Revista Hábitat Sustentable Vol. 14, N°. 2. ISSN 0719 - 0700 / Págs. 112 - 125
https://doi.org/10.22320/07190700.2024.14.02.09

Recibido 26/11/2024
Aceptado 12/12/2024

BIOCOMPOSITE OF BANANA FIBER, PEANUT SHELLS FROM MANABÍ (ECUADOR), AND RECYCLED EXPANDED POLYSTYRENE

BIOCOMPUESTO DE FIBRA DE BANANEIRA, CÁSCARA DE AMENDOIM DE MANABÍ (ECUADOR) Y POLIESTIRENO EXPANDIDO RECICLADO

BIOCOMPOSTO DE FIBRA DE BANANEIRA, CASCAS DE AMENDOIM DE MANABÍ (ECUADOR) E POLIESTIRENO EXPANDIDO RECICLADO

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ABSTRACT

This research involves the development of a thermoplastic polymer biocomposite in a matrix of recycled expanded polystyrene reinforced with banana pseudostem fiber and crushed peanut shells. Six models were produced with different doses, of which the one that obtained the best result was the last one, with a content of 63% EPS, 25% banana fiber (40 mm), and 12% crushed peanut shells (1 to 3 mm). In the bending test, it achieved an MOR of 12 N/mm2 and an MOE of 55 N/mm2; the compressive strength was 8.60 N/mm2; moisture absorption was 10%; and in the thermal conductivity test, it had a value of 0.095 W/m⍰k, which means it has an adequate insulating capacity. The values obtained comply with the Ecuadorian standard INEN 3110 for particleboards. This work shows the capacity of the materials used to produce different light, resistant, insulating components that can be used in buildings.

Keywords
recycling, natural fibers, panel, expanded polystyrene

RESUMEN

Esta investigación consiste en el desarrollo de un biocompuesto polimérico termoplástico en una matriz que se obtiene de la disolución del poliestireno expandido (EPS) reciclado, reforzado con fibra del pseudotallo de plátano y cáscara de cacahuete. Se elaboraron 6 modelos con los materiales, de los cuales el que obtuvo el mejor resultado fue la última dosificación, con un contenido del 63% de EPS diluido, 25% de fibra de plátano en tiras (40 mm) y 12% de cáscara de cacahuete triturado (1 a 3 mm). En la prueba de flexión alcanzó un MOR de 12 N/mm2 y un MOE de 55 N/mm2; la resistencia a la compresión fue de 8,60 N/mm2; 10% de absorción de humedad; y en el ensayo de conductividad térmica tuvo un valor de 0,095 W/m⍰k que le otorga la propiedad de material aislante. Los valores alcanzados cumplen con las normas ecuatorianas INEN 3110 para tableros de partículas. Este trabajo evidencia la capacidad de los materiales utilizados para la manufactura de diversos componentes ligeros, resistentes y aislantes que se pueden emplear en las edificaciones.

Palabras clave
reciclado, fibras naturales, panel, poliestireno expandido

RESUMO

Esta pesquisa envolve o desenvolvimento de um biocompósito de polímero termoplástico em uma matriz de poliestireno expandido reciclado reforçado com fibra de pseudocaule de bananeira e cascas de amendoim trituradas. Foram produzidos seis modelos com diferentes doses, dos quais o que obteve o melhor resultado foi o último, com um teor de 63% de EPS, 25% de fibra de banana (40 mm) e 12% de casca de amendoim triturada (1 a 3 mm). No teste de flexão, alcançou um MOR de 12 N/mm2 e um MOE de 55 N/mm2; a resistência à compressão foi de 8,60 N/mm2; a absorção de umidade foi de 10%; e no teste de condutividade térmica, apresentou um valor de 0,095 W/m⍰K, o que significa que tem uma capacidade de isolamento adequada. Os valores obtidos estão em conformidade com a norma equatoriana INEN 3110 para painéis de partículas. Este trabalho mostra a capacidade de materiais utilizados para produzir diferentes componentes leves, resistentes e isolantes que podem ser empregados em edificações.

