reported a range from 2.7 to 8.9 g/100 g DM for different clones of *I. batatas*. Leonel *et al*. [2023] analyzed data from multiple authors and reported values between 1.3 and 9.5 g/100 g DM.

The dietary fiber content was observed to be an average of 10.51 g/100 g DM, with 9.09 g/100 g DM being insoluble fiber and 1.42 g/100 g DM being soluble fiber. The white variety had the highest amount of soluble fiber, while the purple one had the highest amount of insoluble fiber (**Table 1**). Armijos *et al*. [2020] reported a soluble fiber content of 2.82 g/100 g DM and an insoluble fiber content of 10.17 g/100 g DM in differently colored Ecuadorian SP. Additionally, Leonel *et al*. [2023] reported a dietary fiber content of 19.36 g/100 g DM.

The average metabolized energy value of the three types of sweet potato was 371 kcal/100 g DM, according to theoretical data (**Table 1**). However, there were statistically significant (p<0.05) differences between the three varieties, being higher in the yellow variety and lower in the purple one. Vergun *et al*. [2020] found that the energy values of SP from Ukraine, when determined using calorimetric equipment, ranged from 342 to 362 kcal/100 g

To sum up, the macronutrient composition of sweet potatoes varied depending on their variety. Yellow potatoes had a higher content of carbohydrates and lipids, purple ones – dietary fiber, and white ones – proteins and ash.

Micronutrients of sweet potatoes

The mineral analysis results displaying the content of calcium, iron, potassium, magnesium, sodium, and zinc in dry matter of sweet potatoes are presented in **Table 2**. The copper was also analyzed but not detected. The level of calcium ranged from 44.4 to 139.8 mg/100 g DM, with the yellow variety having almost twice as much of this element as the other varieties. Our results were lower than those obtained by Armijos *et al*. [2020], who reported an average calcium content of 229 mg/100 g DM in Ecuadorian potatoes. Musilová *et al*. [2017] also determined a higher calcium content in the pulps of SP from the Slovak Republic (average of 468 mg/100 g DM). The average potassium content in Mexican potatoes in our study was found to be 2,778 mg/100 g DM, which was lower than the values reported by Armijos *et al*. [2020] (average of 3,501 mg/100 g DM) and higher than those reported by Musilová *et al*. [2017] (1,204 mg/100 g DM in pulp). The sodium levels varied significantly (p<0.05) among the three samples in the range of 54.0–106.9 mg/100 g DM, (**Table 2**). The average value found in this study was higher than those reported by other authors in the field; with Armijos *et al*. [2020] reporting 75.7 mg/100 g DM, while Musilová *et al*. [2017] reporting 63.4 mg/100 g DM in flesh.

Iron was determined in this study within a range from 10.5 to 12.8 mg/100 g DM (**Table 2**). Armijos *et al*. [2020] and Grüneberg *et al*. [2017] reported the iron content of 13.7 and 15.6 mg/100 g DM, respectively. Magnesium was recorded within a range from 75.3 to 117.4 mg/100 g DM with an average of 98.9 mg/100 g DM (**Table 2**). Lower magnesium levels were found in yellow, orange, and purple varieties from Ecuador with an average of 50.0 mg/100 g DM [Armijos *et al*., 2020] and in pulps of Slovak sweet potatoes with an average of 75.2 mg/100 g DM [Musilová *et al*., 2017]. Zinc was not detected in the white variety and its content in the yellow and purple SPs was 0.40 and 1.17 mg/100 g DM, respectively. Armijos *et al*. [2020] reported an average zinc content of 1.57 mg/100 g DM; Grüneberg *et al*. [2017] reported 0.93 mg/100 g DM, and Musilová *et al*. [2017] determined it at 0.92 mg/100 g DM.

This study found that, among the analyzed SP varieties, the yellow variety was the rich source of calcium, iron, and magnesium. On the other hand, the purple variety had the highest content of sodium and zinc but a lower potassium content.

Table 2 also shows the percentages of the dietary reference intakes (DRI) of the analyzed minerals by consuming 100 g of fresh sweet potato, which were calculated based on the recommendations of the National Institutes of Health (NIH) in USA, [NIH, 2022] (the average content of each mineral for the three

Table 3. Content of antioxidants and antioxidant capacity of Mexican sweet potatoes and extrudates obtained therefrom.

