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Biodegradable foam tray based on starches isolated from different Peruvian species



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ABSTRACT

Starch was isolated from three Andean-native crops – arracacha (*Arracacia xanthorrhiza*), oca (*Oxalis tuberosa*), and sweet potato (*Ipomoea batatas*) – for use as a raw material for the production of foam trays. The starches were characterized in their proximal composition, crystallinity, microstructure and thermal properties. The sweet potato starch showed the highest amylose content (42.65%) and the lowest protein content (0.30%). The oca starch granules were larger (10–30 μ m) than sweet potato and arracacha starch. The highest crystallinity of sweet potato starch caused larger values of onset temperature (To), peak temperature (Tp), conclusion temperature (Tc) (67.64 °C, 72.83 °C, and 81.20 °C, respectively) than arracacha and oca starch. The novel foam trays showed good appearance, adequate expansion, and low density; however, all foam trays showed a water absorption capacity >50%, which was related to their prosity and low density. Also, sweet potato and oca starch trays (0.52 MPa).

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1. Introduction

The expanded polystyrene (EPS) is a petroleum-based plastic packaging foam most commonly used in the food industry due to its good thermal insulation capacity, moisture resistance, low weight, moldability, and low cost [1]. However, EPS is resistant to biodegradation and is difficult to recycle [2], leading to the accumulation of large quantities of waste, and it may also generate toxic decomposition products. For instance, styrene, the structural unit of EPS, has been linked to an increased risk of cancer [3]. This component seeps through when in contact with food, especially hot food with high content of fat, alcohol, or acid.

Plastic materials considered for one-time uses are difficult to recycle. In the United States, >7.7 billion kg of plastic materials are generated at year, and the use of items such as plastic bags is now restricted [4]. As an alternative, biopolymers such as starch are being considered by several researchers for use in the production of single-use biodegradable materials because of its low cost, expansion capacity, ready availability, and production from renewable resources [5].

Starch foam articles such as plates, cups, and trays can be prepared by subjecting a mixture of starch and water at high temperatures to thermoforming [6,7]. The rapid evaporation of water causes starch to expand into the shape of the mold [4]. The properties of starch-based

* Corresponding author. *E-mail address:* rsiche@unitru.edu.pe (R. Siche). foam trays such as density, flexibility, and water absorption capacity (WAC) are highly dependent on the starch type used in the manufacturing process [8].

Foams made from cassava starch [1,9–11], wheat starch [12], corn starch [13], and potato starch [14] have been commonly used in the production of starch-based foam trays. These foams presented remain sensitive to water, and their water absorption capacities are different from each other; thus, further improvement in their water resistance is necessary for commercial applications [15]. In order to improve the water resistance some authors have performed starch crosslinking [16,17] or addition of different types of fibers such as kraft fibers, jute and flax fibers, cassava and wheat fibers, sugarcane and asparagus peel [5,14,18,19]. However, there is a lack of research on starch-based foam trays produced with new native starches sources, which could be a new option for foam tray manufacturing.

In Peru, there are tuberous species such as sweet potato (*Ipomoea batata*), oca (*Oxalis tuberosa*), and arracacha (*Arracacia xanthorrhiza*) that could be suitable for use in manufacturing foam trays for food packaging due to their starch content, between 9.8 and 27.5%, 10.0–15.0%, and 12.0–25.0% of edible fresh matter, respectively [20,21]. In 2016, 269.4 miles' ton of sweet potato and 92.3 miles' ton of oca were produced, while the average annual production of arracacha was 22.8 miles' ton [22]. These tubers are commonly used for human consumption in the towns near the production areas without the possibilities of reaching the markets of large cities. Therefore, studying the properties

of native tuber starches and their use for the development of biodegradable packaging foam could add value and help improve the living conditions of areas that produce these tubers as well as offer news alternative for the food packaging industry.

In this sense, this work aims (1) to isolate and characterize sweet potato, oca, and arracacha starches, and (2) to produce and characterize foam trays based on these starches. The physical and mechanical properties of starch-based foam trays were compared.

2. Material and methods

2.1. Isolation of starches from Andean-native crops

Starches from arracacha (*Arracacia xanthorrhiza*), oca (*Oxalis tuberosa*), and sweet potato (*Ipomoea batatas*) were isolated by the wet-milling method [23]. The roots of arracacha and sweet potato (peeled) and oca (unpeeled) were cut into 2-cm pieces and suspended in a sodium bisulfite solution (1500 ppm) at a 1:3 (w/v) ratio and then milled in a food processor (Model I5, Industrias Maguiña, Peru) for 5 min to reduce the particle size. The resulting paste of each root was then filtered through 300- and 53-µm stainless steel sieves, and the fibers retained in the sieves were reprocessed and filtered again two additional times, and the residual fiber was finally discarded. The filtered suspension was stored at 4 °C for 24 h to recover the starch. The supernatant liquid was discarded; the starch fraction was washed three times by resuspension in distilled water and dried at 37 °C for 48 h in a UN55 PLUS oven (Memmert GmbH Co. KG, Germany). Finally, dry starch was milled until it passed through a metal sieve of 106-µm diameter.