Palavras-chave:
reciclagem, fibras naturais, painel, poliestireno expandido

INTRODUCTION

Bananas are one of the most representative crops in the world, covering an area of 5,557,060 ha in 2020. The largest producer is India (31,504,000 t), and the largest exporter is Ecuador (7,039,839 t) (FAOSTAT, n.d.). Industries can use a significant amount of fiber extracted from the pseudostem for various applications (Balda et al., 2021). Researchers have conducted several studies on the uses of these fibers, such as in the reinforcement of mortar (Akinyemi & Dai, 2020); in the pharmaceutical and food industries (Kumar et al., 2022); in wastewater treatment, where they act as absorbents for environmental pollutants such as heavy metals, dyes, and pesticides, among others (Ahmad & Danish, 2018); as reinforcements in composite materials, including epoxy resin, vinyl ester, polyester, polypropylene and polyethylene (Ogunsile & Oladeji, 2016). The structure of banana fiber (BF) consists of 60-65% cellulose, 19% hemicellulose, 5% lignin, 2.5% pectin, and a moisture content of 10%. It has a microfibrillar angle of 11°, a fiber diameter of 173 μm, and a density of 1,350 g/ cm^3. Its high cellulose content gives it high mechanical strength; the modulus of elasticity ranges from 27 to 32 GPa, and the tensile strength has a range of 529 to 914 N/mm^2, and the percentage of elongation of the cultivated banana is 21.26%. These values are higher than those of bamboo, coconut, and sisal fibers (Balda et al., 2021; Senthilkumar et al., 2018; Jayaprabha et al., 2011; Chattaviriya et al., 2022; Addis et al., 2023). Banana pseudostem fiber is suitable for reinforcing polymer composites to replace synthetic fibers due to its excellent mechanical strength (Kalangi et al., 2022).

Research has shown that incorporating natural fibers improves mechanical properties as well as thermal and acoustic insulation. Studies show that banana fiber has a noise reduction coefficient of 0.55-0.89 at frequencies from 250 to 6300 Hz (Chattaviriya et al., 2022; Mendes & de Araújo Nunes, 2022). In hybrid composites, it has a thermal conductivity of 0.003 W/m·K (Saravanan et al., 2020), while in polymer composites, it achieves tensile strength of 21-93 N/mm^2, flexural strength of 48-55 N/mm^2, and impact resistance of 7-18 J (Immanuel Durai Raj et al., 2023; Kalangi et al., 2022).

Banana fiber can be treated with chemicals to improve its mechanical performance, as in the work of T. A. Nguyen and T. H. Nguyen, who developed a composite of 30 mm long banana fiber treated with sodium hydroxide (NaOH) at 10%, 15%, 20% and 25% by mass, achieving high performance with a ratio of 80% epoxy resin and 20% banana pseudostem fiber (Nguyen & Nguyen, 2021). Treatment of the fibers improves load transfer and delays crack propagation after shear failure (Chenrayan et al., 2023).

However, controlling the fiber length, orientation, and volume is essential. Excessive amounts can create voids in the matrix, weakening the interfacial bond and reducing the strength (Prem Chand et al., 2021; Addis et al., 2024; Wongsa et al., 2020; Korniejenko et al., 2016). Sandwich composites have also been developed by hand, using overlapping layers of fiber and polymer (Ramprasath et al., 2020).

Peanut shells consist of 45% cellulose, 32.8% lignin, 23-30% hemicellulose, and 4.9% protein, with a moisture content of 8-10% (Binici & Aksogan, 2017a; Gatani et al., 2010; Zaaba & Ismail, 2018). Currently, there is research based on the use of peanut shell ash and its derivatives in construction components as a replacement for cement in concretes and mortars, using mainly ground nutshell ash obtained at temperatures ranging from 400°C to 800°C, the ideal temperature being 500°C (Gatani et al., 2010; Abd-Elrahman et al., 2023). It has been used as a stabilizer for earthen materials and has applications as a fine aggregate in concrete blocks and masonry (Sathiparan et al., 2023). Manufacturers have also used peanut shells as a component in the production of thermal and acoustic insulation materials (Binici & Aksogan, 2017b).

Peanut shells have also been used in manufacturing particleboard using urea-formaldehyde as a binder, with particle sizes ranging from 0.5 to 3 mm (Guler et al., 2008; Akindapo et al., 2015). Prabhakar et al. investigated the properties of an epoxy composite reinforced with peanut shell powder, using fibers treated with NaOH at concentrations of 2, 5, and 7 w/v %, and three shell dosages of 5, 10, and 15 wt% (Prabhakar et al., 2015). S. Ramu et al. worked with a hybrid composite in an epoxy matrix with peanut shell and rice husk, treated with NaOH (1-2 hours) to improve their mechanical properties (Ramu et al., 2023). R. Girimurugan et al. (2022) carried out an experimental study on the compressive properties of a hybrid composite of high-density polyethylene, nano-alumina, and peanut shell, in a ratio of 95: 2.5: 2.5 respectively, which is the ratio that gave the highest values of mechanical strength (Girimurugan et al., 2022). Sada et al. (2013) used peanut shells as a substitute for fine aggregate (sand) with a size no larger than 4.76 mm; as the amount of peanut shell increases, the workability decreases, and the density decreases (Sada et al., 2013).

