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TECHNIQUE FOR UTILIZING COCONUT WASTE AND POLYETHYLENE IN THE CONSTRUCTION OF ECOLOGICAL ROOF TILES

TÉCNICA DE APROVEITAMENTO DE RESÍDUOS DE COCO E POLIETILENO NA CONSTRUÇÃO DE TELHA ECOLÓGICA

TÉCNICA DE APROVECHAMIENTO DE RESIDUOS DE COCO Y POLIETILENO EN LA CONSTRUCCIÓN DE TEJAS ECOLÓGICAS

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ABSTRACT

This paper presents the production route of thermoacoustic sandwich roof tiles obtained from coconut waste and high-density polyethylene (HDPE), integrating sustainability and materials engineering concepts. The proposal arose in an engineering education context, involving students in the development of a composite core for metal roofing, replacing conventional materials such as EPS and polyurethane. Coconut fibers were shaped with a tannin-based adhesive, while recycled HDPE was melted and molded into sheets later formed into trapezoidal tiles. Design parameters for temperature, pressure, fiber–adhesive ratio and HDPE mass were defined, and both direct and indirect production costs were estimated. Nine coconut-fiber composite panels and six HDPE tiles were produced, and their mass, density and suitability as sandwich-tile cores were evaluated. Results indicate that the proposed system has technical potential for roofing applications with thermoacoustic performance, in addition to adding value to urban solid waste. The economic analysis shows that, at industrial scale, the direct cost tends to approach that of commercial products, making the ecological roof tile a promising alternative for sustainable construction.

KEYWORDS: *Coconut waste. Recycled polyethylene. Sandwich tile.*

RESUMO

Este trabalho apresenta a rota de produção de telhas sanduíche termoacústicas obtidas a partir do aproveitamento de resíduos de coco e polietileno de alta densidade (PEAD), integrando conceitos de sustentabilidade e engenharia de materiais. A proposta surgiu em contexto de ensino em engenharias, envolvendo discentes na concepção de um compósito para preenchimento de telhas metálicas, substituindo materiais convencionais como EPS e poliuretano.

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As fibras de coco foram conformadas com adesivo à base de tanino, enquanto o PEAD reciclado foi fundido e moldado em chapas posteriormente conformadas em perfis trapezoidais. Foram definidos parâmetros de projeto para temperatura, pressão, proporções fibra–adesivo e massa de PEAD, bem como estimados custos diretos e indiretos de produção. Nove protótipos de artefatos em fibra de coco e seis telhas em PEAD foram produzidos, avaliando-se massa, densidade e viabilidade de aplicação como núcleo de telhas sanduíche. Os resultados indicam que o sistema proposto apresenta potencial técnico para uso em coberturas com desempenho termoacústico, além de agregar valor a resíduos sólidos urbanos. A análise econômica mostra que, em escala industrial, o custo direto tende a se aproximar dos produtos comerciais, tornando a telha ecológica uma alternativa promissora para a construção civil sustentável.

PALAVRAS-CHAVE: Resíduos de coco. Polietileno reciclado. Telha sanduíche.

RESUMEN

Este trabajo presenta la ruta de producción de tejas sándwich termoacústicas obtenidas a partir del aprovechamiento de residuos de coco y polietileno de alta densidad (PEAD), integrando conceptos de sostenibilidad e ingeniería de materiales. La propuesta surgió en el contexto de la enseñanza en ingenierías, involucrando a los estudiantes en el desarrollo de un material compuesto para el núcleo de tejas metálicas, en sustitución de materiales convencionales como el EPS y la espuma de poliuretano. Las fibras de coco se conformaron con un adhesivo a base de tanino, mientras que el PEAD reciclado se fundió y moldeó en placas posteriormente conformadas en perfiles trapezoidales. Se definieron parámetros de diseño para temperatura, presión, proporciones fibra–adhesivo y masa de PEAD, además de estimarse los costos directos e indirectos de producción. Se produjeron nueve prototipos de artefactos de fibra de coco y seis tejas de PEAD, evaluando masa, densidad y viabilidad de uso como núcleo de tejas sándwich. Los resultados indican que el sistema propuesto presenta potencial técnico para cubiertas con desempeño termoacústico, además de agregar valor a residuos sólidos urbanos. El análisis económico muestra que, a escala industrial, el costo directo tiende a aproximarse al de los productos comerciales, convirtiendo la teja ecológica en una alternativa prometedora para la construcción sostenible.