2.2. Physicochemical and structural characterization of Andean-native starches

2.2.1. Chemical composition and amylose content

Ash, protein, and lipid contents of the starches were obtained according to the methods described by AOAC [24]. The ash content was determined by incineration in a muffle furnace at 550–600 °C (Official Method 923.03). The protein content was determined by the micro-Kjeldahl method according to the method 926.86 using a conversion factor of 6.25 for the calculation of the protein content. The lipid content was determined by the Soxhlet method using petroleum ether as the solvent. All analyses were accomplished in triplicates.

The amylose contents were determined according to the iodine colorimetric method, according to Morrison & Laignelet [25]. All analyses were accomplished in triplicates.

2.2.2. Scanning electron microscopy

The morphological characteristics of the native starches were examined by scanning electron microscopy (SEM) according to Maniglia & Tapia-Blácido [26]. Samples were mounted on aluminum stubs and coated with gold in a sputtering system (Bal-Tec, SCD050, Fürstenstein, Liechtenstein). All samples were analyzed using a scanning electron microscope (Zeiss, EVO 50, Cambridge, United Kingdom) at an accelerating voltage of 20 kV. The analyze was carried out in the laboratory of Scanning Electron Microscopy and Elementary Microanalysis at the São Paulo University (Ribeirão Preto, São Paulo, Brazil).

2.2.3. Crystallinity analysis by X-ray diffraction

The X-ray diffraction pattern of the Andean-native starches was determined according to method described by Maniglia & Tapia-Blácido [26]. The samples were dehydrated in a desiccator containing silica gel for 1 week. They were then placed on an aluminum specimen stub and analyzed at ambient temperature on an X-ray diffractometer (Siemens D5005, Baden-Württemberg, Germany) operating with monochromatic filter, CuK α radiation, 30 mA current, and 40 kV voltage. The scanning rate was 0.02°; 2 θ varied from 2° to 50°. The relative crystallinity [% crystallinity index (CI)] of the starches was estimated as the ratio between the crystalline area (Ac) and the total area (At = Ac + Aa) of the diffractogram, where Aa is the amorphous area. The software Microcal Origin 6.0 (OriginLab Corporation, MA, USA) was used for this purpose.

2.2.4. Thermal analysis by differential scanning calorimetry

The thermal properties of the native starches were determined based on the methodology applied by Cruz et al. [27], using a differential scanning calorimetry (DSC) 2010 (TA Instruments, New Castle, DE, USA). Samples (1 mg) were directly weighed using aluminum pans, and then 9 mg of deionized water was added with a microsyringe. Heating was performed from 30 °C to 110 °C at a rate of 10 °C min⁻¹. The onset temperature (T_o), the peak temperature (T_p), the conclusion temperature (T_c), and the enthalpy (Δ H_{gel}) associated with the starch gelatinization interval were calculated using the Universal Analyzer software (TA Instruments). All analyses were performed in triplicates.

2.3. Starch foam trays preparation by thermopressing

The foam trays were prepared by thermopressing using formulations based on starch (100 g), water (100 g), glycerol (6.25 g), and magnesium stearate (7.5 g). These proportions were determined in preliminary tests (not published). Glycerol (used as plasticizer [28]) and magnesium stearate (used as release agent [19]) were purchased from Fluka, Sigma-Aldrich Corp. (Buchs SG, Switzerland).

To prepare each formulation, starch, water, and glycerol and magnesium stearate were mixed for 10 min using a mechanical stirrer at 1500 rpm (Imaco, China). For the thermopressing process, a compression molding machine (RELES, Lima, Peru) was built specially for the project. 50–60 g of each formulation was homogeneously layered on the Teflon mold (27 cm \times 20 cm \times 25 mm, 3.0 mm in thickness). The thermopressing process was carried out at 140 °C for 18 min and 60 bar. Finally, the trays were unmolded and stored for 4 days at 25 °C and 60% relative humidity before characterization.

According to Mello & Mali [1], the amount of water used in each formulation must be optimized to maintain batter fluidity and foaming ability, allowing the production of homogeneous dispersions and complete foam trays. On other hand, the batter amount was 50 g for oca and arracacha starch-based foam tray, while for sweet potato starchbased foam trays was 60 g. The batter amount was fixed in order to obtain a complete tray, and this value is dependent on the starch features and viscosity of batter.