Content/Activity	Purple	Yellow	White
Sweet potatoes			
Ascorbic acid content (mg/100 g DM)	64.8±4.2^{b}	106.0±6.4^{a}	60.6±3.8^{b}
Total xanthophyll content (µg/g DM)	175±12^{b}	395±25^{a}	185±13^{b}
Total phenolic content (mg GAE/100 g DM)	581±36^{a}	388±25^{b}	216±14^{c}
DPPH$^{\bullet}$ radical scavenging activity (µmol TE/g DM)	39.8±2.1^{a}	41.7±2.8^{a}	40.5±2.4^{a}
ABTS$^{\bullet+}$ scavenging activity (µmol TE/g DM)	28.2±1.7^{a}	22.1±1.8^{b}	19.9±1.3^{b}
Extruded sweet potatoes			
Total flavonoid content (mg QE/100 g DM)	60.6±1.2^{a}	29.6±0.4^{b}	11.4±0.3^{c}
Total phenolic content (mg GAE/100 g DM)	307±14^{a}	115±3^{b}	45±4^{c}
DPPH$^{\bullet}$ radical scavenging activity (µmol TE/g DM)	10.9±0.4^{b}	16.9±1.5^{a}	9.2±1.0^{b}
ABTS$^{\bullet+}$ radical scavenging activity (µmol TE/g DM)	15.5±0.2^{a}	13.8±0.5^{b}	13.3±0.4^{b}

Results are shown as mean ± standard deviation. Different letters in the same row indicate the significant differences (p<0.05). QE, quercetin equivalents; GAE, gallic acid equivalents; TE, Trolox equivalents; DM, dry matter.

varieties was used). The reference values are for people aged 19 to 50 years. It is noted that sweet potatoes were a micronutrient--rich food, providing high levels of potassium and iron, as well as magnesium. In addition, the sodium content was very low, providing only 1.8% of the recommended daily intake.

Contents of ascorbic acid, total xanthophylls and total phenolics in sweet potatoes

The contents of ascorbic acid, total xanthophylls, and total phenolics in different varieties of SP are shown in **Table 3**. The ascorbic acid content ranged from 60.6 to 106.0 mg/100 g DM. The yellow variety had the highest content, being 1.7 times higher than that of the other varieties. According to literature data, ascorbic acid content of Ecuadorian yellow, orange, and purple varieties of sweet potatoes was on average 67.2 mg/100 g DM [Armijos *et al*., 2020], while Ukrainian SP contained approximately 41.5 mg of this compound in 100 g of pulp [Vergun *et al*., 2020]. Vidal *et al*. [2018] compiling information from various authors, reported an ascorbic acid content ranging from 2.4 to 25.0 mg/100 g wet matter (WM), and Gichuhi *et al*. [2014] reported a value ranging from 6.4 to 15.5 mg/100 g WM for organic sweet potatoes from the USA. Considering the average content of ascorbic acid in the samples in our study and DRI of vitamin C recommended by NIH regulations [NIH, 2022], women and men over 19 years would receive 32.8% and 27.3% of DRI, respectively, by consuming 100 g of fresh sweet potato.

Total xanthophyll content of three SP varieties ranged from 175 to 395 µg/g DM with an average of 252 (**Table 3**). The yellow variety showed its highest quantity, followed by white and purple varieties. Escobar-Puentes *et al*. [2022] analyzing studies of several authors, reported that the carotenoid content of sweet potatoes was 509 µg/g DM, with the highest content found in orange, followed by yellow, white, and purple potatoes. The authors also noted that these contents could be higher than those found in carrots and mangoes, which are typically recognized as reliable sources of carotenoids.

