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RESEARCH ARTICLE

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The addition of sugarcane bagasse and asparagus peel enhances the properties of sweet potato starch foams

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The agro-industrial wastes, sugarcane bagasse (SB) and asparagus peel (AP), were used to enhance the properties of biodegradable foam trays based on sweet potato starch-based foam trays (starch/SB and starch/AP trays, respectively). Starch/SB and starch/AP trays containing different concentrations of SB and AP (0%-40%, *w*/w) were prepared, and their microstructure and physical, thermal, and mechanical properties were characterized. The addition of fibers wastes allowed obtaining a yellowish foam tray with lower luminosity and higher porosity, mechanical resistance, deformability, and better ability to absorb water as compared with the sweet potato starch foam trays without fibers. The addition of SB yielded foam trays less porous, with lower water absorption capacity and greater tensile strength than the addition of AP. Higher concentrations of AP fibers (greater than 30%) generate more extendible foam trays. The addition of fibrous wastes improved the thermal stability of the sweet potato starch foam trays. The composite foam trays produced in this work could be used as substitutes for expanded polystyrene in dry food packaging.

KEYWORDS
agro-industrial waste, asparagus peel, biodegradable trays, new material, sweet potato starch

1 | INTRODUCTION

The high strength, low production cost, low density, and high water resistance of synthetic polymers such as expanded polystyrene (EPS) have allowed their use in the production of foam trays for food storage.[1] However, the growing use of EPS has raised environmental concerns: EPS is nonbiodegradable, and it may generate toxic decomposition products that may contaminate the food contained in the package.[2,3] To overcome this issue, new technologies like baking or extrusion have been developed to produce starch-based foams that can replace polystyrene.[4]

Starch is a promising raw material to produce foam; it is naturally abundant, renewable, inexpensive, a little dense, a little toxic, and biodegradable. Cassava, potato, corn, or wheat starches[5-7] have been commonly used in the production of starch-based foam trays. Tuber starches can be used to produce foam with lower densities and higher flexibilities than cereal starches.[8] Sweet potato (*Ipomoea batatas*) is a native tuber of Andean countries such as Peru. In the first quarter of 2016, the production of sweet potato was 292.7 thousand tons.[9] This tuber is mainly used as raw material to produce starch and to bake foods, snack foods, and confectionery products.[10] Recently, the use of sweet potato starch to manufacture foam tray has been reported in literature.[1,11]

However, starch-based foam poses some problems compared with petroleum-based packaging, like poor mechanical properties and hydrophilicity, which hinders its application.[12] Additives such as cellulose and cellulosic material[13,14] have been used as reinforcing materials to improve the mechanical properties in starch-based foams. Likewise, lignocellulosic fibers can be used to reduce water absorption capacity (WAC), improve elongation, and increase the biodegradability of the starch-based foam composites.[15] Some studies have been conducted using lignocellulosic fibers from malt bagasse,[13] sugarcane bagasse (SB),[5,15] eucalypt,[14] aspen,[7] kraft,[16] asparagus peel (AP),[17] among others.

In this sense, agro-industrial biomass, such as SB and AP, can be employed to reinforce starch matrixes. SB is a by-product of the sugar and alcohol industries, which usually ends up being burned in the fields. This fiber contains about 40% to 50% cellulose.[15] Some researchers have used SB in different proportions to reinforce starch-based foams.[8,16] In general, the use of lower concentrations of SB fibers (less than 20%) gives more flexible and more mechanically resistant foams.[18] Asparagus (*Asparagus officinalis* L.) is a high-valued perennial vegetable that is widely cultivated in Peru. Two varieties of asparagus exist, green asparagus (374 thousand tons in 2013) and white asparagus (198 thousand tons in 2013). Peru is the second world producer of this vegetable after China.[19] During the production of canned asparagus, peeling provides a waste material that corresponds to 40% to 50% of the fresh weight of asparagus and that displays high cellulose content (22%).[17] Several authors have used asparagus by-products to obtain compounds of interest including dietary fiber,[20] peroxidases,[21] and value-added compounds like phenols, flavonoids, hydroxycinnamic acids, and saponins.[22] However, the application of AP as reinforcement in biodegradable packaging based on sweet potato starch has not been described yet.

This work aimed to evaluate how the addition of SB and AP fibers affects the physicochemical and mechanical properties of sweet potato starch-based foam trays. The addition of fibers (both) enhanced the thermal stability of sweet potato starch trays; furthermore, AP fibers increased the water adsorption capacity, and SB fibers improved the mechanical resistance of the composite trays.

2 | MATERIALS AND METHODS

2.1 | Materials

The Laboratory of Agro-industrial Process Engineering of the National University of Trujillo (Trujillo, Perú) provided the sweet potato (*Ipomoea batata*, pink variety) starch, which contained 42.65% amylose and 9.27% moisture.

Sociedad Agrícola Virú S.A. (Virú-La Libertad, Peru) and Cartavio S.A. (Cartavio-La Libertad, Peru) supplied the AP and SB, respectively. The fibers were transported to the laboratory, washed with distilled water, and dried at 45°C for 48 hours in a UF 55 Plus oven with forced-air circulation (Mermmet, Germany). The dried samples were ground in a knife mill and sieved through 50-mesh sieves (Tyler series). The fiber size distribution was between 180 and 300 μm.

Glycerol and magnesium stearate were purchased from Su Man (Pflücker e Hijos S.A., Lima, Peru).

2.2 | Chemical composition of the fibers

The cellulose, holocellulose, and lignin content of the SB[23] and AP[24] fibers was determined by TAPPI T19 om-54, TAPPI T 222 om-22, and the methodology presented by Sun,[25] respectively.

The AOAC official method 92504 was used to determine the moisture[25] content in an oven operating at 105°C. The experiment was conducted until constant weight was achieved, and the weight loss was calculated as percent moisture. The ash content (AOAC Official Method 94205) was determined by incineration in a muffle furnace at 550°C to 600°C.[26] Each experiment was replicated three times, for a total of two samples.

2.3 | Preparation of starch foam trays by thermopressing

The sweet potato starch-based foam trays added with SB or AP fibers (starch/SB and starch/AP trays, respectively) were prepared by thermopressing. Seven formulations were used for each type of fiber, as shown in Table 1. The following ratios based on weight of sweet potato starch and fibers (SB or AP) were used to prepare the foam trays: 100/0, 95/5, 90/10, 85/15, 80/20, 70/30, and 60/40.