PALABRAS CLAVE*: Residuos de coco. Polietileno reciclado. Teja sándwich.*

1. INTRODUCTION

Higher education in the various branches of engineering provides a suitable environment for the development of product-innovation projects, such as the production route of an ecological roof tile addressed in this study. Within the challenges of teaching, research and extension in engineering education, the students were asked to develop a construction material that integrates sustainability concepts through the valorization of urban solid waste. Integrated learning is crucial for engineers in the labour market; therefore, active student participation in real problems is essential.

Thermodynamics, for instance, is a core discipline in several engineering programmes, as it deals with energy conversion in different processes. In classroom practice, lecturers are frequently confronted with student proposals and questions related to environmental issues, sustainability and ecological processing routes. Engineers must master multiple competencies to design efficient and sustainable systems, such as the product investigated in this work.

In this context, a sandwich roof tile with thermoacoustic properties was proposed by exploiting natural coconut fibres. Coconut fibres cannot be safely discarded in the environment, since they are slowly degradable and contain antifungal substances that may affect local biota when inadequately disposed of. This challenge required students to revisit fundamental concepts of sound waves, thermal and acoustic insulation, and to explore alternative uses for polymeric residues and natural adhesives.

Across engineering fields, materials engineering plays a central role in characterizing waste streams and defining their reuse routes, as in the case of polyethylene, which can be remelted more than once. In the present project, this perspective enabled the consolidation of concepts related to sustainability and efficient use of natural resources, including the materials life-cycle approach as a means of mitigating environmental impacts.

Environmental sustainability is a global goal. In this regard, Brazil, supported by its availability of natural fibres, can contribute significantly. Compared with synthetic fibres, natural fibres have gained prominence in new product development because they originate from renewable resources, present low density and low cost, are non-toxic, can be incinerated, are biodegradable and, above all, are regarded as sustainable (OLIVEIRA *et al.*, 2017).

Coconut fibres present particular advantages in terms of abundance and cost, since Brazil is an important producer of green coconut and, after water consumption, the husk becomes waste. These fibres also exhibit attractive physical properties. Their extraction can be carried out with simple equipment, without the need for harmful chemicals or the generation of greenhouse gases (DOS SANTOS, D. E.; MARTINEZ, F. C. C.; JUIZ, P. J. L., 2019; VASCONCELOS, 2020). Nevertheless, although Brazil is rich in coconut production, the development of value-added products from coconut residues remains incipient when compared with countries such as the United States and Germany, and the full utilisation of this potential is still far from being achieved (DOS SANTOS, D. E.; MARTINEZ, F. C. C.; JUIZ, P. J. L., 2019).

In addition to coconut fibres, plastic residues are also available, particularly high-density polyethylene (HDPE), a thermoplastic that can be remelted multiple times and is frequently found discarded in the environment. In Brazil, a considerable fraction of solid waste is plastic; HDPE, very common in household refuse, contributes significantly and is routinely observed in dumps, landfills and aquatic environments (COSTA *et al.*, 2016).

Given this scenario, the objective of this work is to define the production route of sandwich roof tiles and to assess the economic feasibility of manufacturing them using coconut fibres bonded with a tannin-based matrix, thus forming a composite core. This material is proposed as an alternative to expanded polystyrene (EPS) or polyurethane foams, combined with outer plates molded from recycled HDPE. In this way, commercial value is added to the residues while a sustainable product concept is established.

In the construction sector, roof tiles represent an important application for residue-based materials, supporting the adoption of more sustainable practices. Environmental concerns have become increasingly central in construction worldwide. One of the major challenges is to reduce environmental impacts through appropriate selection of building materials. Preference should be given to locally available materials that are minimally processed, renewable, non-toxic and potentially recyclable (DE FARIAS, L. M.; MARINHO, J. L., 2020).