The average total phenolic content of SP was 395 GAE mg/100 g DM with a range from 216 to 581 mg GAE/100 g DM. Sweet potatoes cultivated in the Philippines had an average total phenolic content of 567 mg GAE/100 g DM, with a higher content found in the purple varieties, followed by yellow and white ones [Rowena *et al*., 2009]. Escobar-Puentes *et al*. [2022] in a review publication reported values ranging from 140 to 1,230 mg GAE/100 g DM, with the highest noted for purple potatoes, followed by orange, yellow, and white ones. The findings of this study indicated that the purple variety exhibited the highest total phenolic content, followed by the yellow and then the white variety, which was consistent with the above-mentioned literature data. Musilová *et al*. [2017] reported that the content of total phenolics in the peel of SP was higher than in the pulp. On the other hand, Murnihati *et al*. [2020] found that the main antioxidant compounds in purple sweet potatoes were anthocyanins and other polyphenols, while orange and yellow sweet potatoes mainly contained carotenoids. Our research findings are consistent with these conclusions.

Antioxidant capacity of sweet potatoes

The results of the antioxidant capacity of potatoes measured as the antiradical activity against DPPH$^{\bullet}$ and ABTS$^{\bullet+}$ and reported as µmol TE/g DM are shown in **Table 3**. The DPPH assay results showed homogeneity of values with no statistical difference (p≥0.05) between differently colored potatoes. However, the ABTS assay indicated that the purple potatoes had significantly (p<0.05) higher antioxidant capacity compared to the other samples.

Table 4. Proximate composition, metabolized energy value and texture parameters of extruded sweet potatoes.

Constituent/Parameter	Purple	Yellow	White
Moisture (g/100 g)	6.41±0.51^{a}	6.86±0.58^{a}	5.97±0.54^{a}
Carbohydrate (g/100 g DM)	88.57±0.77^{a}	89.76±0.73^{a}	88.43±0.83^{a}
Crude fiber (g/100 g DM)	2.30±0.20^{a}	0.99±0.12^{c}	1.46±0.15^{b}
Protein (g/100 g DM)	6.76±0.42^{a}	6.60±0.44^{a}	7.63±0.53^{a}
Lipid (g/100 g DM)	0.13±0.02^{b}	0.50±0.04^{a}	0.14±0.02^{b}
Ash (g/100 g DM)	2.24±0.14^{a}	2.15±0.12^{a}	2.35±0.13^{a}
Energy value (kcal/ 100 g)	387±1^{b}	392±1^{a}	388±1^{b}
Hardness (N)	64.4±4.0^{a}	46.9±5.7^{b}	30.5±4.4^{c}
Adhesiveness (N)	0.251±0.056^{a}	0.237±0.054^{ab}	0.183±0.069^{b}
Fracturability strength (N)	28.1±3.2^{a}	23.7±2.4^{b}	17.7±1.6^{c}
Number of fractures	11.1±2.3^{b}	14.3±3.6^{ab}	16.9±4.4^{a}

Results are shown as mean ± standard deviation. Different letters in the same row indicate the significant differences (p<0.05). DM, dry matter.

The average DPPH• radical scavenging activity of Mexican sweet potatoes was 40.7 µmol TE/g. This value was consistent with that reported by Zhang *et al*. [2022] for Chinese pigmented sweet potatoes (average of 39.3 µmol TE/g) and was slightly higher compared to that noted by Tang *et al*. [2015] (average of 25.1 µmol TE/g). In the second mentioned study, unlike in our study, higher DPPH• radical scavenging activity was observed in the purple and orange sweet potatoes than in the white and yellow ones. Makori *et al*. [2020] found that antiradical activity against DPPH• was dependent on the part of the potato tuber and reported higher values for the skin than for the flesh.

The mean value in the ABTS assay obtained in our study was 23.4 µmol TE/g. Armijos *et al*. [2020] and Zhang *et al*. [2022] reported the averages of 33.6 and 28.2 µmol TE/g for Ecuadorian and Chinese sweet potato varieties, respectively.

Proximate composition of sweet potato extrudates

In preliminary studies on obtaining extruded sweet potatoes, the fresh potatoes were dried at 50–60°C for various times to achieve different moisture contents of 5–10% (120 min), 10–15% (60 min), and 15–20% (30 min), and subsequently extruded. The dried products with a 5–10% moisture content had good color and flavor; however, they became excessively stiff over time. On the other hand, the extruded products with a moisture content of 10–15% exhibited favorable organoleptic properties and a crunchy consistency. Furthermore, these products demonstrated a seamless and uniform flow within the equipment. In contrast, the extruded products with a moisture content of 15–20% exhibited a pasty consistency and an indeterminate shape, which resulted in equipment blockages. Based on these findings, SP with a humidity range of 10–15% were selected for further production. According to the preliminary sensory evaluation, the products had a sweet taste, pleasing color and odor, high hardness, medium breaking, and high dryness, without being adhesive to the palate.