To prepare each formulation, the proportion of starch, fiber, water, glycerol (used as plasticizer), and magnesium stearate (7.5% *w*/w, used as release agent) was mixed at 1500 rpm for 10 minutes with a mechanic stirrer (Imaco, China). Then, 45 to 60 g of each formulation was homogeneously layered on a teflon mold

TABLE 1 Compositions of the batters used to prepare the sweet potato starch-based foam trays added with sugarcane bagasse or asparagus peel fibers

Starch/Fiber Ratios[a]	Starch (g/100 g of solids)	Fiber (g/100 g of solids)	Glycerol, g	Water (g/100 g of solids)	Batter Amount, g	Production Yield, %
100/0	100	0	6.5	90	60	100
95/5SB	95	5	6.5	90	60	90
90/10SB	90	10	6.5	90	60	100
85/15SB	85	15	6.5	95	60	80
80/20SB	80	20	6.5	100	60	75
70/30SB	70	30	6.5	105	65	60
60/40SB	60	40	6.5	110	65	60
95/5AP	95	5	6.5	90	60	100
90/10AP	90	10	6.5	90	55	95
85/15AP	85	15	6.5	90	57	90
80/20AP	80	20	6.5	100	57	80
70/30AP	70	30	6.5	110	60	60
60/40AP	60	40	6.5	120	60	55

[a]The starch/fiber ratios represent the percentage of starch and fiber content in the batter.

(27 cm × 20 cm × 25 mm, thickness of 30 mm) in a compression molding machine (RELES, Lima, Peru) operating at140°C for 18 minutes and 60 bar. Finally, the foam trays were removed, unmolded, and stored at 25°C and 60% relative humidity for 4 days before characterization.

The volume of water added to each formulation was directly related to the fiber content. Starch pastes must have certain rheological characteristics, which prevent a collapse as the water evaporates. Pastes with low water contents are very viscous and result in less expandable and higher density foams, and the presence of fibers in the formulations is responsible for increasing the viscosity of the mixture, which decreases the foaming ability.[15] The mixtures with a higher proportion of AP fibers (70/30 and 60/40) needed a greater quantity of water than the mixtures with SB fibers. This indicated that the addition of AP fibers increased the viscosity of the mixture, so a greater amount of water was necessary to obtain a homogeneous dispersion (Table 1). During the baking process, an appropriate amount of the mixture was placed in the mold so that a full foam tray formed upon expansion of the starch.[13] For the same starch/fiber ratio, the foam trays reinforced with SB fibers required a greater amount of the mixture than the foam trays reinforced with AP fibers to obtained a complete tray (Table 1). This behavior is due to the AP fibers offering less resistance to the expansion of starch were better integrated in the polymer matrix and required a lower amount of batter to form the complete foam tray.

2.4 | Production yield of foam tray

Foam trays with different formulations were produced separately over a period of 4 hours, and the efficiency of the process was calculated for each formulation as the percentage of complete foam trays that were obtained at the end of the process (Equation 1).[13]

$$\textit{Production yield} = \frac{\textit{number of successful trays}}{\textit{number of attempts}}. \tag{1}$$

Production yield represents the capacity of the thermoforming process to form complete trays, without cracks or apparent defects. Table 1 lists the production yield for the starch/SB and starch/AP trays. The production yield ranged from 55% to 100%. Maximum production yield (100%) was achieved for the sweet potato starch foam tray without added fiber (100/0), the starch/SB 90/10 foam tray, and the starch/AP 95/5 foam tray. These trays were obtained whole and undamaged, as seen in Figure 1.

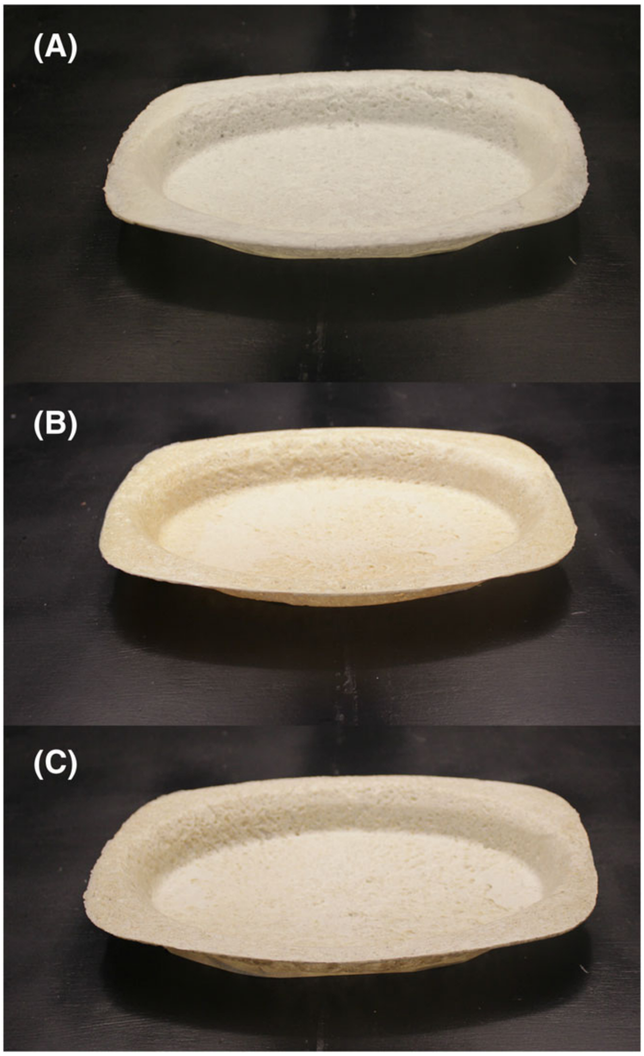

FIGURE 1 Foam trays based on (A) starch/fiber 100/0, (B) starch/AP 95/5, and (C) starch/SB 90/10

2.5 | Thickness and density of foam tray

The thickness of the foam trays was measured with a manual micrometer (Stainless Hardened, 0-150 mm). For this purpose, strips of 100 × 25 mm (cut from the base of the tray) were used. For each formulation, the reported thickness was the average of 36 values (three measurements taken from each of the 12 samples).

The density of the foam trays (g/cm^3) was calculated from the mass (g) and volume (cm^3) of each sample.[27] The density tests were performed with rectangular strips measuring 100 × 25 mm. Each sample was weighed, and the volume was calculated by multiplying the length, width, and thickness together. The reported density values were the averages of 12 samples per formulation.

2.6 | Scanning electron microscopy of foam trays

Foam trays with different formulations were stored at 25°C and 60% relative humidity for four 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, EE UU). The foam pieces were mounted for visualization of the cross-section of the bronze stubs; double-sided tape was employed. The surfaces were coated with a thin gold layer (40-50 nm). All the samples were examined under an accelerating voltage of 20 kV.