2.4. Starch foam tray properties

2.4.1. Moisture, thickness and density of trays

The moisture content of the starch foam trays was determined using a MX-50 Halogen Moisture Analyzer (A&D Company, Japan). The analyses were accomplished in triplicates.

The thickness and density were determined according to the method proposed by Mello & Mali [1]. For each formulation, the reported values were the means of 30 values (three measurements from each of 10 samples). The thickness of the trays was measured using a stainless hardened manual micrometer (0–150 mm). Density (g cm⁻³) was calculated from the mass (g) and volume (cm³) of each sample. Density tests were performed using rectangular strips measuring 100 mm × 25 mm. Each sample was weighed, and its volume was calculated.

2.4.2. Color parameters

The color parameters of the starch trays were determined using a colorimeter JZ-300 (Shenzhen Kingwell Instruments Co., China) as described by Salgado et al. [19]. The CIElab scale coordinates L^* from 0 (black) to 100 (white), a^* from -a (greenness) to +a (redness), and b^* from -b (blueness) to +b (yellowness) were recorded. Measurements were accomplished in triplicates.

2.4.3. Scanning electron microscopy

Samples of foam trays were stored at 25 °C and 60% relative humidity for 4 days. Scanning electron microscopy (SEM) analyses were performed on a Tecsan VEGA 3 LM equipped with a gold coating system SPI 11430-AB (TESCAN, USA). The foam tray pieces were mounted for visualization of the cross-section of the bronze stubs; double-sided tape was used. The surfaces were coated with a thin gold layer (40–50 nm). All the samples were examined under an accelerating voltage of 20 kV. The analyze was carried out in the Multidisciplinary Research Laboratory at the Antenor Orrego Private University (Trujillo, Peru).

2.4.4. Water absorption capacity

The WAC test determines the quantity of water that can be absorbed by a sample in a given time [6]. WAC was determined according to ABNT NBR NM ISSO 535 method, adapted by Vercelheze et al. [7]. Regular tray samples with dimensions of 25 mm \times 50 mm were weighed immediately before (W_i) and immediately after immersion (W_f) in distilled water for 1 min at 25 °C. Analysis was accomplished in triplicates, and WAC was calculated using the following equation:

Water absorption capacity (WAC, %) =
$$\frac{Wf - Wi}{Wi} \times 100$$

2.4.5. Mechanical properties

A TA.HD plus texture analyzer (Stable Micro System, United Kingdom) with a 25-N load cell was used to determine the mechanical properties, i.e., tensile strength (MPa) and elongation at break (%) of the foam trays, according to the ASTM D828-97 Standard Test Method [29]. The samples analyzed (dimensions of 25 mm \times 100 mm) were cut from the center of the tray (3 samples from each tray). In total, 9 tensile tests were assayed to obtain an average value of each test (tensile strength and elongation).

Samples were fixed on the machine base with an initial grip separation of 80 mm and a crosshead speed of 1 mm s^{-1} to simple break (rupture). The tensile strength and elongation at break values were determined. Besides, the mechanical properties of commercial EPS trays (2.61 mm in thickness and 0.04 g cm⁻³ of density) were performed in the same conditions as described for starch foam tray samples.

2.4.6. Thermogravimetric analyses

The thermal properties of the foam trays were evaluated under nitrogen atmosphere (100 mL min⁻¹) using a SETSYS Evolution TGA-DTA/DSC (SETARAM Instrumentation, France) analyzer. The samples (approximately 6 mg) were heated from 25 to 600 °C at a heating rate of 10 °C min⁻¹ [5]. Sample pan type: alumina/referent pan: empty alumina. Weight (mass) loss was determined on the basis of the difference in mass in the thermogravimetric (TG) curve using the instrument's software.

2.5. Statistical analysis

To compare the properties of the Andean-native starches and foam trays, an analysis of variance and Fisher's least significant difference (LSD) test at a 5% significance level were performed using Statistica software version 7.0 (Statsoft, OK, USA).

3. Results and discussion

3.1. Physicochemical and structural characterization of native starches

3.1.1. Chemical composition and crystallinity index (CI)

Table 1 shows the approximate composition of starches extracted from sweet potato, oca, and arracacha. The lipid content of sweet potato

Table 1

Chemical composition, crystallinity index and thermal properties of the Andean-native starches isolated from arracacha, oca, and sweet potato (results are presented as mean \pm SD).