Expanded polystyrene (EPS) is an inert, non-biodegradable material that does not contain chlorofluorocarbons (CFCs), so it cannot contaminate environmental vectors, but it can cause problems if it is not recycled. One ton of discarded polystyrene is equivalent to 200 m3 and takes up a lot of space, comprising 98% air and 2% polystyrene. Thermal and chemical techniques are used to recycle this product. Chemical options involve the use of solvents. Other

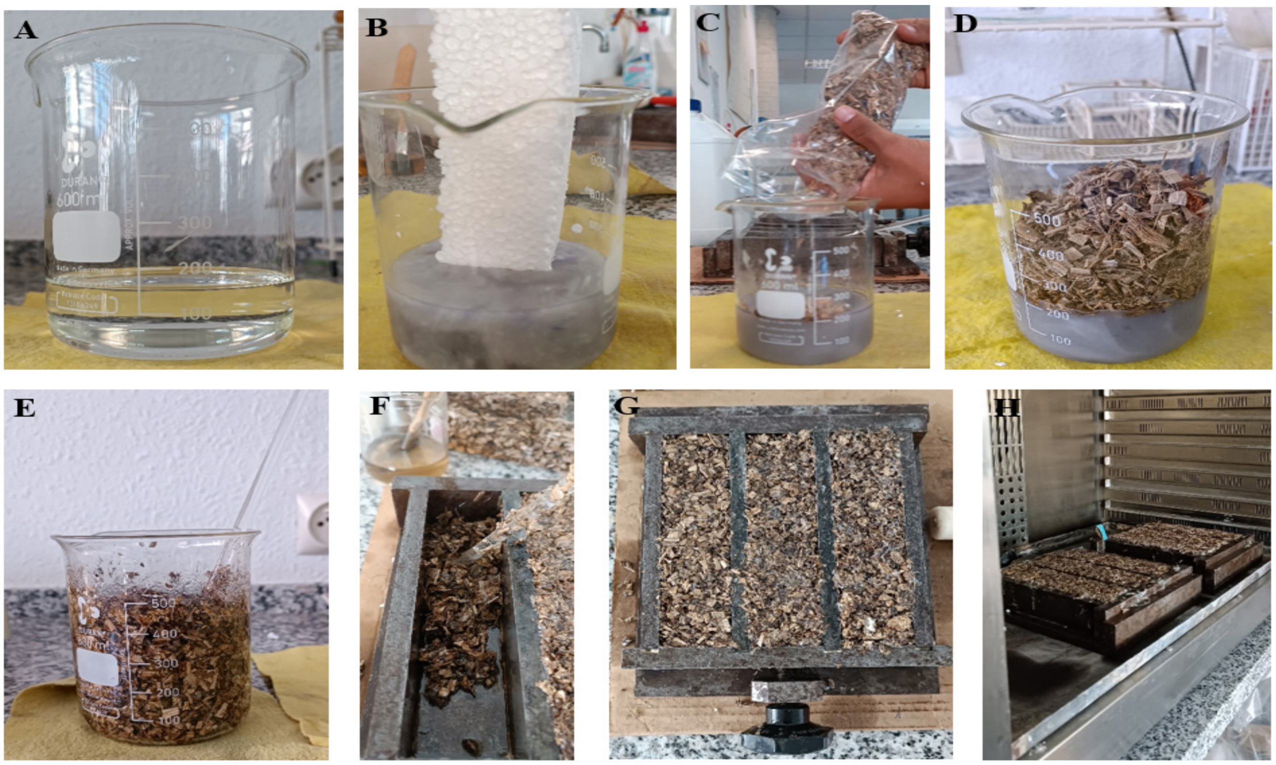

Figure 1. Prototyping procedure. (a) universal solvent; (b) expanded polystyrene solution (EPS); (c) and (d) a blend of the natural aggregates with the binder; (e) mixing of the components; (f) placement in the mold; (g) compaction in mold and resting for 48 hours; (h) drying in the oven. Source: Prepared by the authors

processes, like hot air shrinking and frictional heat compression (Martínez & Laines, 2013), can incorporate additional materials, such as wood flour (Poletto et al., 2011). Plastic recycling is an alternative to avoid environmental pollution and emission of toxic gases from incineration and consists of collection, storage, and reprocessing to obtain new products (Segura, Noguez & Espín, 2007.).