The results of a proximate analysis conducted on extrudates of each sweet potato variety are shown in **Table 4**. The moisture contents of the extruded purple, yellow, and white potatoes were 6.41 g/100 g, 6.86 g/100 g, and 5.97 g/100 g, respectively, and no significant (p≥0.05) differences were found between them. The extrudates had a protein content with an average of 7.00 g/100 g DM, with no significant (p≥0.05) difference between the three products. Extruded potatoes were also rich in carbohydrates (88.43–89.76 g/100 g DM), while the constituent which was devoid of any significant content was lipid (0.13–0.50 g/100 g DM). The average energy value was 389 kcal/100 g DM, theoretical data, being significantly (p<0.05) higher for the extruded yellow potatoes compared to the other varieties. The macronutrient content and energy value of the extrudates were consistent with the literature data, *e.g.*, the carbohydrate, protein and lipid contents of extruded purple sweet potatoes reported by Palupi *et al*. [2024] were 85.57, 5.51 and 0.56 g/100 g DM, respectively, and provided 369.28 kcal/100 g.

Total phenolic content, total flavonoid content, and antioxidant capacity of sweet potato extrudates

The contents of total phenolics and total flavonoids, as well as the antioxidant capacity of extruded Mexican sweet potatoes are shown in **Table 3**. A significant difference was observed in the total flavonoid content among the extrudates obtained from the three sweet potato varieties, with the product from purple variety exhibiting the highest total flavonoid content and the extruded potatoes of white variety exhibiting the lowest. Simultaneously, the purple extrudate exhibited the highest total phenolic content, followed by yellow, and finally white one, with a notable distinction (p<0.05). Regarding the results

of the DPPH assay, the yellow extrudate exhibited the highest value, demonstrating a statistically significant difference ($p<0.05$) compared to the other varieties; conversely, the purple and white extrudates did not differ statistically significantly ($p\geq0.05$) from one another. The extruded potatoes of the purple variety exhibited the highest values in the ABTS assay, while no statistically significant difference ($p\geq0.05$) was observed between the yellow and white varieties.

A decrease was observed in all extruded SP with respect to fresh SP when total phenolic content was subjected to analysis. A similar trend was observed in antioxidant activity, as determined by both the DPPH and ABTS assays. The blanching and extrusion process has a direct impact on the content of bioactive compounds and antioxidant capacity. Tang *et al*. [2015] reported that thermal treatment can reduce the quality of SP due to chemical degradation and the reduction of bioactive compounds such as phenolics and carotenoids. Boiling is a better heating method for keeping carotenoids, while steaming preserves more phenolic substances (excluding anthocyanin), and roasting keeps more anthocyanins.

Texture parameters of sweet potato extrudates

The texture properties of the three extrudates (purple, yellow, and white) were determined by evaluating several physical parameters, including hardness, adhesiveness, fracturability strength, as well as the number of fractures according to fracturability strength, and respective results are presented in **Table 4**. The proximate chemical composition of the three types of sweet potatoes was found to affect the texture properties of the extrudates obtained therefrom, resulting in observable differences among them.

Hardness is defined as the force required to compress or penetrate a food item with teeth; according to results (**Table 4**), the extruded purple sweet potato exhibited the highest hardness, followed by the yellow and finally the white extruded products, showing a significant ($p<0.05$) difference between the three samples. The proximate composition indicated that the purple variety had the highest dietary fiber content (**Table 1**). In contrast, the white sweet potato, the least hard extrudate of the three varieties, exhibited the highest protein content and a lower content of dietary fiber than the purple sample. The yellow sweet potato exhibited an intermediate value. Considering these findings, it can be posited that the high fiber content in potatoes was associated with enhanced hardness of the extruded products, whereas the high protein content was linked to a reduction in hardness.