		Arracacha	Oca	Sweet potato
Chemical composition	Ash (%) Lipids (%) Protein (%) Amylose (%)	$\begin{array}{c} 0.47 \pm 0.02^{a} \\ 0.04 \pm 0.01^{c} \\ 0.36 \pm 0.06^{ab} \\ 22.77 \pm 0.88^{c} \end{array}$	$\begin{array}{c} 0.39 \pm 0.03^b \\ 0.24 \pm 0.05^b \\ 0.40 \pm 0.05^a \\ 31.87 \pm 0.42^b \end{array}$	$\begin{array}{c} 0.09 \pm 0.01^c \\ 0.34 \pm 0.03^a \\ 0.30 \pm 0.07^b \\ 42.65 \pm 0.85^a \end{array}$
Crystallinity index Thermal properties	CI (%) T_o (°C) T_p (°C) T_c (°C) ΔH_{gel} (J g ⁻¹)	$\begin{array}{c} 35.75\% \\ 56.14 \pm 0.74^b \\ 62.38 \pm 0.38^b \\ 67.47 \pm 0.76^b \\ 16.06 \pm 0.92^a \end{array}$	$\begin{array}{c} 36.26\% \\ 53.66 \pm 0.84^c \\ 57.95 \pm 1.12^c \\ 63.99 \pm 1.33^c \\ 16.42 \pm 0.30^a \end{array}$	$\begin{array}{c} 37.96\% \\ 67.64 \pm 0.16^a \\ 72.83 \pm 0.11^a \\ 81.20 \pm 0.21^a \\ 13.47 \pm 0.51^b \end{array}$

Different letters in the same row indicate significant differences between means (Fisher's LSD test, p < 0.05).

Onset temperature (To), peak temperature (Tp), conclusion temperature (Tc), and enthalpy (Δ Hgel) associated with the starch gelatinization interval.

starch (0.34%) was similar to that reported in native varieties from Mexico by Tian et al. [30] (0.05%–0.60%), whereas the lipid content in oca starch (0.24%) was lower than that reported by Hernández-Lauzardo et al. [31] in a variety of Mexican oca (0.52%), but higher to that reported by Cruz et al. [27] in a variety of Argentine oca (0.15%).

Regarding ash content, arracacha starch presented the highest value (0.47%), close to that obtained by Tapia et al. [32] (0.56%). Oca starch had an ash content of 0.39%, higher than that reported by Valcárcel-Yamani et al. [33] and Cruz et al. [27], i.e., 0.15% and 0.24%, respectively, but lower than that reported in a Mexican native variety by Hernández-Lauzardo et al. [31] (0.52%). Sweet potato starch showed an ash content of 0.09%, a value lower than those reported for different varieties of Peruvian sweet potato grown in coastal areas (0.17%–1.77%) [34], probably due to the different growing conditions from those in the high Andean regions.

Protein content is of vital importance in starches because it influences the structure of the polymer matrix during the gelling process, with effects on humidity, WAC, and deformation of biomaterials [19]. The highest value was obtained for oca starch (0.40%), higher than that reported in a Mexican variety (0.34%) by Hernández-Lauzardo et al. [31], but lower than that obtained by Cruz et al. [27] in an Argentine variety (0.58%). On the other hand, the protein content obtained for sweet potato starch (0.30%) was similar to that reported in different starches obtained from Peruvian sweet potato (0.04%–0.35%) [34].

An important characteristic of starches is the amylose to amylopectin ratio. Amylose content can affect the mechanical properties of starch foam trays. Table 1 shows that native starches presented amylose contents in the range of 22%–42%. Sweet potato starch had an amylose content of 42.65%, higher than that reported by Moorthy [35] (15%–25%) and García & Walter [34] (20.48%–25.54%). The amylose content found in oca starch was 31.87%, a value higher than that reported by Valcárcel-Yamani et al. [33] in Peruvian yellow oca (27.60%) and that reported in other oca varieties (17.4%–33.0%) by different authors [27,31,36]. On the other hand, arracacha starch is a typical starch with a high amylopectin content [37], presenting low amylose contents due to its low content of the *granule-bound-starch-synthase* (GBSS) enzyme, which is responsible for amylose synthesis [38]. However, the value obtained in our study (22.77%) was higher than that reported by other authors [32,36,37] (3.0%–18.5%).

Respect to crystallinity index (CI) values of the native starches of sweet potato, oca, and arracacha, although the information available regarding the CI values of these starches is limited (information consulted in the ScienceDirect database), results show that sweet potato starch presented a higher CI value than oca and arracacha starches. Rocha et al. [38] and Huang et al. [39] reported CI values for arracacha and sweet potato starches of 37.1% and 38.4%, respectively, similar to those found in this study. However, the CI value obtained in oca starch was higher than 23.8%, the value reported by Cruz et al. [27], which could be explained by differences in the chemical composition of the starch, climatic conditions, and type of crop soil.