The general objective of the research is to develop a material, using banana peels and peanut shells from agricultural waste, that can be used to make an architectural panel. This panel should be sufficiently durable and have insulating properties. This process is expected to help reduce the carbon footprint associated with the construction and manufacture of the material. The combined use of the two plant residues and the recovery of EPS is the central element of this research.

MATERIALS AND METODOLOGY

Banana fibers and peanut shells were collected from agricultural residues in the rural area of Carrasco, located in Manabí (Ecuador). The fibers were selected after harvesting, sun-dried for seven days, and then transported to the Universidad Laica Vicente Rocafuerte laboratories in Guayaquil. Expanded polystyrene from household appliance packaging was also collected.

The fibers underwent chemical treatment in a NaOH solution to clean and improve their physical and mechanical performance. They were then dried in the sun for seven days and in an oven for 48 hours at a temperature of 100°C. Once dried, the banana fibers were cut into strips measuring 40 mm by 2 mm and 20 mm by 2 mm. The EPS was diluted in solvent, resulting in a whitish-grayish viscous substance. The fibers were mixed with the conglomerate (diluted EPS) for 15 minutes, then placed in metallic molds previously lubricated with a release agent, accompanied by 50 percussion strokes, to eliminate air bubbles and improve its coupling. The substance remained in the mold for seven days; then, it was removed and left to dry in the environment for 14 additional days (Figure 1).

To prepare the specimens, the specimen model outlined in the *UNE-EN 196-1:2018 standard*, initially designed for cement testing, was utilized solely to establish the dimensions of the 40 mm x 40 mm and 160 mm specimens. Six different types of dosages of their components were established, and three prototypes were prepared for each dosage to calculate the average value (Table 1, Figure 2). The workability of the final batch was verified by testing the consistency of fresh mortar on a vibrating table.

The models underwent a characterization process involving physical and mechanical tests, with analysis conducted following the particleboard specifications

Table 1. Prototype composition. Source: Prepared by the authors

Sample average	BF (g)	CPS (g)	EPS (g)	Solvent (ml)	Fibers
1 (I, II, III)	0	54	60	150	CPS_5 mm
2 (IVV, V, VI)	54	0	60	150	BF_40 x 2 mm
3 (VII, VIII, IX)	20	34	70	180	BF_ 40 x 2 mm CPS_1 a 3 mm
4 (X, XI, XII)	20	40	60	150	BF_ 40 x 2 mm CPS_ 1 a 3 mm
5 (XIII, XIV, XV)	20	40	60	150	BF_ 20 x 2 mm CPS_1 a 3 mm
6 (XVI, XVII, XVIII)	40	20	100	250	BF_ 40 x 2 mm CPS_ 1 a 3 mm

outlined in the European standard UNE-EN 312:2010 and the Ecuadorian standard INEN 3110 (Aguillón et al., 2024). In the physical properties, density was determined based on the UNE-EN 323: 1994 standard (Benítez et al., 2013), moisture absorption based on the UNE-EN 317:1994 standard (Preethi & Murthy, 2013), and thermal transmittance based on ISO 8302:1991. In the mechanical tests, flexural strength was assessed by determining the modulus of rupture (MOR) and modulus of elasticity (MOE), following the guidelines of *UNE-EN 310:1994)*. Finally, compressive strength was evaluated according to UNE 56535:1977 (2017). The mechanical tests were performed on a Shimadzu UH-F500kNX universal testing machine.

The basic statistical parameters have been considered for the different properties studied.