2.7 | Mechanical properties

A texture analyzer model TA HD Plus (Stable Micro System, Surrey, UK) with a 100-kg load cell was used to determine the mechanical properties of the foam trays prepared herein and of EPS trays (thickness of 2.53 mm and density of 0.041 g/cm) by tensile and compression tests. The tensile tests were performed with strips measuring 100 × 25 mm, initial grip separation of 80 mm, and crosshead speed of 2 mm/s. Stress–strain curves were recorded during the extension, and stress and strain at break were determined.

The compression tests were accomplished with squares measuring 50 × 50 mm. The puncture resistance and deformation of the foam trays were measured with an HDP/CFS accessory and a spherical stainless steel probe P/0 25S. The test speed was 1 0 mm/s, the probe displaced a distance of 25 mm. For the penetration test, graphs of force (g) vs time (s) were constructed, hardness was the highest point of the curve. For the deformation test, graphs of distance (mm) vs time (s) were plotted; the distance where the sample was fractured corresponded to a value of one. Each formulation was assayed 12 times, and the reported values were the averages of these determinations.

2.8 | Thermogravimetric analysis

The thermal properties of foam trays were evaluated on a SETSYS evolution thermogravimetric analysis (TGA)-differential thermal analysis (DTA)/differential scanning calorimetry (DSC) (SETARAM Instrumentation, France) analyzer. The analyses were carried out under nitrogen atmosphere (100 mL/min); the samples (approximately 6 mg) were heated from 23°C to 600°C at a heating rate of 10°C/min. The sample holder was an open alumina crucible. The reference cell was the corresponding empty alumina crucible. The weight (mass) loss is determined on the basis of difference in mass in the TG curve using the software of the instrument.

2.9 | Optical properties of foam trays

The color of the foam trays was determined on a colorimeter JZ-300 (Kingwell Shenzhen Co, China) as described by Salgado et al.[14] The range of the color parameters were as follows: L^* from 0 (black) to 100 (white), a* from $-a$ (greenness) to $+a$ (redness), and b* from $-b$ (blueness) to $+b$ (yellowness). The reported values were averages of 12 measurements per sample (25 × 25-mm cut from the center of the base of the tray). The foam trays were measured on the surface of the standard white plate with coordinates $L = 897$, $a = 19$, and $b = -49$. Total color difference (ΔE) was calculated from Equation 2, using the "L", "a" and "b" values of standard white plate.

$$\Delta E=\sqrt{\left(L^{*}-L\right)^{2}+\left(a^{*}-a\right)^{2}+\left(b^{*}-b\right)^{2}} \qquad (2)$$

2.10 | Water absorption by the samples during immersion

Samples measuring 2.5 × 5 cm were weighed and immersed in distilled water at 25 ± 10°C for 30 seconds. After excess water was removed with a tissue paper, the samples were weighed again. The quantity of absorbed water was calculated as the weight difference, expressed as mass of absorbed water per mass of original sample.[28] Reported values were the mean of five determinations for each formulation.

2.11 | Statistical analysis

Analysis of variance (ANOVA) and Tukey's test were carried out to compare the formulations (starch/fiber ratio) and the types of fiber, with significance set at $P < 0.05$. The Statistica software version 7.0 (StatSoft, USA) was employed.

3 | RESULTS AND DISCUSSION

3.1 | Chemical composition of the fibers

Table 2 shows the composition of the SB and AP fibers; SB fibers contained 31.7% more cellulose than the AP fibers. Both the SB and AP fibers had higher content of insoluble lignin and hemicelluloses. Oliveira et al[29] reported major cellulose and hemicellulose content for SB (45 ± 0.2% and 29.9 ± 0.2%, respectively) than the value obtained herein. This difference might have been due to the sugarcane growing conditions and variety. The cellulose content of the AP fibers was similar to the content reported by Fuentes-Alventosa et al[20] for asparagus by-products (19.1%-25.3% dry basis), but it was lower than the content reported by Chen et al[30] for asparagus stems (34.6%). While the hemicellulose content of the AP fibers was similar to the content reported by Chen et al[30] for white asparagus stems. The soluble lignin content of the AP fibers was significantly higher as compared with the soluble lignin content of the SB fibers (Tukey's test, $P < 0.05$). The total lignin content of the AP fibers was 21.71%, which was higher than the values of 11% to 18% reported by Fuentes-Alventosa et al[20] and Chen et al.[30] The total lignin content (19.43%) of the SB fibers was close to the value reported by Oliveira et al[29] (21.2%).

3.2 | Optical properties of foam trays

The foam color could have an effect of acceptance or rejection by the consumer[31] because the consumer's preference to choose packaging is associated with the white or transparent color of petroleum-based packaging. Figure 2 shows that the addition of fibers influenced the luminosity (L^*), redness (a^*), yellowness (b^*), and color difference (ΔE) of the sweet potato starch-based foam. The control tray (100/0) presented $L^* = 75$, $a^* = 0.8$, and $b^* = 3.15$, whereas the starch/SB trays had $L^* = 60$ to 68, $a = 1$ to 2.35, and $b = 8.65$ to 11.9, and the

TABLE 2 Composition of lignocelulosic material (g/100 g of dry mass)

	Sugarcane Bagasse	Asparagus Peel
Moisture^a	8.1 ± 0.1^b	15.0 ± 1.0^a
Ash	5.9 ± 0.1^a	8.4 ± 0.2^a
Cellulose	24.0 ± 1.0^a	16.0 ± 1.0^b
Hemicellulose + polysaccharides	19.0 ± 1.0^a	20.0 ± 1.0^a
Soluble lignin	1.5 ± 0.2^b	2.4 ± 0.1^a
Insoluble lignin	18.0 ± 1.0^a	19.0 ± 1.0^a

Means with different superscript letters in the same line are statistically different at $P < 0.05$ according to Tukey's test.

[a] Value expressed on a wet basis.