The same trend was observed for adhesiveness as for hardness, with the extruded potatoes of the purple variety exhibiting the highest values and these of the white variety demonstrating the lowest values (**Table 4**). Adhesiveness is the force required to separate a food substance from another surface, such as the palate, lips, or teeth.

The requisite force to fracture the extrudates and the number of fractures generated by this force were also determined. In terms of fracturability, the extrudates from the purple variety required a greater degree of force to break them, whereas these made of the white variety necessitated less force. This finding aligns with the hardness data, as extruded white sweet potato was the least hard, and therefore required less force to fracture. Similarly, the white potato extrudate generated a greater number of fractures *per* unit of piece, with a statistically significant difference ($p<0.05$) compared to the purple potato extrudate, and yellow extrudates exhibited an intermediate value between the purple and white ones.

Sensory analysis of sweet potato extrudates

A sensory analysis was conducted by 40 untrained panelists for the three SP extrudates. A 5-point hedonic scale was used, and scores of color, odor, texture, and taste are shown in **Table 5**. The purple extruded product was the one with the best sensory characteristics, presenting an average score of 4.45, followed by the yellow product with a value of 4.25 and finally the white extruded product with a value of 3.89. The purple and yellow extrudates exhibited no significant difference ($p\geq0.05$), and comparable white and yellow were not different significantly ($p\geq0.05$) from one another. However, the white extrudate was found to differ from the purple extrudate ($p<0.05$), demonstrating a lower level of acceptance. The main difference was in the color, since the purple color was more pleasant and accepted and white was less acceptable. No differences were observed between the extrudates in terms of odor and texture. On the other hand, the purple extrudate was rated more favorably in terms of taste, followed by the yellow and white extrudates. In general, the panelists commented that the taste was pleasant and sweet, although no sugar or other sweetener was utilized. Overall acceptance of the three extruded products was 84%.

Color parameters of fresh, blanched and extruded sweet potatoes

The color of fresh, blanched, and extruded products from the three types of sweet potatoes were evaluated, and the values of parameters L^*, a^* and b^* according to the CIELab scale are shown in **Table 6**. **Figure 1** depicts the images of fresh sweet potatoes. At the L^* parameter level, the purple variety exhibited a value of 29.13, while the yellow variety demonstrated a value of 71.38 and the white variety exhibited a value of 84.58. Armijos *et al*. [2020] reported L^* values ranging from 13.89 to 71.61 for a variety of pigmented sweet potatoes. In turn, Tang *et al*. [2015] reported a value of 49.25 for the purple variety, 85.53 for the orange, 87.39 for the yellow, and 86.74 for the white one. The findings align with the values recorded in our research. The parameter a^*, in which positive values correlate with red pigments and negative values with green pigments, showed 26.38 for the purple sample, 28.78 for the yellow sample, and 1.58 for the white one (**Table 6**). Armijos *et al*. [2020] referred to values from 13.07 to 34.30, which were reported for different Ecuadorian varieties. Conversely, Tang *et al*. [2015] reported 23.83 for purple, 9.05 for orange, 5.72 for yellow, and 0.08 for white potatoes; with the data for the purple and white varieties aligning with our findings, whereas the orange and yellow varieties exhibiting lower values, suggesting that our varieties possess a greater degree

Table 5. Results of sensory evaluation of extruded sweet potatoes.

Attribute	Purple	Yellow	White
Color	4.60±0.24^{a}	4.35±0.14^{a}	3.55±0.20^{b}
Odor	4.55±0.15^{a}	4.20±0.25^{a}	4.05±0.28^{a}
Texture	4.20±0.27^{a}	4.35±0.26^{a}	4.05±0.27^{a}
Taste	4.45±0.16^{a}	4.10±0.27^{ab}	3.90±0.13^{b}
Average score	4.45±0.20^{a}	4.25±0.23^{ab}	3.89±0.22^{b}

The values correspond to the scores on the five-point hedonic scale. Results are shown as mean ± standard deviation. Different letters in the same row indicate represent the significant differences ($p<0.05$).

Table 6. Color parameters of fresh, blanched and extruded sweet potatoes.