3.1.2. Scanning electron microscopic images

Fig. 1 shows the micrographs of sweet potato, oca, and arracacha starches obtained by SEM. The granulometry and shape are related to the source of the starches. In general, granules showed different shapes and sizes, with no apparent agglomeration. The oca starch granules were larger ($10-30 \mu m$) than the sweet potato ($5-20 \mu m$) and arracacha ($5-15 \mu m$) starch granules. Similar results were reported by Santacruz et al. [36], who obtained larger oca starch granules compared with arracacha starch granules. On the other hand, oca granules were oval and circular, whereas sweet potato and arracacha starch granules were circular and polyhedral, with arracacha starch granules having the highest number of irregular granules in agreement with the reports by Moorthy [35] and Santacruz et al. [36].

3.1.3. Differential scanning calorimetry

DSC identifies melting and crystallization events, as well as glass transition temperatures (T_g), allowing the measurement of energy required for the starch gelatinization process [40]. The temperature values for the gelatinization process interval, i.e., T_o , T_p , T_c , and ΔH_{gel} , are shown in Table 1.

These properties were different for the three types of native starches (Fisher's test, p < 0.05). Sweet potato starch showed higher T_o, T_p, and T_c values (67.64 °C, 72.83 °C, and 81.20 °C, respectively) than arracacha (56.14 °C, 62.38 °C, and 67.47 °C) and oca starches (53.66 °C, 57.95 °C, and 63.99 °C), which can be explained by the greater crystallinity of sweet potato starch (Table 1). More crystalline starch granules usually show higher gelatinization temperatures due to their greater stability [27].

With respect to other studies with these native starches, in the case of sweet potato starch, Moorthy [35] reported T_o and T_c values of 64 °C and 84 °C, respectively, whereas Valetudie et al. [41] reported T_o , T_p , and T_c values of 67.3 °C, 72.7 °C, and 79.6 °C, respectively. On the other hand, Santacruz et al. [36] obtained T_o , T_p , and T_c values of 53.8 °C, 60.1 °C, and 65.9 °C for the arracacha starch and 50.2 °C, 55.9 °C, and 63.3 °C for the oca starch, showing a slight difference from the values found in this study. Meanwhile Rocha et al. [38] found similar values of T_o (57 °C) and T_p (62 °C) for arracacha starch.

In spite of the higher temperature values corresponding to the gelatinization interval and the higher CI values shown by the sweet potato starch, the ΔH_{gel} value was lower than those shown by the arracacha and oca starches, which is related to the high amylose content and therefore lowers amylopectin content in sweet potato starch. The higher amylopectin content of arracacha and oca starches could explain the higher ΔH_{gel} value of these starches (16.06 and 16.42 J g⁻¹, respectively). However, our results are comparable to those of previous studies, for example, 12.90 J g⁻¹ [35] and 13.6 J g⁻¹ [41]. On the other hand, Santacruz et al. [42] obtained ΔH_{gel} values of 17.60 J g⁻¹ and 14.60 J g⁻¹ for arracacha and oca starches, respectively. Other authors including Rocha et al. [38] and Cruz et al. [27] found values of 16.00 J g^{-1} and 17.70 J g^{-1} for arracacha and oca starches, respectively.

Compared with conventional thermoplastic materials, the behavior of starches during thermoforming is more complex, as various physicochemical changes can occur. During the application of thermal energy, the movement and sliding of starch molecules starts at a characteristic temperature called Tg [43]. If heat supply continues and Tg is exceeded, the molecular mobility increases, causing structural changes in the amorphous regions, a molecular disorder known as "gelatinization" [44]. Also, if water absorption from the medium increases in these amorphous regions, a plasticizing effect can occur, causing a depression in Tg [45]. As thermoforming is performed at high temperatures (140-200 °C), gelatinization is rapidly reached, forming a mass that takes the shape of the mold, to then go on to evaporation and the drying of the tray [19]. A lower Tc value of the process could allow obtaining the trays in shorter time, which could lead cost saving of the process; however, this would not necessarily ensure that the trays are obtained with correct expansion of the starch.

3.2. Tray manufacturing by thermopressing

All formulations used in our research were optimized to obtain complete trays without cracks. Magnesium stearate was used to release the foam trays from the mold after the thermoforming process [6]. Glycerol was used as a plasticizing agent, causing a depression in the Tg of the mixture and lessening the proximity between starch chains, in addition to improving the flexibility, reducing the fragility and increasing the resistance to breakage of foam trays [28].

3.3. Starch foam trays testing

3.3.1. Physicochemical properties of starch foam trays

The moisture content, thickness, density, and color parameters of trays made from native starches are shown in Table 2.

The moisture values obtained were similar to those reported in cassava starch trays [9,13]. According to the results, the trays' humidity was not significantly affected by the starch type.