According to the Brazilian performance standard for residential buildings, NBR 15.575, materials are not classified as “good” or “bad”, but rather by specific performance characteristics that must be considered in selection and application. In this study, bibliographic research in books, websites and journals was combined with commercial quotations to estimate the costs associated with producing nine coconut-fibre tile prototypes and six tiles made from recycled HDPE. The prototypes were manufactured separately to be later assembled into a sandwich tile, within an interdisciplinary framework involving Civil, Materials, Production, Environmental and Chemical Engineering. This approach highlights opportunities for future industrialisation of sustainable roofing products for the civil construction sector.

2. NATIONAL SOLID WASTE POLICY

The solid waste generated by society produces continuous impacts and damage to the environment, which can be verified by any individual walking, especially, through urban areas. To address this problem, Brazil enacted, in 2010, the National Solid Waste Policy (Política Nacional de Resíduos Sólidos – PNRS). Among its goals, this policy aims to promote shared solutions for the implementation of efficient systems for sorting and final allocation of recyclable materials (VANSETTO; GHISI, 2019).

Law No. 12.305/2010, which instituted the PNRS, establishes that waste management is a shared responsibility based on four main actors: public authorities, waste pickers, companies and the general population. Under this framework, municipalities are encouraged to design and operate their own logistics for selective collection and final destination of waste through the Municipal Solid Waste Plan.

Items of the PNRS particularly relevant to this study are contained in Chapter II, Articles 6 and 7, which state:

> Art. 6 – The principles of the National Solid Waste Policy include:
>
> VIII – recognition of reusable and recyclable solid waste as an

> economic good with social value, capable of generating labour and income and promoting citizenship.
> Art. 7 – The objectives of the National Solid Waste Policy include:
>
> VI – encouragement of the recycling industry, in order to foster the use of raw materials and inputs derived from recyclable and recycled materials” (BRASIL, 2010, p. 86).

As noted by Pereira (2019), inadequate waste disposal not only causes environmental damage but also constitutes an illegal activity, subject to legal penalties. The author also emphasises that environmental agencies must be consulted, as they issue specific regulations concerning waste disposal.

Another important aspect of the PNRS, highlighted in Title IV, Article 51, on final transitional provisions, establishes that:

> The environmentally adequate final disposal of rejects shall be implemented by 31 December 2020, except for municipalities that, by this date, have prepared an intermunicipal solid waste plan or a municipal plan for integrated solid waste management […] that ensures their economic and financial sustainability, as provided for in Article 29 of Law No. 11.445 of 5 January 2007 (BRASIL, 2010, p. 92).

In other words, the law defines deadlines for municipalities to comply with the regulations in force since its publication. At the time this research was conducted, some of these deadlines were approaching, particularly those related to the mandatory elaboration of municipal solid waste management plans in Brazilian municipalities.

3. SANDWICH ROOF TILES

In order to foster the integration of engineering students in the development of roofing systems that adopt the “sandwich” concept, a research and development project for a new product was proposed. This type of roof tile consists of two outer metallic sheets enclosing a low-density core material, which provides enhanced mechanical strength and thermal insulation.