Figure 2. Specimens of 40 x 40 x160 mm used for physical and mechanical tests (the numbers are the designation assigned to the specimens). Source: Prepared by the authors

RESULTS AND DISCUSSION

DENSITY

Banana fibers and peanut shells, like most lignocellulosic biomass (Karuppuchamy et al., 2024), have a low density (Akcali et al., 2006). This intrinsic property is transferred to the new composite material and its derivatives. The fibers' incorporation in the composite may generate additional porosity in the matrix and be followed by a density decrease, as Belkadi et al. studied. (Belkadi et al., 2018). To determine the density of the prismatic models, from the physical relationship between mass and volume, an average value of 0.53 kg/m^3 was obtained with a composition of 60% EPS and 40% natural aggregates (Table 2). Model I, made only with crushed peanut shells, accounting for 47% of its volume, had the lowest density. On the other hand, the hybrid model VI, consisting of 37% natural fibers and 63% EPS, had the highest density. The fibers' incorporation in the composite may generate additional porosity in the matrix, followed by a decrease in density. Peanut shells are less dense than banana fibers.

Table 2. Density of the prototypes. Source: Prepared by the authors

Sample average	Density (kg/m³)	Standard deviation
1	0.49	0.3321
2	0.52	0.6996
3	0.50	0.2356
4	0.55	0.9555
5	0.50	0.4545
6	0.64	0.1822

ABSORPTION

The moisture test was carried out following the UNE-EN 317:1994 standard. The samples with less expanded polystyrene and more natural fibers absorbed a higher percentage of moisture (Table 3). The use of EPS significantly reduces water absorption¸ however, when used as natural fibers, the morphological parameters must be taken into account in terms of their ability to absorb water (Kesikidou & Stefanidou, 2019). Sample VI achieved the lowest percentage of absorption of all the samples, with a value of 10%, following the Ecuadorian standard INEN 3110 for particleboards in humid environments, which sets a maximum value of 12%. The higher dose of EPS traps the fibers inside and protects them from external agents.

THERMAL CONDUCTIVITY

The thermal conductivity test follows ISO 8302:1991 using the hot plate method, which measures thermal conductivity in the range of 0.002 to 2500 W/m·K. The tests can be carried out over a temperature range of 10°C to 40°C, with a 15° difference between the plates. Samples measuring 200 x 200 x 30 mm were prepared for this test. All samples showed low thermal conductivity, demonstrating the insulating potential of the material. A higher fiber content resulted in a lower heat transfer rate (Table 4). Air voids within the matrix improve the insulation properties, but may reduce the material's mechanical strength.

A clear relationship between density and thermal conductivity coefficient is observed, confirming the influence of dosage and shell/fiber typology on this property. Other research confirms that vegetable fibers and polymer addition reduced thermal conductivity (Mo et al., 2017; Zouaoui et al., 2021).

FLEXURAL STRENGTH

The bending test was carried out following the UNE-EN 310:1994 standard. This test makes it possible to determine the modulus of rupture (MOR), which is the maximum stress the specimen can withstand before fracturing, thus evaluating the plastic properties of the composites. The modulus of elasticity (MOE) was also determined, which is the average force the specimen can withstand without breaking and returning to its original state, expressing the elastic property of the material. (Table 5). It is important to note that fiber and matrix treatments tend to improve the mechanical behavior of cementitious matrix composites (Laverde et al., 2022).

The highest flexural strength value obtained was 12 N/mm^2. This result complies with the Ecuadorian standard INEN 3110 for particleboard, which establishes a minimum strength value of 9 N/mm^2; the MOE value reached 55 N/mm^2, demonstrating its elastic property before deformation.

MOR is the property that has shown the most significant variation in results.

COMPRESSIVE STRENGTH

Following UNE 56535:1977, the compression test obtained the highest compressive strength of 8.60 N/mm^2 with dosage 6. This sample contains a higher percentage of

Table 3. Moisture absorption. Source: Prepared by the authors

Sample average	Absorption (%)	Standard deviation
1	16	0.9631
2	20	0.2655
3	25	0.7851
4	21	0.0236
5	19	0.5999
6	10	0.1222

Table 4. Thermal conductivity. Source: Prepared by the authors.

Sample average	Density (kg/m^3)	Thermal conductivity (W/m·K)	Standard deviation
1	0.49	0.062	0.2555
2	0.52	0.065	0.3694
3	0.50	0.083	0.9563
4	0.55	0.081	0.5844
5	0.50	0.085	0.2411
6	0.64	0.093	0.4922

Table 5. Flexural strength. Source: Prepared by the authors.

Sample average	MOR (N/mm^2)	Standard deviation	MOE (N/mm^2)	Standard deviation
1	4.20	0.9631	41.00	0.9102
2	5.10	1.0265	73.00	0.0658
3	4.26	0.9452	21.00	0.3599
4	4.60	1.1532	34.00	0.8425
5	4.85	0.9620	66.50	0.2261
6	12.00	1.2002	55.00	0.3102

Table 6. Compressive strength. Source: Prepared by the authors.