The trays' thickness ranged between 2.51 and 2.62 mm, higher than those obtained by Matsuda et al. [11] and Mello & Mali [1] (2.12 and 2.24 mm, respectively), and lower than those reported by Machado et al. [10] and Pornsuksomboon et al. [6] (4.6 and 3.7 mm, respectively) for cassava starch trays.

For its part, the trays' densities oscillated between 0.14 and 0.18 g cm⁻³ (Table 2), lower than those obtained for trays based on cassava starch (0.19–0.41 g cm⁻³) [1,7] and corn starch (0.44 g cm⁻³) [13]. However, our results are higher than the values obtained for EPS trays used as a reference (0.04 g cm⁻³). Trays with lower density can be prepared with starches with lower amylose content [46], which can also be less compact. In this sense, arracacha starch trays, which had lower



Fig. 1. Scanning electron micrograph of Andean-native starches isolated from A) arracacha, B) oca, and C) sweet potato.

Table 2

Moisture, thickness, density, water absorption capacity, and color parameters of the Andean-native starch foam trays (Results are presented as mean \pm SD).

		Arracacha	Oca	Sweet potato	EPS
Moisture (%) Thickness (mm) Density (g cm ⁻³) WAC (%) Color parameters	L* a*	$\begin{array}{c} 11.79 \pm 0.06^{a} \\ 2.51 \pm 0.06^{b} \\ 0.14 \pm 0.01^{b} \\ 99.72 \pm 5.30^{a} \\ 72.23 \pm 0.76^{b} \\ 1.00 \pm 0.32^{b} \end{array}$	$\begin{array}{c} 11.97 \pm 0.27^a \\ 2.57 \pm 0.04^{ab} \\ 0.17 \pm 0.01^a \\ 78.88 \pm 9.52^b \\ 72.57 \pm 1.30^{ab} \\ 1.60 \pm 0.11^a \end{array}$	$\begin{array}{c} 11.87\pm0.39^{a}\\ 2.62\pm0.04^{a}\\ 0.18\pm0.03^{ab}\\ 55.41\pm6.80^{c}\\ 75.05\pm1.45^{a}\\ 0.80\pm0.24^{b}\end{array}$	N.D. 2.61 ± 0.07^{ab} 0.04 ± 0.00^{c} N.D. N.D. N.D.
	b*	4.58 ± 0.37^{a}	$1.53\pm0.23^{ m b}$	3.15 ± 1.35^{a}	N.D.

EPS: samples of expanded polystyrene trays, used as reference.

N.D.: not determined.

Different letters in the same row indicate significant differences between means (Fisher's LSD test, p < 0.05).



Fig. 2. Foam tray color and microstructure: A) Expanded polystyrene used as reference, B) arracacha starch foam tray, C) sweet potato starch foam tray, and D) oca starch foam tray.

amylose content, were less dense, suggesting that arracacha starch has a better capacity for expansion.

With respect to the trays' color parameters (Table 2), the most pronounced visual effects were seen in the red and yellow tones (Fig. 2). Luminosity (L^*) was greater for trays made from sweet potato starch. Several investigations have linked the darkening of trays with Maillard reactions (non-enzymatic browning), as a product of the reaction between carbohydrates and proteins [1,10,19]. Since sweet potato starch had the lowest protein content (Table 1), and therefore less obscuration, a higher value of L^* is justified.

In the case of the red tonality, manifested by the increase in the parameter a^* , the highest value was obtained for oca starch trays ($a^* = 1.60$), which may be related to the presence of anthocyanins in the oca peel [47]. Lower values of a^* were obtained for arracacha and sweet potato starch trays (1.00 and 0.80, respectively). Another colorimetric parameter evaluated was the yellow tonality, which showed high values for arracacha and sweet potato starch trays (4.58 and 3.15, respectively), whereas the lowest value corresponds to oca starch trays ($b^* = 1.53$), results that could be explained by the presence of yellowish pigments in the pulp of arracacha and sweet potato [21,48].

3.3.2. Microstructure

SEM was used to see the morphology of the cross section of foam trays based on arracacha, oca, and sweet potato starches and of a sample of EPS tray (Fig. 2). The cross section of the EPS tray presented a much more compact structure, with smaller air cells inside.

Trays made from starch show a sandwich structure, with dense outer layers that enclose small cells, whereas the internal structure is less dense with large cells, similar to those reported for cassava native [5,10] and corn starch trays [13]. The large cells seen in the internal structure of trays can be related to the evaporation of water and its sudden exit through the mold, consequently causing the rupture of the cells [14].

Trays based on arracacha (Fig. 2C) and oca starches (Fig. 2D) have larger internal cells, which indicates a good expansion capacity of these starches [10], a property related to the trays' density [11], so that the arracacha and oca starches would have a good capacity for tray formation, a property also related to the lower amylose content of these starches (Table 1), thus giving rise to less dense trays (Table 2), in accordance Sjöqvist & Gatenholm's report [46]. Conversely, in the case of the trays based on sweet potato starch, the more compact structure and smaller internal cells (Fig. 2B) would be related with the higher amylose content (Table 1), thereby generating trays with high density.