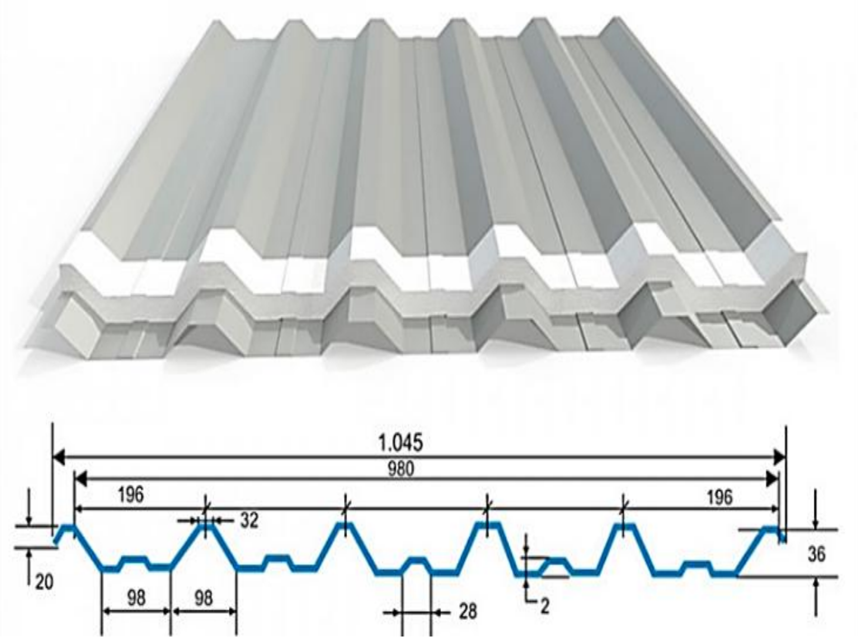
The project involves the active participation of undergraduate engineering students, who are responsible for prototype development. It was carried out in partnership with companies from the construction sector, which supplied the necessary materials and technical support for specific prototyping steps, such as treating the fibres with a natural tannin-based adhesive.

Student participation in this research and development initiative was fundamental for training professionals capable of entering the labour market with broader technical and environmental perspectives. Furthermore, the transversality of teaching during the development and research stages enabled the application of knowledge acquired in classroom-based disciplines that are common to several engineering programmes, such as Physics and Chemistry.

The project contributed to the development of innovative and sustainable solutions, since sandwich roof tiles offer advantages over conventional aluzinc tiles: they present greater durability, lower weight and equivalent thermal and acoustic insulation performance. The proposal therefore not only enriches engineering education, but also supports technological advancement and sustainable development in the country.

Conventional sandwich tiles comprise two metallic faces and a low-density core, as illustrated in Figure 1. In the market, this core is typically produced from two main raw materials, polyurethane or polystyrene, with bonding usually achieved by adhesives. The core thickness can vary from 30 to 100 mm or more, according to customer requirements, with 30 mm being the most common commercial option (TOKUSUMI; FOIATO, 2019).

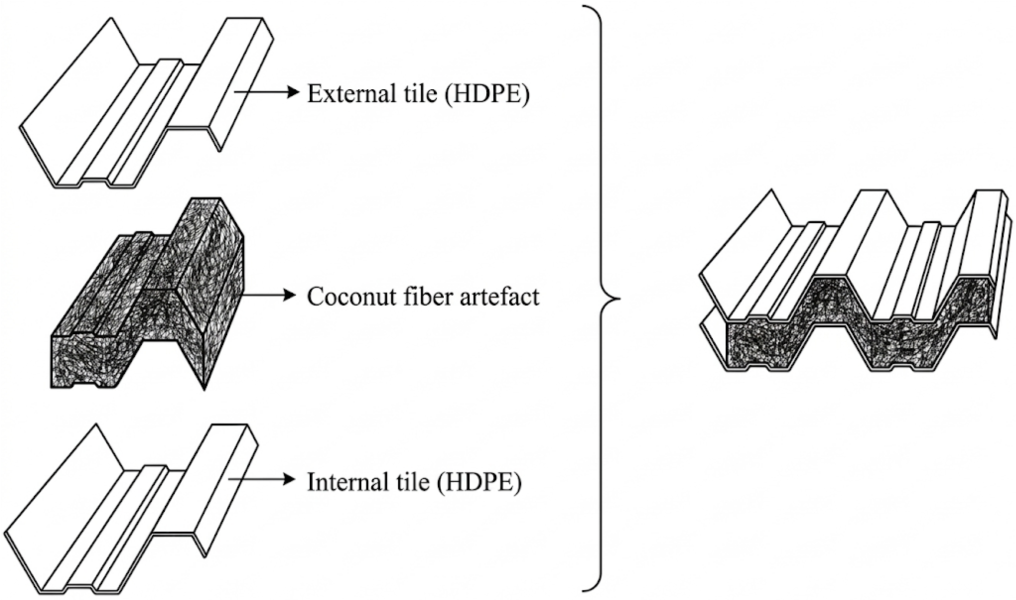
Figure 1. Trapezoidal sandwich roof tile with EPS core source



Gaidzinsk (2020).