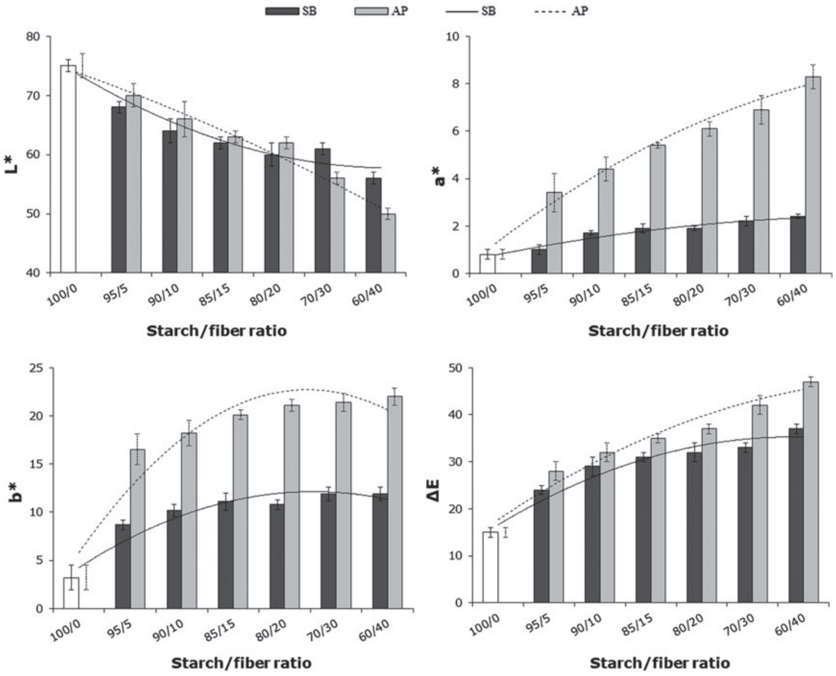

FIGURE 2 Color parameters of the composite sweet potato starch-based foam trays added with sugarcane bagasse (SB) or asparagus peel (AP) fibers. The full and dotted lines show the trend of thickness and density with respect to the content of SB and AP fibers, respectively

starch/AP trays displayed $L^* = 50.4$ to 69.6, $a = 3.4$ to 8.3, and $b = 16.5$ to 22.

According to these results, an increase in the concentration of fibers decreased the luminosity (L^*) of the starch/SB and the starch/AP trays (Tukey's test, $P < 0.05$). Because the SB and AP fibers contain lignin as shown in the Table 2, the composite trays were darker than the control.[7,12] Furthermore, the starch/AP trays were darker than the starch/SB trays because the AP fibers had higher lignin content (Table 2). The hydrolysis of hemicellulose at elevated temperatures can release xylose, mannose, acetic acid, galactose, and glucose. At higher temperature and pressure, the xylose can be decomposed to furfural providing a brown color in composite trays.[12] Moreover, probably a greater proportion of phenolic compounds bound to the lignin structure favors the darkening of the foam trays during thermopressing. At high temperature, aliphatic side chains might get split from the aromatic ring with the breaking of C—C linkages between lignin structural units.[32] This would explain why trays with AP fiber (higher lignin content, Table 2) are darker than trays with SB fiber.

The b^* parameter of the sweet potato starch-based foam significantly increased with the addition of SB or AP fibers—the starch/SB and the starch/AP trays were yellow (Figure 2). While a^* parameter slightly increased with the addition of SB fibers, being this parameter more affected by addition of AP fiber (Tukey's test, $P < 0.05$), probably because of the high concentration of lignin in the AP fibers.[13,33] In their physicochemical analysis of lignin obtained from SB, Miléo et al[34] found nitrogen compounds that could come from plant amino acids or urea incorporated during processing. These nitrogen compounds possibly reacted with carbohydrates, which in the presence of high thermoforming temperature, elicited caramelization and the Maillard reaction, to darken the foam trays and increase the values of a^* and b^*. In addition, a higher lignin content in the AP fiber could cause a greater redness and yellowness in the trays, similar to the reported in films based on sago starch incorporated with lignin.[35] On the other hand, the increasing in color (ΔE) observed in the trays with fiber (significant differences respect to control according to Tukey's test, $P < 0.05$) could generate a problem in the commercialization and acceptance of the product, especially of the trays with AP fiber. Although the change in color (ΔE) does not have any effect on the physical, mechanical, or water absorption properties of the material, it is essential to find a balance between the material's applicability properties (color/water absorption/mechanical properties) allowing a future industrialization.

3.3 | Thickness and density of foam trays

Graphical representations of the changes in thickness and density of the starch-based trays, as functions of fiber contents and types, are given in Figure 3. The thickness and density of the control tray (100/0) were 2.62 mm and 0.16 g/cm^3, respectively. Low concentrations of SB fibers (5%, 10%, and 15%) and high concentrations of AP fibers (20%, 30%, and 40%) significantly reduced the thickness of the composite trays (significant differences respect to control according to Tukey's test, $P < 0.05$). The tray produced with 40% AP fibers had the smallest thickness (2.53 mm).

Regarding the effect of fiber type and content on these parameters, Figure 3 shows different behaviors. In the case of the thickness, no definite trend was observed. For its part, the addition of fibers (SB or AP) to the sweet potato starch matrix increased the density of the sweet potato starch-based foam trays (significant differences according to Tukey's test, $P < 0.05$), which was more evident for the starch/AP trays.

The foam tray density is one of the most important properties for practical use.[3] The tray produced with 40% AP had the highest density (0.3 g/cm^3). Probably, the AP fiber (20%-40%) incorporated into the

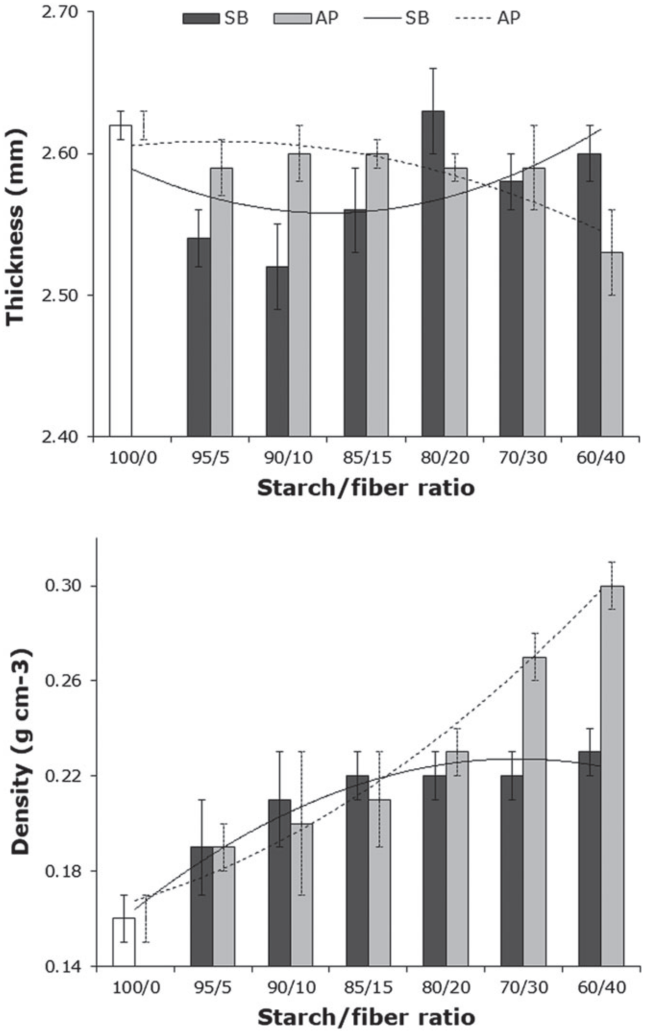

FIGURE 3 Thickness and density of the composite sweet potato starch-based foam trays added with sugarcane bagasse (SB) or asparagus peel (AP) fibers. The full and dotted lines show the trend respect to the content of SB and AP fibers, respectively