According to the results shown in Table 1, crystallinity has a direct relationship with amylose content, similar to that previously reported by Tapia et al. [32], with arracacha starch having the lowest CI value. According to Lawal et al. [49], the crystallinity order would explain the swelling pattern of starches because it would involve the breakage of intermolecular bonds within the crystalline components of granules. Therefore, foams' capacity of expansion would also be related to starch crystallinity, i.e., starch granules with lower CI values would not have the same swelling capacity as granules with higher CI values, causing larger pores to be generated in the tray structure (Fig. 2C, D), which could affect the resistance of trays.

3.3.3. Water absorption capacity of native starch foam trays

Water absorption capacity values of 55.41, 78.88, and 99.72% for the sweet potato, oca, and arracacha starch trays, respectively, were obtained after 1 min of immersion in water (Table 2). These high WAC values can be due to the large number of hydroxyl groups (OH) interacting with water molecules within the porous structure originated during thermoforming [7,8]. However, these WAC values were lower than those obtained by Sjöqvist et al. [50] in sweet potato starch trays (110%–170%) after 1 min of immersion.

Sweet potato starch trays had the lowest WAC value, due to their more compact, higher density, and less porous structure (Fig. 2).

These WAC values were similar to those obtained by Vercelheze et al. [7] around 50% after 1 min of immersion in water for cassava starch trays. Conversely, arracacha starch trays showed the highest WAC value (99.72%), as well as the lowest density (0.14 g cm⁻³), and a more porous structure, which facilitated water entry into the polymeric matrix.

These results allow the WAC of native starch trays to be related with their density and size of the air cells of the internal structure. However, the WAC values of oca and arracacha trays are still high and should be improved, whereas that of sweet potato starch, due to their low WAC value, would be more suitable as a low humidity food packaging material.

3.3.4. Mechanical properties of starch foam trays

The mechanical properties of starch trays are considered the most important ones and may be limiting in their commercial applicability when compared with the properties of EPS [19]. Table 3 shows the values of tensile strength and elongation at break for all trays.

Sweet potato and oca trays showed the highest values of tensile strength (0.67 and 0.65 MPa, respectively). According to Wang et al. [51], the amylose content is proportional to the starch granule size and has a direct effect on tensile strength, which explains the results for sweet potato and oca starches (Table 3), with higher amylose contents (Table 1) and larger starch granule size (Fig. 1). Similarly, Table 3 shows higher values of tensile strength obtained by other authors, although the formulations used in those studies include other additives that could improve the trays' properties.

Lawton et al. [12] reported that the use of starches with high amylopectin content (such as the arracacha starch) results in lighter trays with lower resistance. No information is available on the mechanical properties of these native starch trays obtained by thermoforming process; however, Machado et al. [10] and Kaisangsri et al. [8] obtained tensile strength values of 1.16 and 0.69 MPa, respectively, for native cassava starch trays. Uslu & Polat [13] obtained a tensile strength value of 1.54 MPa for native maize starch trays; nevertheless, their trays had greater thickness and higher density, which would explain the high value of this mechanical property [19]. On the other hand, according to Machado et al. [10], the properties of the proteins are affected when subjected to heat and shear forces, weakening hydrogen bonds and their rearrangement in the polymer matrix. This rearrangement of protein bonds may be the cause of the low density and fragility of trays, when compared with trays obtained in other studies (Table 3).

The source of starch did not significantly affect the trays' elongation at break (Table 3). Our results are in agreement with those observed for cassava starch trays obtained by Schmidt & Laurindo [6], with elongation values between 0.85% and 1.10%, despite the fact that these authors used eucalyptus cellulose fibers as reinforcement material.

Finally, no information is available on the production and study of the trays' mechanical properties based on arracacha, oca, and sweet potato starches obtained by thermoforming process (ScienceDirect database). Current studies point to research with cassava, potato, or corn starches [1,6,7]; therefore, our study is an important step in the use of these Peruvian crop starches to develop biodegradable trays with application potential for food packaging.

3.3.5. Thermal properties of the starch foam trays

Thermogravimetric analysis was conducted to investigate the thermal stability of the native starch foam trays and elucidate how interactions between the components affect their degradation process (Fig. 3).