In Figure 2, an illustrative schematic of the proposed model is presented, highlighting the use of coconut residues and recycled HDPE. The coconut fibers were shaped using an adhesive composed of tannin–formalin–water to produce molded elements in the form of trapezoidal tiles. In a separate process, the HDPE was melted into square sheets obtained from pellets for subsequent molding.

Figure 2. Schematic of trapezoidal sandwich roof tile with coconut residues and HDPE



Source: author's personal archive (DE SOUZA, 2020).

The choice of coconut fibers as the core material in the sandwich tile design was driven by their application potential. These fibers have an amorphous nature and are well suited for thermal and acoustic insulation, decomposing in the range of 200–260 ºC. When processed and formed into boards or molded components, they become an excellent option for thermal and acoustic insulation, with a wide range of possible applications in the manufacture of different products (MORETTO *et al.,* 2020).

4. PROJECT PARAMETERS

The project parameters are associated with the technical information required to obtain the prototypes, namely temperature, pressure, tile dimensions and mass ratios of the constituent materials, both for preparation of the fibre adhesive and for the fibre-to-adhesive proportions.

For fibre bonding, the technical formulation supplied by Tanac S.A. was adopted. The adhesive is based on tannin extracted from black wattle and is produced by combining tannin powder, water and formalin in the following mass fractions: 40% tannin powder, 50% water and 10% formalin. It is worth noting that several commercial adhesives are available for fibre bonding; however, most are of petrochemical origin and many do not provide adequate water resistance, which is undesirable for roofing applications. For this reason, a tannin-based adhesive was selected, owing to its water resistance and vegetal origin, which adds value to the product in terms of sustainability.

For the coconut-fibre tile prototypes, the elements were conceived as alternatives to expanded polystyrene (EPS). A core thickness of 3.0 cm was adopted, based on typical commercial EPS thickness for sandwich tiles.

Pressure and temperature parameters were defined from the studies by Wiedman (2002) and Lira *et al.* (2014), in combination with the technical bulletin of Tanac. For fibre consolidation, the applied pressure was varied between 3.0 and 0.3 g/cm² to identify the optimum fibre–adhesive ratio yielding the lightest possible composite. The curing temperature was stabilised at 160 ºC, in accordance with the adhesive manufacturer's recommendations.

For HDPE melting and molding, a working temperature of 190 ºC was adopted, as reported by Costa *et al.* (2016). The forming pressure was varied from 5.0 to 20.0 g/cm², adjusted to the available laboratory resources. Steel washers were used as dead weights to simulate the action of an industrial press for both melting and molding steps. In industrial practice, HDPE would normally be processed using extruders and sheet laminators.

Cost-estimation parameters followed the methodologies proposed by Ribeiro (1997) and Riffel (2018), combining market surveys of commercial products with the calculation of estimated direct and indirect production costs. Costs were assessed by simulating the manufacture of small-scale prototypes.

Commercial sandwich tiles are commonly available in trapezoidal profiles. The most usual configuration comprises a 0.5 mm zinc sheet and a 30 mm insulation core, although thicknesses from 30 to 100 mm can be supplied depending on client requirements (RIFFEL, 2018). Based on the defined parameters, product prototypes were fabricated and used to estimate the production cost per square metre of material, which is the standard unit adopted in the market.

5. MATERIALS AND METHODS

Manufacturing was conducted in three stages, in the following order: production of the coconut-fibre composite boards; melting of HDPE pellets into sheets; and molding of these sheets into trapezoidal tiles. Each stage, together with the corresponding procedures, materials andresources, is described below.

For the coconut-fibre composites, the following materials and equipment were used: coconut fibres donated by the company "Coco Verde"; tannin powder donated by "Tanac"; formalin; personal protective equipment (gloves, mask and safety glasses); a manually operated spray gun; a digital balance; a digital thermometer; a square steel mold (46 cm side); a four-burner industrial oven; a blender; and sets of steel washers of different masses.