polymeric matrix interferes with the expansion capacity of the starch during the thermoforming process, generating foam trays with higher density (inverse ratio between the expansion capacity and density).[36] Also, this would explain the weak points in the trays, which caused a decrease in production yield (Table 1), although the mixtures are incorporated with a greater amount of water to guarantee homogeneity.[7,37] Since foam trays with low density are desirable, fiber concentrations below 20% should be used.

The density values obtained in this study were higher as compared with the density values obtained for EPS foam trays (thickness of 2.53 mm and density of 0.04 g/cm^3). Nevertheless, the density values were similar to reported in foam trays made of cassava starch and SB[5,15,16] fibers: 0.19 to 0.33 g/cm^3. The density of the trays has a relation with its resistance (direct relation) and handling. Then, the choice of the biomaterial should be based on the use that is going to be given. Probably, the materials developed in this research cannot be used to supply polystyrene in the transport of very heavy materials or food. However, applications can be found in dry and lighter foods: grains, potato chips, flours, etc.

3.4 | Water absorption capacity

The ability to absorb water from biodegradable trays is an important property that defines the applicability of the material, being that a material with a low capacity to absorb water is desired.

According to Figure 4, the addition of fibers (AP or SB) affected the WAC of the sweet potato starch-based foam trays. Further, the WAC of the control foam tray (ratio 100/0) was 55.4 g of water per 100 g of dry mass, whereas the WAC of the starch/SB and the starch/AP trays ranged from 34.4 to 76.6 g of water per 100 g of dry mass and from 70.5 to 126.7 g of water per 100 g of dry mass, respectively. Therefore, the addition of AP fiber produced more hygroscopic composite trays when compared with SB fiber (Figure 4). Because AP fibers have lower cellulose content (crystalline phase) (Table 2) as compared with SB fibers, the starch/AP trays can be more hygroscopic and absorb more water at a higher rate than starch/SB trays. The concentration of fiber also affected the WAC of the sweet potato starch-based foam significantly. At lower concentration of SB fibers (from 5% to 15%), the WAC of the starch/SB foam remained constant at 76.6 g of water per 100 g of dry mass, being more hygroscopic than the control tray. Probably, this behavior is associated to the low density of trays with low concentrations of fiber (Figure 3, density). While at higher concentration of SB fibers (from 20%), the hygroscopicity of the composite starch tray was reduced (WAC < 34.4 g of water per 100 g of dry mass) being lower than the control tray. Because the cellulose present in the fibers reducing the hygroscopicity of trays,[7,8] the addition of higher concentrations of SB fibers (30% and 40%) yielded trays with lower WAC than the control tray. At high fiber concentrations, the density of trays was high, which could also have avoided the water absorption (capillarity effect). Other authors also observed that an increase in the concentrations of fibers decreased the WAC of starch-based foam.[5,7]

Petroleum-based packaging has a wide range of applications that include the packaging of liquid, semiliquid, and powdered foods. Obviously, the water absorption values found in this research suggest that

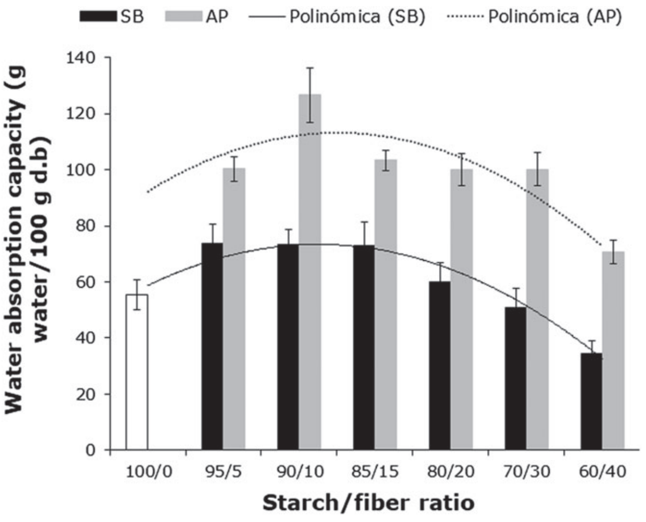

FIGURE 4 Water absorption capacity of the trays prepared with sweet potato starch and added with fibers. The full and dotted lines show the trend of thickness and density with respect to the content of sugarcane bagasse (SB) and asparagus peel (AP) fibers, respectively

tray application should be limited to foods or low moisture materials, for instance, fried foods (which is one of the largest markets that consumes EPS), flours, spices, low moisture herbs, or grains.

3.5 | Mechanical properties of the foam trays

The knowledge of the mechanical properties of the trays allows to determine the resistance of the material for a future use as container of some food.

The effect of the concentration of fibers on the tensile strength of trays was different for SB and AP fibers (Figure 5). An increase in the concentration of SB fibers increased the tensile strength of the trays, whereas the concentration of AP fibers did not impact the tensile strength of the trays significantly (differences respect to control according to Tukey's test, $P < 0.05$), even when the density of trays with AP fiber is greater than the density of trays with SB fiber (concentrations of 30% and 40%) (Figure 3).

Some authors have mentioned that increased foam density is directly related to higher elastic modulus and tensile strength.[38] In this sense, the SB was better incorporated into the starch matrix since SB fibers did not interfere in direct interactions between the starch chain, so under tensile forces, the force was transmitted to the SB fibers, enhancing the strength of the trays.[39] Furthermore, for high proportions of fibers, the amylose content was lower, and the fibers affected the starch bonds, generating trays with mechanical properties that depended on the fiber concentration and type.[14] Because SB fibers had higher cellulose content than AP fibers (Table 2), the starch/SB trays had better mechanical properties.