A similar course of the decomposition was observed for all foam trays, with a first step up to approximately 150 °C that resembled the evaporation of the adsorbed and structural water from glycerol-starch composites [5,8]. Above this temperature, a second step was observed, in which the foam trays decomposed at temperatures of 230 °C, 256 °C, and 324 °C for oca, sweet potato, and arracacha foam trays, respectively (red color lines). The loss of mass in the second step (between 160 °C and

Ta	bl	e	3

Mechanical properties: tensile strength (MPa) and elongation at break (%) of Andean-native starch foam trays (Results are presented as mean ± SD).

Foam tray		Density (g cm ⁻³)	Tensile strength (MPa)	Elongation at break (%)	Reference
Cassava starch and malt bagasse fiber	Control	0.45 ± 0.03	12.10 ± 1.97	1.80 ± 1.36	Mello & Mali [1]
	F10	0.44 ± 0.03	12.92 ± 1.57	1.22 ± 0.17	
Cassava starch, sugarcane bagasse fibers, and montmorillonite	Control	0.28 ± 0.03	11.39	1.69	Vercelheze et al. [7]
	F10	0.21 ± 0.02	4.37	2.19	
Cassava starch and organically modified nanoclays	Control	0.28 ± 0.03	11.39 ± 1.22	1.69 ± 0.09	Matsuda et al. [11]
	Starch/C30B2.5	0.31 ± 0.03	112.12 ± 20.11	1.99 ± 0.23	
Native corn starch and corn starch cross-linked with glyoxal	Control	0.44 ± 0.04	1.54 ± 0.37	0.87 ± 0.28	Uslu & Polat [13]
	Starch/glyoxal	0.27 ± 0.03	1.08 ± 0.42	1.85 ± 0.79	
	(G2)				
EPS		$0.04\pm0.00^{\circ}$	1.32 ± 0.10^{a}	2.74 ± 0.38^{a}	Present study
Arracacha starch		0.14 ± 0.01^{b}	$0.52 \pm 0.06^{\circ}$	1.13 ± 0.27^{b}	Present study
Oca starch		0.17 ± 0.01^{a}	$0.65\pm0.07^{ m b}$	1.10 ± 0.17^{b}	Present study
Sweet potato starch		0.18 ± 0.03^{ab}	$0.67\pm0.03^{\rm b}$	1.03 ± 0.13^{b}	Present study

EPS: samples of expanded polystyrene trays used as reference.

Different letters in the same column indicate significant differences between means (Fisher's LSD test, p < 0.05).

400 °C) was caused by loss of glycerol (boiling point of ~290 °C) and/or starch amylopectin–CH₂OH groups [8], as well as the degradation of saccharide rings [52].

The additional fase at temperatures >400 °C, especially in the case of the sweet potato composite, can be related to the oxidation of decomposed starch to generate inorganic residues, similar to the decomposition of other polymers described by Martelli-Tosi et al. [53]. Above this temperature, CO_2 would be released as a result of the pyrolysis process.

With respect to the differences between starch types, the foam trays based on sweet potato starch was almost totally decomposed at >450 °C (black lines), whereas the decomposition of the oca and arracacha foam trays was only partial (residues amount of approximately 16% and 20%, respectively, at the end of the process), with a very slow decomposition rate. Oca and arracacha starches showed higher amylopectin contents (Table 1), especially arracacha starch. The thermal stability of the respective foam trays could be influenced by the presence of amylopectin, generating a higher number of interactions between the components, preventing the evaporation of compounds generated during the foam tray decomposition [54] and increasing its maximum degradation temperature and therefore their thermal stability.

Likewise, these results would be related to the thermal properties of starches (Table 1). Although sweet potato starch granules showed higher temperature values in the gelatinization process, the value of ΔH_{gel} (13.47 J g⁻¹) was lower than those shown by the arracacha and oca starches (16.06 and 16.42 J g⁻¹, respectively), which would be



Fig. 3. Thermogravimetric analyses of foam trays made from Andean-native starches.

related to the lower amylopectin content in sweet potato starch. This would also explain its higher degradation rate of >450 °C (Fig. 3).

4. Conclusions

This work has demonstrated the feasibility of using Peruvian cropsnative starches to produce foam trays by thermopressing. The native starches presented high values of amylose content and a crystalline structure, which favored the formation of the tray. Proper expansion of the trays was observed, which led to the creation of low density biomaterials; however, all foam trays showed a WAC>50%, which is related to their porosity and low density, as well as low values of mechanical properties respect to similar composites manufactured in previous studies. A high content of amylopectin in the arracacha starch favored a greater thermal stability of the biomaterial, which is important for a possible use in hot foods. Further studies are needed to improve the structural and mechanical properties of the foam trays, such as the use of lignocellulosic fibers, chemically modified starches, and/or incorporation of hydrophobic additives. These improvements can be useful considering the potential of these novel biodegradable materials for dry food commercial packaging, like a viable alternative to petroleumbased packing foams currently in use such as EPS.

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