Nine coconut-fibre composite prototypes were produced. The composites were prepared using 1 kg of liquid adhesive for fibre masses ranging from 200 to 500 g of dried coconut fibres. The adhesive was homogenised in a blender and then sprayed over the dry fibres, which had been previously distributed in a 50 × 30 × 4 cm tray to ensure uniform impregnation.

The adhesive-to-fibre ratio was intentionally oversized (1 kg adhesive) in order to quantify the amount of adhesive lost by drainage through the mold and the amount effectively incorporated into the composite, thereby allowing the definition of an optimal fibre–adhesive proportion.

The adhesive-impregnated fibres were placed in the mold and subjected to different pressures inside an oven preheated to 200 ºC. According to the Tanac technical bulletin, for industrial hot-pressing the recommended curing time is 15 s per millimetre of thickness. For a 30 mm-thick panel, this would correspond to approximately 8 min at a constant temperature of 160 ºC. In the present study, with adapted equipment, the prototypes were consolidated using the oven and the steel mold loaded with washers, both initially at room temperature.

Although the oven was initially set to 200 ºC, insertion of the cold assembly led to a temperature drop to around 70 ºC, as monitored by an infrared digital thermometer. The temperature then gradually increased and stabilised at approximately 160 ºC. Under these conditions, each prototype required about 60 min of processing time.

For the recycled HDPE tiles, the materials used were: HDPE pellets supplied by the industrial plant MMS Plásticos (Rio de Janeiro, Brazil); a steel mold tailored for the prototypes; and two tempered-glass plates of 1 cm thickness and 45 × 45 cm in area. The glass plates were used to confine the pellets during sheet formation and, owing to their transparency, allowed visual monitoring of the melting process.

Approximately 1 kg of HDPE pellets was placed inside the steel mold between the glass plates, and the assembly was introduced into an oven preheated to 200 ºC. The temperature evolution was monitored until the system reached about 190 ºC. This stage required roughly 110 min.

After sheet formation and trimming of excess material, the plates were reheated and then pressed between 45 × 45 cm zinc tile segments to mold the trapezoidal geometry. The working pressure in this step was varied from 5.0 to 20.0 g/cm², similarly to the previous HDPE processes.

The molding time was reduced to approximately 50 min until the material reached about 170 ºC. This temperature was sufficient for molding and required less time because a smaller mass of cold steel was introduced into the oven; in this step, the large mold box used for sheet and fibre consolidation was not employed.

5.1. Prototype characterisation

The coconut-fibre tile prototypes are shown in Figure 3. The images depict the composites produced with coconut fibres and the tannin-based matrix (adhesive). In the photograph on the left, the surface that was in contact with the upper part of the mold can be observed, whereas the photograph on the right shows the surface that was in contact with the lower part of the mold.

Figure 3. Photographs of coconut-fibre tile prototypes

Source: author’s personal archive (DE SOUZA, 2020).

In the photograph above, on the right, a darker coloration can be observed on the lower surface of the produced specimens. These faces were positioned at the bottom of the mold. The tannin adhesive, in its fluid state, accumulated at the bottom of the device; part of it drained through the lateral gaps, while another portion solidified in contact with the fibres, producing a colour similar to partial carbonisation of the material. Nevertheless, as shown in the images in Figure 4, the obtained artefacts did not exhibit any signs of deterioration.

Figure 4. Photographs of coconut-fibre tile artefacts

Source: author's personal archive (DE SOUZA, 2020).

Figure 4 presents two views of the nine artefacts produced. From the lateral faces of the specimens, it can be observed that the solidified tannin sometimes appears with a carbonized aspect and, in other regions, with shades similar to the natural colour of the coconut fibres. It is important to emphasise that the oven used for fibre treatment and HDPE reheating, although of industrial size, was not designed for this specific purpose. As a result, significant heat losses occur through its side walls, preventing full exploitation of its heating capacity

Considering that these artefacts are intended to be used as core fillers in sandwich tiles, the desirable characteristics are low water absorption and minimum density, in order to obtain a lightweight material. Table 1 summarises the variation in specimen masses as a function of the different consolidation pressures applied to the fibre composites.