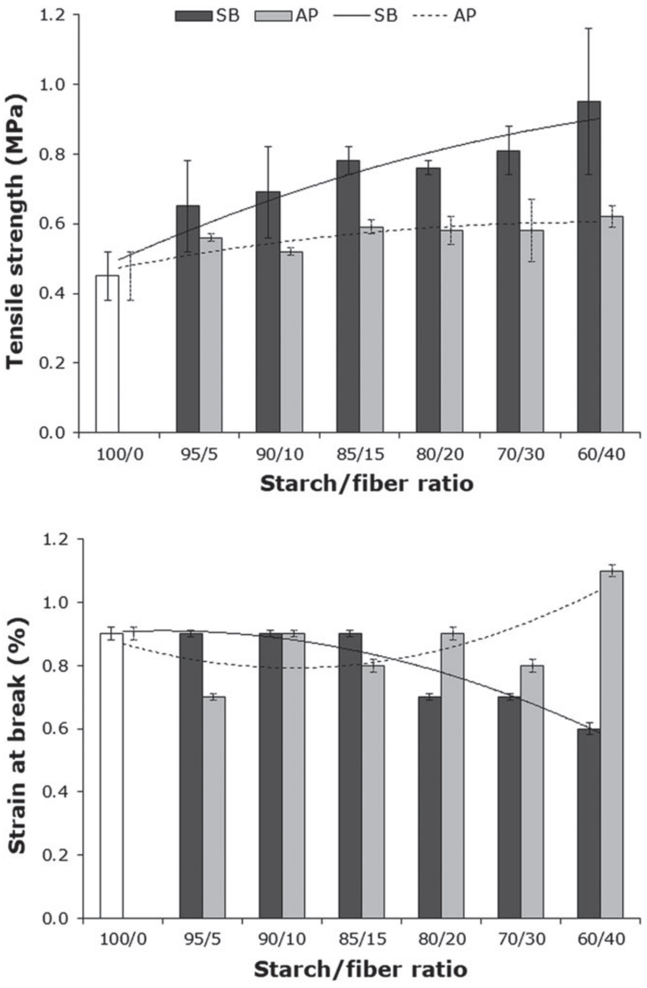

FIGURE 5 Tensile strength and elongation (measured by tensile tests) of the sweet potato starch-based trays added with sugarcane bagasse (SB) and asparagus peel (AP) fibers. The full and dotted lines show the trend respect to the content of SB and AP fibers, respectively

Nevertheless, the addition of higher concentrations of SB fiber (greater than 20%) slightly reduced the strain at break (% elongation) of the sweet potato starch (respect to control). The addition of AP fibers elicited an inverse behavior: 40% AP fibers yielded the most elongable composite trays. Because the starch/AP 60/40 tray presented higher density and lower WAC, high concentrations of AP fibers favored the formation of a more compact and less porous structure that retained water through the establishment of hydrogen bonds, with water acting as plasticizer in the trays with the highest elongation. Some studies have reported that the presence of other components in the starch matrix, such as fibers, reduced cohesive forces and brittleness in the polymeric matrix, decreasing the tension and increasing the deformation at break of these materials.[7,37] This behavior emerged for the starch/AP 60/40 tray.

On the other hand, the starch/AP with higher AP concentrations (greater than 20%) were more elongable than the starch/SB trays. At high concentrations of fibers, the elongation of sweet potato-based foam trays depended on the fiber type. Because AP fibers generated trays with greater capacity to absorb water than SB fibers (Figure 4), and given that water acted as a plasticizer, the elongation capacity of starch/AP trays was greater than the elongation capacity of starch/SB trays.[40]

The mechanical properties of EPS were tensile strength of 0.83 ± 0.11 MPa and strain at break of 2.82 + 0.38%. The tensile strength values of the processed trays were close to the EPS stress values (especially in bagasse fiber concentrations of 30% and 40%); however, the elongation values (strain at break, %) were almost one-third of the value of the EPS. The values of elongation are related to the ability of the material to deform before breaking, and because large air bubbles are generated inside the biodegradable tray, these values are lower than those of the EPS (pores of smaller size and distributed more homogeneously).[1] These results indicate that the biomaterial can be used to transport or store light foods such as chips or grains or perhaps to transport spices or dried herbs. Undoubtedly, it is a disadvantage that must be overcome in future studies, perhaps with other additives, in order to expand the field of application of sweet potato starch trays.

Figure 6 shows that the addition of SB or AP fibers to the sweet potato starch matrix increased the hardness and deformation of the starch foam trays (significant differences respect to control according to Tukey's test, $P < 0.05$). The starch/SB 60/40 tray was the hardest and the most elongable. This demonstrated that the SB fibers in the concentrations range studied (5%-40%) were well incorporated into the starch matrix showing an excellent arrangement of the fibers in the tray yielded tray more flexible and harder. In contrast, increasing concentrations of AP fibers maintains the

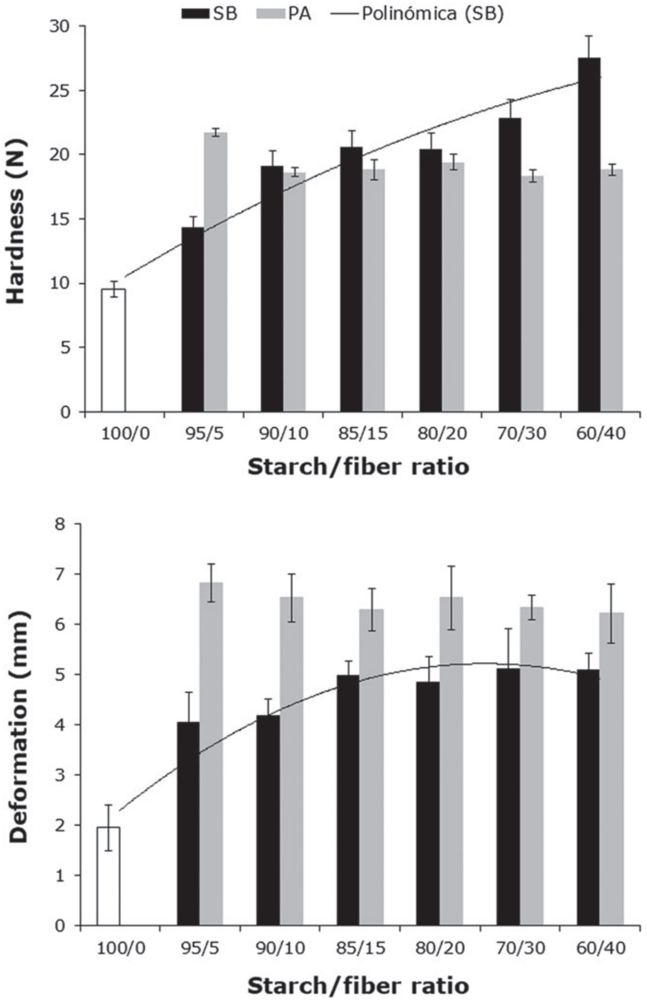

FIGURE 6 Hardness and deformation (measured by puncture tests) of the sweet potato starch-based trays added with sugarcane bagasse (SB) and asparagus peel (AP) fibers. The full and dotted lines show the trend respect to the content of SB and AP fibers, respectively