Sample average	Compressive strength (N/mm2)	Standard deviation
1	4.99	0.8864
2	5.00	0.9541
3	4.12	0.7500
4	4.44	0.8674
5	3.97	0.8551
6	8.60	0.8999

banana fiber (25%). The higher percentage of banana fiber and the reduced peanut shell size probably influenced the higher axial strength (Table 6).

The results obtained provide sufficient values for the performance expected of a material of this type (Attia et al., 2022). Some research confirms that alkaline pre-treatment improves the mechanical performance of the fiber in the compression test (Lamichhane et al., 2024), improving the mechanical properties of mortar with short and thin banana fibers: A sustainable alternative to synthetic fibers (Ali et al., 2022; Lamichhane et al., 2024).

Combining the two types of plant residue allows the granular effect of the peanut shell to be combined with the fibrous effect of the banana residue, thus reinforcing each other's influence on the mechanical behavior of the prototypes.

CONCLUSIONS

The product developed in this work differs from other products created in previous research by using a completely autonomous process that avoids using resins and sophisticated equipment or tools. This innovation allows communities to implement the production process locally. The test results meet the standards and demonstrate the potential of the material.

The specimens made with banana fibers and peanut shells, agglomerated with an EPS solution, achieved a suitable consistency for the tests. They easily conformed to the shape of the mold, indicating that the final composite could take on different shapes. The natural fibers were pretreated in a NaOH solution to remove impurities and increase the mechanical strength of the final product.

The percentage of water absorption ranges from 10 to 25%. The models with more natural fibers and less binder have a high percentage of water absorption. Model 6 has the lowest percentage of water absorption. The thermoplastic content in the composite can protect and insulate the natural fibers from moisture, contributing to the material's durability.

Thermal conductivity ranged from 0.062 to 0.093 W/m·k. The higher number of natural fibers incorporated in the matrix decreases heat conduction. Model 6 achieves a conductivity value of 0.093 W/m·k compared to the other samples. This value achieved is within the range of materials with insulating properties. It is important to highlight the influence of the fibers on this property.

Specimen 6 gave the best results of all the samples, achieving in the flexure test a MOR of 12 N/mm^2, which determines the resistance to flexural stress before fracture, the degree of plasticity, and a MOE of 55 N/mm^2, which determines the elastic capacity of the material before deformation. The compressive strength was 8.60 N/mm^2. The flexural strength exceeds this value, possibly due to a disaggregation effect during the test, the length of the fibers, and the reduction in the particle size of the peanut shell. Increasing the polymer content resulted in a water absorption rate of 10%, thereby improving the encapsulation and protection of fibers.

The fibers exhibit robust interfacial bonding with the polymer (dissolved EPS), but air bubbles were observed within the specimens. The presence of air bubbles was reduced by incorporating the peanut shell in smaller particle sizes, thus improving the molecular cohesion in the matrix. It is recommended to apply a constant load during the drying process. In addition, the application of heat contributes to the consolidation of the material, although this was not one of the research objectives.

The test results demonstrate the effectiveness of the components used, including the EPS waste, which was dissolved to form the matrix conglomerate reinforced with banana and peanut shell fibers. The values obtained comply with the Ecuadorian INEN 3110, based on the UNE EN 312 standard, for particleboards. This allows us to consider that lightweight, durable construction components with insulating properties can be produced.

AUTHOR CONTRIBUTIONS CRediT

Conceptualization, E.E.M., V.F.A., J.J.M.D.R.; Data Curation, E.E.M.; Formal Analysis, E.E.M., V.F.A., J.J.M.D.R.; Funding Acquisition; Research, E.E.M., V.F.A., J.J.M.D.R.; Methodology, V.F.A., J.J.M.D.R.; Project Management, V.F.A., J.J.M.D.R.; Resources, E.E.M., V.F.A., J.J.M.D.R.; Software, E.E.M.; Supervision, V.F.A., J.J.M.D.R.; Validation, V.F.A., J.J.M.D.R.; Visualization; Writing - original draft, E.E.M.; Writing - revision and editing, E.E.M., V.F.A., J.J.M.D.R.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to CITIUS at the University of Seville for the use of their laboratories for the characterization analyses.

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