Table 1. Masses and consolidation pressures applied in the production of the artefacts

Prototype	**Dry fibres (g)**	**Final mass (g)**	**Adhesive incorporated (g)**	**Applied pressure (g/cm²)**
1	500	692	~ 192	~ 3,0
2	400	609	~ 209	~ 3,0
3	400	574	~ 174	~ 3,0
4	350	543	~ 193	~ 1,5
5	350	540	~ 190	~ 1,5
6	350	520	~ 170	~ 1,2
7	200	265	~ 65	~ 1,0
8	200	249	~ 49	~ 0,6
9	200	229	~ 29	~ 0,3

Source: prepared by the authors (2020).

The amount of adhesive prepared was intentionally oversized in order to quantify the mass effectively incorporated into the fibrous material. As the applied pressure decreased, as shown in the last column of Table 1, it was observed that the artefacts remained well consolidated down to 0.6 g/cm². When the pressure was further reduced to 0.3 g/cm², the panels became excessively flexible and some fibres detached from the composite.

Considering the adhesive incorporation behaviour, it is possible to suggest that the material can be produced using approximately 200 g of dry fibres for every 50 g of adhesive. However, this fibre–adhesive ratio should be confirmed by analysing Table 2, which presents the densities of the produced artefacts.

Table 2. Density of coconut-fibre artefact prototypes

Prototype	**Final mass (g)**	**Specimen dimensions (cm)**	**Volume (cm^3)**	**Density (g/cm^3)**
1	692	45 x 19 x 4	~ 3420	~ 0,202
2	609	45 x 19 x 3,5	~ 2992,5	~ 0,203
3	574	45 x 19 x 3,5	~ 2992,5	~ 0,192
4	543	45 x 19 x 3	~ 2565	~ 0,211
5	540	45 x 19 x 3	~ 2565	~ 0,210
6	520	45 x 19 x 3	~ 2565	~ 0,202
7	265	45 x 19 x 2	~ 1710	~ 0,154
8	249	45 x 19 x 3	~ 2565	~ 0,145
9	229	45 x 19 x 3	~ 2565	~ 0,089

Source: prepared by the authors (2020).

Table 2 summarises the masses and corresponding approximate volumes of the nine artefacts produced, and the last column reports the resulting approximate densities. These values were calculated as the ratio between the specimen mass and its volume.

Disregarding prototype 9, which was poorly consolidated, the densities listed in Table 2 vary by no more than 0.1–0.2 g/cm^3 when rounded to one decimal place. This indicates that prototype 8 yielded the lowest density values, and therefore represents the most suitable reference for cost analysis, with a fibre–adhesive proportion of approximately 200 g of dry fibres to 50 g of adhesive.

The HDPE roof-tile prototypes are shown in Figure 5, which presents photographs of the HDPE sheets (left) and the molded tiles (right).

Figure 5. Photographs of sheets and tiles made from recycled HDPE

Source: author's personal archive (DE SOUZA, 2020).

For cost estimation at this stage, the HDPE masses used during sheet production and subsequent molding were systematised in Tables 3 and 4, which compile the data obtained for the fusion of the material into sheets and for their conversion into tiles.

Table 3. HDPE fusion data for sheet production

Prototype	**Granulated HDPE (g)**	**Sheet without flash (g)**	**Applied pressure (g/cm²)**	**Resulting thickness (mm)**
1	1000	868	~ 5,0	~ 5,5
2	1000	854	~ 5,0	~ 5,5
3	1000	775	~ 10,0	~ 4,5
4	1000	813	~ 10,0	~ 4,5
5	1000	788	~ 20,0	~ 4,0
6	1000	798	~ 20,0	~ 4,0

Source: prepared by the authors (2020).