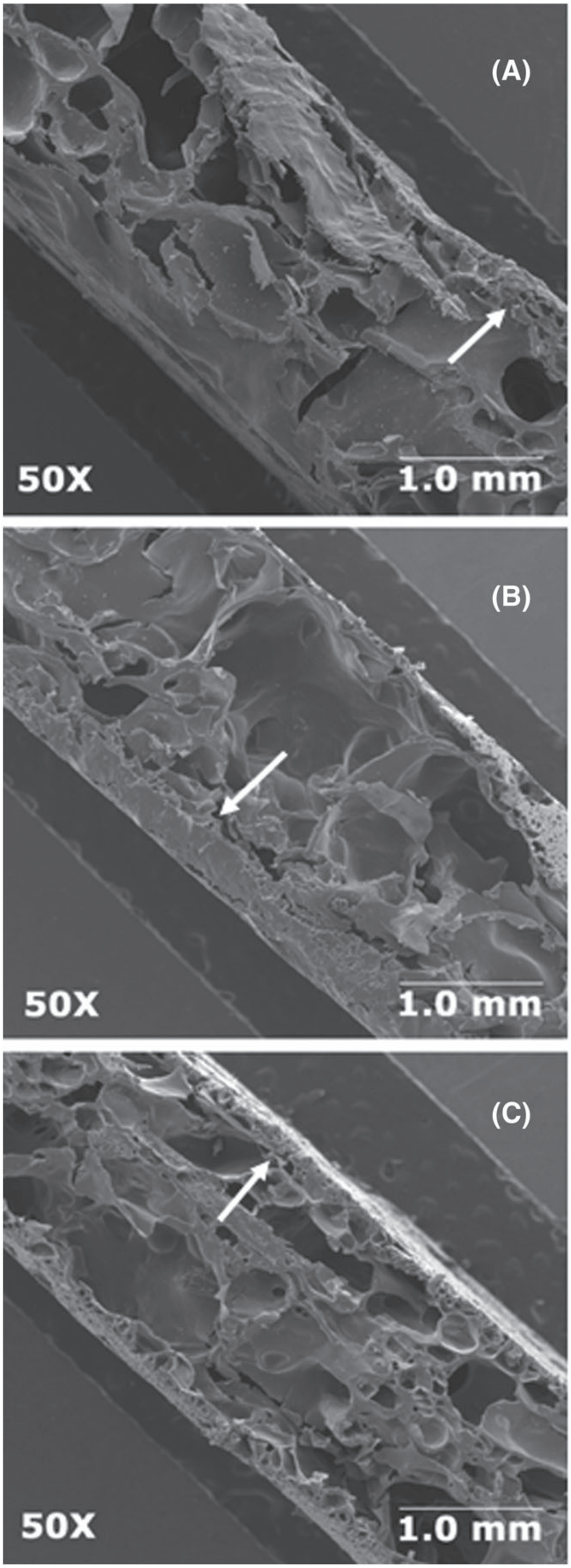

FIGURE 7 Images of the trays with the best mechanical properties: (A) starch/fiber 100/0, (B) starch/AP 95/5, and (C) starch/SB 90/10

hardness and the deformation constant when compared at 5% PA fiber. Higher concentrations of AP fibers could produce discontinuity in the matrix of the trays generating a less mechanically resistant material.[7] Comparison between the SB and AP fibers revealed that only concentrations of SB fibers from 10% promoted harder starch/SB trays as compared with the starch/AP trays, whereas all the concentrations of AP fibers investigated herein gave more deformable trays as compared with the starch/SB trays. This behavior can be associated with the ability of AP fibers to absorb water, to decrease resistance, and to increase flexibility. Moreover, low concentrations of AP fibers (95/5PA) provided more deformable and mechanically resistant trays.

Since trays manufactured with starch/PA and starch/SB (low fiber concentration, 5% and 10% respectively) presented 100% production yield, low density, good mechanical resistance, and moderate elongation, these have a potential use in packaging of dry foods. In this sense, it is important to study the microstructure and thermal properties of these trays in order to evaluate the effect of addition of PA and SB in the structure of control foam tray.

3.6 | Scanning electron microscopy

The final microstructure of the trays is the result of the interactions of its components (starch/fiber) and process conditions (temperature and cooking time) during the thermoforming process.

Figure 7 depicts the SEM micrographs of the cross-sections of the control, the starch/SB (90/10), and the starch/AP (95/5) trays, which presented 100% production yield.

All the three sweet potato starch-based foam trays had a sandwich-type structure consisting of two layers (marked by an arrow) and larger cell size in the interior of the foam, to yield a more expanded structure with some difference because of fiber type added in the starch matrix.[37,41] The micrographs did not show any oriented fibers, regardless of the fiber type (SB or AP). Lawton et al[7] also verified the lack of orientation of fibers in corn starch/aspen fiber foam. According to these authors, there was no flow direction during the baking process, so the fibers were not able to align along the direction of the flow. Thus, during the baking process, the fibers were trapped within the gelatinized starch matrix and became part of the cell walls during the foaming process (see Figure 8).

The thickness of the layers (skins) and the cell size in the interior of the starch/SB, the starch/AP, and the control trays were different. The starch/SB trays showed broad distribution of smaller cell sizes in the outer skins (outer layer) and different air cell size inside the foam (Figure 7C), whereas the starch/AP trays presented denser outer skins, larger air cell size, and more porous structure (Figure 7B). The control tray showed a less dense and an expanded structure (Figure 7A) than the starch/SB and the starch/AP trays.

3.7 | Thermal properties of the foams tray

The raw material (starch and fibers) and three trays (control, starch/PA 95/5, and starch/SB 90/10) were analyzed by thermogravimetry to investigate their thermal stability and to find out how interactions among the components affected the degradation of sweet potato starch-based foam trays (Figure 9). All the samples exhibited a first mass loss event that corresponded to desorption of bound water and evaporation of volatile compounds. For the starch and the SB and AP fibers alone, the first event presented maximum intensity at 33°C and referred to a mass loss of 6%. The control (100/0), starch/SB (95/5), and starch/AP (90/10) trays presented maximum peak at approximately 102°C (Figure 9B). These differences in the temperature of the first event of loss of mass could be explained by the WAC and the diffusion of water molecules that are related to the porosity and the thickness of the cells. This weakened the binding between starch and water molecules in the tray and afforded a material with lower WAC as verified in the WAC test. Martelli-Tosi et al[42] reported maximum peak at 50°C and mass loss of 76% for soybean straw, which was close to the results obtained for the SB and AP fibers. The starch/SB and the starch/AP trays had a first mass loss stage that resembled the first mass loss step reported by other authors[3,43,44] for glycerol-starch biocomposites (maximum intensity at 110°C).