Parameter	Variety	Fresh	Blanched	Extruded
*L**	Purple	29.13±0.57^{c}	30.99±1.01^{b}	40.40±0.48^{a}
	Yellow	71.38±1.19^{a}	55.31±2.51^{b}	38.36±1.57^{c}
	White	84.58±0.40^{a}	78.45±2.31^{b}	60.70±3.46^{c}
*a**	Purple	26.38±1.31^{a}	15.93±0.97^{b}	8.71±0.25^{c}
	Yellow	28.74±1.77^{a}	30.18±1.26^{a}	14.49±0.60^{b}
	White	1.58±0.08^{b}	0.32±0.03^{c}	2.29±0.03^{a}
*b**	Purple	−5.82±0.35^{b}	12.89±0.78^{a}	12.25±0.35^{a}
	Yellow	37.13±1.28^{b}	40.93±1.81^{a}	17.05±0.48^{c}
	White	18.20±1.15^{a}	16.98±0.18^{a}	12.00±0.32^{b}

Results are shown as mean ± standard deviation. Different letters in the same row show significant differences ($p<0.05$). *L**, darkness/brightness; *a**, intensity green/red; *b**, intensity blue/yellow.

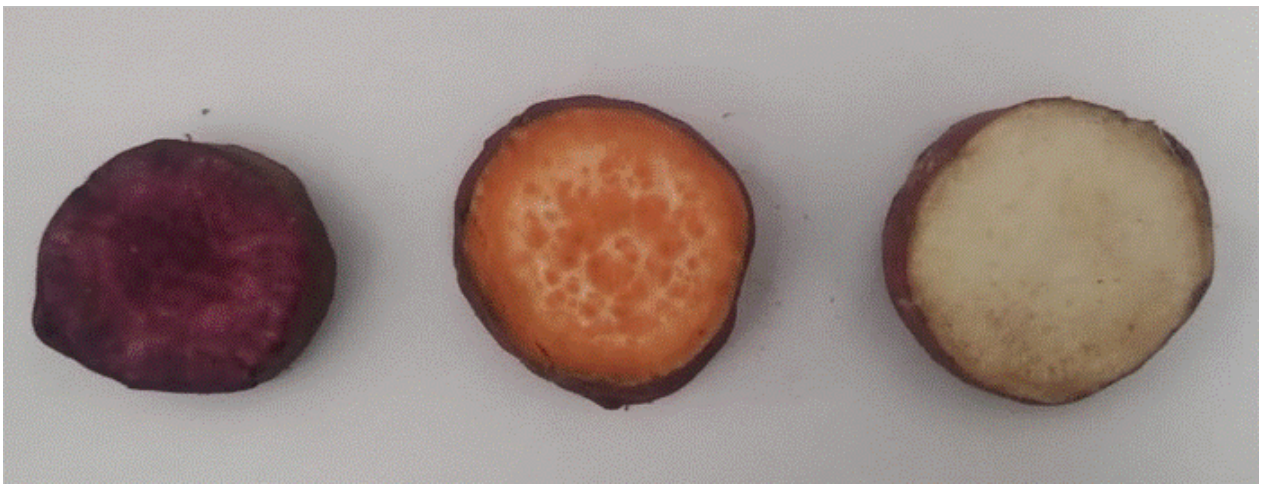

Figure 1. Appearance of fresh purple (left), yellow (center) and white (right) sweet potatoes.

of red pigmentation than those reported by the aforementioned author. Regarding the *b** parameter, where positive values are associated with yellow tones and negative values with blue, a significant difference was observed among the three sweet potato varieties (**Table 6**). The values of 37.13 and 18.20 were measured for yellow and white varieties, respectively. The color of the purple variety was characterized by a negative value of *a** parameter, −5.82, indicating a tendency towards blue. Armijos *et al.* [2020] referred to values from −8.89 to 57.81, whereas Tang *et al.* [2015] reported −9.56 for purple, 23.21 for orange, 25.83 for yellow, and 15.41 for white potatoes. These values are in accordance with those measured in this study.