Table 3 presents the masses of HDPE pellets fused into square sheets with side length of 43 cm. Following the same rationale adopted for defining the fibre–adhesive ratio, these data were used to determine the amount of plastic required to manufacture each HDPE tile.

The six HDPE sheet prototypes exhibited flat surfaces, impermeability and an apparent mechanical strength comparable to common domestic HDPE packaging, such as containers used for chlorine-based disinfectants. During sheet production, the applied pressure was limited to a maximum of 20.0 g/cm² in order to avoid obtaining thicknesses below 4.0 mm. This constraint is justified by the fact that, in the subsequent molding stage, the thermoplastic material tends to undergo further thickness reduction when shaped into tiles; it must be remembered that thermoplastics behave as viscous fluids when heated.

In the molding stage, the masses measured after trimming the flash were compiled in Table 4. These values provided the basis for estimating the amount of HDPE effectively consumed in forming a single tile prototype.

Table 4. HDPE sheet-molding data for tile production

Prototype	Sheet (g)	Molded tile without flash (g)	Applied molding pressure (g/cm²)	Resulting tile thickness (mm)
1	868	777	~ 1,0	~ 4,5
2	854	774	~ 1,0	~ 4,5
3	775	646	~ 1,5	~ 3,5
4	813	675	~ 1,5	~ 3,5
5	788	627	~ 2,0	~ 3,0
6	798	625	~ 2,0	~ 3,0

Source: prepared by the authors (2020).

From the data in Table 4, it can be observed that the tile thickness decreased by approximately 1 mm in all six cases. The same pressure levels used during sheet fusion were applied in the molding stage. After trimming, the tiles presented nearly square geometry with side length of about 41 cm. For the cost analysis of the HDPE tile, a reference configuration of approximately 625 g of HDPE and 3.0 mm thickness was adopted.

Figure 6. Photographs of the sandwich tiles produced

Source: authors' personal archive (2020).

6. FINAL CONSIDERATIONS

At first glance, the results suggested that the proposed product would be economically unfeasible, since the total production cost was estimated at approximately R$ 341.06, whereas conventional commercial models are sold at an average price of R$ 89.57. However, when the analysis is restricted to direct costs only, bearing in mind that indirect costs are usually high in small-scale manufacturing, the scenario changes (SANTOS *et al.*, 2021). The estimated direct cost of about R$ 80.02, which is close to the market selling price, is expected to decrease significantly when production is transferred to an industrial environment and scaled up, a behaviour already reported for eco-efficient roofing systems produced with agro-industrial residues (FERREIRA; LOPES; COSTA, 2020). Considering the methods adopted, the use of adapted equipment and the purchase of inputs as a natural person, the production cost can be regarded as promising.

All procedures were carried out outside an industrial plant, which typically has equipment and machinery designed for large-scale production, allowing better utilisation of inputs, time optimisation and reductions in energy and labour consumption (MARTINS; SILVA, 2022). As a legal entity, industry acquires raw materials at lower prices, usually in bulk. This is particularly relevant for the items with the greatest impact on direct costs, coconut fibres and tannin powder, which were the main contributors to the increase in the direct cost of the fibre artefacts.

Industry also has access to suitable equipment for manufacturing these artefacts and assembling sandwich tiles using the proposed residues. Examples include compressed-air spray guns, which would enable more efficient application of the adhesive on dry fibres, reducing processing time and avoiding excess adhesive, and, consequently, waste of material, time, energy and labour. Another example is the use of heated presses, both for HDPE fusion and molding, among other pieces of equipment available in industrial settings, as commonly described in studies on processing of bio-based composites (OLIVEIRA; PEREIRA; RIBEIRO, 2019).

It is believed that, with appropriate equipment, in addition to reducing process-related costs and increasing the number of units produced, it would be possible to fabricate the fibre artefacts by directly applying molten HDPE onto the fibre panels and subsequently subjecting the assembly to hot pressing. This route would further enhance the potential of these residues, as it would eliminate the need for additional adhesive to bond the tiles to the coconut-fibre core, in line with recent proposals for adhesive-free thermoplastic–natural fibre composites (CARVALHO *et al.*, 2023).

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