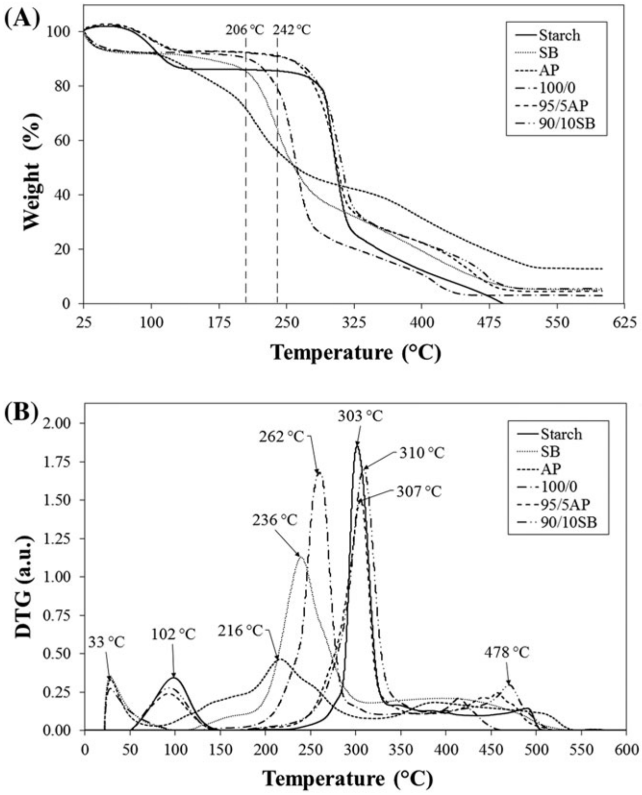

FIGURE 9 Thermogravimetric curves of the sweet potato starch-based foam trays (100/0, 95/5AP, 90/10SB), asparagus peel fibers (AP), sugarcane bagasse fibers (SB), and sweet potato starch

The addition of fibers to the starch matrix decreased the decomposition rate of the sweet potato starch-based foam. Indeed, the second mass loss stage occurred at 242°C for both the starch/SB and the starch/AP trays as compared with 206°C for the control tray (Figure 9 A). Apparently, the SB and AP fibers were positively incorporated into the polymeric matrix, improving the thermal stability of the trays and leading to more stable bonds between starch and glycerol. This could also be related to the property of the fibers of act as a barrier to volatiles generated during decomposition of the polymer.[15]

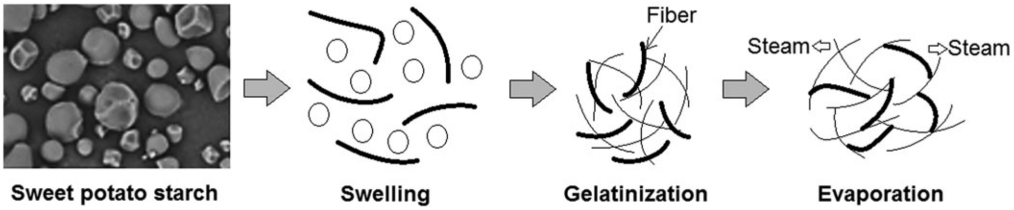

FIGURE 8 Fiber distribution during the thermoforming process of the starch foam trays

On the other hand, the starch/SB and the starch/AP trays showed a decomposition rate significantly slower than the decomposition rate of sweet potato starch alone and of the control tray. Because the starch/SB and the starch/AP foams had higher starch content than the fibers (SB or PA), the thermal stability of the starch/SB and starch/AP trays was mainly influenced by starch. SB and AP fibers degraded at 236°C and 216°C, respectively; this degradation temperature above 210°C referred to the thermo-oxidative reaction of the main organic compounds (decomposition of lignin, hemicelluloses, and mainly cellulose)[42] with overall mass loss around 70%. The mass loss observed for the starch/SB and starch/AP trays between 250°C and 400°C was due to degradation of cellulose by dehydration, depolymerization, or decomposition of glycosyl units, followed by formation of a carbonized residue[42,45] and to degradation of saccharide rings.[46] The third additional event occurred between 360°C and 600°C, with a greater maximum peak almost at 478°C for the composite trays as compared with control tray (408°C), which indicates that the addition of SB or AP fibers increased the thermal stability of the sweet potato starch-based foam tray. This stage is ascribed to the partially decomposed starch underwent oxidation, to generate solid residues such as ashes and inorganic materials (around 20% of the initial mass) and also may be ascribed to the degradation of lignin, which is present in the SB and PA fibers.[42,47,48]

4 | CONCLUSIONS

The starch/SB and starch/AP foam trays produced in this study had a good appearance, lower luminosity, yellow color, adequate expansion, and homogeneous distribution of fibers (SB or AP) in the polymeric matrix. The trays with starch/fiber ratios of 95/5 and 90/10 gave the highest production yields (95%-100%). All the trays obtained here had higher density and thickness than polystyrene trays. Starch/SB trays had a more compact and less porous structure than the starch/AP trays. The addition of SB or AP fibers to the starch matrix improved the thermal stability of the foams trays. In general, the addition of AP fiber produced trays more elongable than the addition of SB fiber because of the greater capacity of the starch/AP trays to absorb water. The hardness and the deformability of the sweet potato starch-based trays were improved with the addition of AP and SB fibers, especially with SB fiber. In regard to the optimum dose of fiber, the obtained results revealed that 5% and 10% of SB fiber promoted starch foam trays with a good tensile strength and hardness, respectively, whereas a low concentration of AP fiber (5%) provided foam trays with a good tensile strength, hardness and deformation, all in respect to control. Finally, further studies in order to improve the WAC are needed because of the fact that the starch-based foam trays have some weaknesses related to their hydrophilicity, so for now, this aspect limits its commercial use on a larger scale. Finally, based mainly on the applicability results of the biodegradable foam trays, the biomaterial should be limited to its use in lightweight materials (because of its elongation capacity) with low moisture content (because of its ability to absorb water), for instance, potato chips, condiments, dried herbs, powders, grains, and even prepared products such as popcorn or fried potato chips. These foods represent large markets worldwide, so the use of these materials would benefit the environment.

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