It is noteworthy that the purple pigmentation of sweet potatoes is attributed to anthocyanins, which impart a dark hue and correspond with the lowest value of the *L** parameter [Tang *et al.*, 2015]. The presence of anthocyanins in purple sweet

potatoes could also be the reason for differences in the *L** value among the three sweet potato varieties included in our study. Additionally, purple pigmentation coincided with the highest content of phenolic compounds (**Table 3**). In contrast, the highest value of the *L** parameter (whiteness) was observed in the white sweet potato. This may be attributed to the absence of colored pigments in the sample, which exhibited the lowest total phenolic content. Similarly, the color of the yellow sweet potato was characterized by the highest *b** value and the highest total xanthophyll content.

A color analysis was also conducted on blanched and extruded sweet potatoes, noting that blanching represents a preliminary step preceding the preparation of the extrudates. Results are shown in **Table 6**. In the purple sweet potatoes, it was observed that the blanching process caused a lightening of the color of fresh sweet potatoes, significantly ($p<0.05$) increasing the *L** value, and this phenomenon was more pronounced in the extruded samples. Regarding parameter *a**, which concerns green/red, the fresh-blanched-extruded sample displayed a significant decrease ($p<0.05$) in purple color in accordance with the prevailing tendency to transition from red to green. With respect to parameter *b**, which refers to blue/yellow, no perceptible differences were observed between the blanched and extruded samples ($p\geq0.05$). However, these samples differed from the fresh sample, exhibiting a tendency towards yellow and a loss of purple color.

In yellow products, the *L** values demonstrated a proclivity towards darkening, fresh sweet potatoes exhibited a higher *L** value than blanched ones, with this effect being further accentuated in extruded sweet potatoes. On the *a** parameter, no distinction was observed between the fresh and blanched samples; however, the extruded samples exhibited a loss of red coloration. Conversely, in the case of the *b** parameter, the blanched product exhibited a greater yellow than the fresh sample, whereas the extruded product displayed a diminished yellow pigmentation in comparison to the fresh and blanched sweet potatoes.

In the white sweet potatoes, it was observed that the brightness tended to decrease with blanching, with a more pronounced decrease evident in the extruded sample. Furthermore, both samples exhibited statistically significant differences ($p<0.05$) with respect to fresh sweet potatoes. The *a** parameter revealed that blanching caused the red color to shift towards green in comparison to fresh sweet potatoes, but extrusion resulted in the opposite effect, with extruded sweet potatoes exhibiting a reddish hue. Additionally, on the *b** parameter, a tendency from yellow to blue was observed, with a more pronounced one in the extruded product. There was no statistically significant difference ($p\geq0.05$) between the fresh and blanched SP samples, but a notable discrepancy was observed when comparing them to the extruded products.

CONCLUSIONS

The assessment of the nutritional value of the three varieties of sweet potatoes native to Mexico: purple, yellow, and white, showed that the purple variety exhibited the highest content of dietary fiber and starch, the yellow demonstrated the highest levels of carbohydrates and lipids, and the white exhibited the highest content of proteins and minerals. Conversely, yellow potatoes exhibited the mayor content of calcium, iron, and magnesium, whereas purple had the highest content of zinc and sodium. With respect to antioxidant content and antioxidant capacity, the yellow variety was characterized by the mayor levels of ascorbic acid and total xanthophylls, while the purple one demonstrated the highest total phenolic content. All varieties demonstrated antioxidant capacity in both the DPPH and ABTS assays. The extrudates prepared from the three varieties were well accepted in sensory analysis, especially the product from purple potatoes, and the panelists noted a sweet taste of the extrudates. Color parameter analysis indicated alterations in the hue of fresh sweet potatoes regarding blanching and extrusion processes. The extrusion process resulted in a reduction in the total phenolic content and antioxidant capacity, as determined by DPPH and ABTS assays, in comparison to the fresh sweet potatoes; however, the extrudates still showed antioxidant potential.

Mexican sweet potatoes can be considered a valuable raw material with nutritional and bioactive properties, suitable for the production of extrudates with good consumer acceptability. Their sweet taste can be used as an advantage in the composition of snacks, replacing sweeteners and preserving the natural character of the product.

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CONFLICT OF INTERESTS

The authors declare that they have no competing interests.

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