INDUSTRIAL PRODUCT DESIGN OF AN ABACA AND BIO-POLYMER COMPOSITE APPLICATION

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ABSTRACT:

Material science has become increasingly important in recent years, driving the development of new materials for green and sustainable design, and promoting circular economy principles. These innovative materials, composed of a natural fiber reinforcement sourced from renewable origins and a polymer matrix, exhibit promising properties, enhancing competitiveness while mitigating pollution associated with traditional materials. Creating a composite material combining abaca and a bio-based polymer matrix offers a sustainable alternative to non-recyclable petroleum-based polymers, thereby reducing environmental impact. Bio-Polyethylene reinforced with abaca holds significant potential for various applications across automotive, construction, and sports industries. This study focuses on designing an industrial product tailored to the characteristics of this composite material. Through comprehensive characterization, including mechanical property assessments and simulation-based evaluations, the feasibility of integrating the material into industrial applications, exemplified by a stackable plastic drawer, is demonstrated. The results highlight the viability of using the composite material to develop sustainable industrial products.

Keywords*: Bio-Polyethylene, Abaca, Product design, Mechanical properties, 3D Simulation*

1.- INTRODUCTION

Nowadays, the escalating issue of climate change on Earth necessitates urgent attention, demanding the development of solutions aimed at significantly mitigating or eradicating its underlying causes. Among the array of initiatives underway for several years, the advancement of environmentally sustainable composite materials has emerged as a viable strategy [1]. These materials are engineered to replicate the properties and attributes of conventional materials, predominantly derived from petroleum or other environmentally detrimental sources.

Musa textilis, commonly referred to as abaca, is a natural fiber distinguished for its diverse applications in industries such as paper, textiles, and construction due to its high mechanical strength and water resistance [2]. Its environmentally friendly nature, being sourced from natural origins and its lightweight properties, makes it an ideal candidate for developing eco-friendly composite materials. Abaca plantations play a crucial role in mitigating soil erosion and enhancing biodiversity restoration. Additionally, the waste material generated from abaca plants is utilized as organic fertilizer, contributing to the replenishment of soil fertility [3]. Previous studies have highlighted the successful utilization of abaca as reinforcement in composites, particularly when combined with polypropylene, showcasing comparable mechanical properties to glass fiber composites [4]. Moreover, investigations into thermoplastic reinforced with abaca fibers have demonstrated significant enhancements in flexural strength, particularly when treated with coupling agents like maleic anhydride polypropylene copolymer (MAPP) [5].

Biopolymers, encompassing bio-based and/or biodegradable polymers, are emerging as sustainable alternatives to conventional petroleum-based polymers [6]. However, for a substitute material to be feasible without necessitating redesigns, it must exhibit mechanical performance and other properties on par with those of the polymers it seeks to replace.

Bio-polyethylene (BioPE), derived from sugarcane juice or lignocellulosic biomass, serves as a promising bio-based plastic with mechanical properties akin to high-density polyethylene (HDPE) [7]. Substituting oil-based matrices with BioPE reduces the environmental impact of composite materials. Research has also focused on evaluating the mechanical properties of abaca-reinforced BioPE composites, showcasing superior characteristics compared to the matrix alone, thus offering a promising alternative to conventional oil-based materials [8].

Composite materials are expected to exhibit superior properties compared to their constituent matrices, with attributes deriving from the combination of their phases. These properties, ranging from mechanical and chemical characteristics to cost and environmental impacts, determine the competitiveness of these materials relative to conventional options. Composite materials are widely used in aerospace [9], automotive, sports and construction applications [10]. Natural fiber-reinforced composites enhance the mechanical properties of matrices by incorporating a more rigid phase, typically in the form of individualized fibers, leading to improved tensile and flexural properties [11,12]. Cost competitiveness is achieved when composite materials offer advantages over traditional materials in terms of cost-effectiveness or property ratios. Environmental impact assessment requires scientific methods such as life cycle analysis [13], where the existing literature presents the ecological advantages of natural fibers over synthetic fibers [14,15] and polymeric matrices [16]. Efforts in composite material development focus on replacing mineral reinforcements with natural fibers [17] and substituting oil-based matrices with renewable sources. Polymer characterization is widespread, particularly for polyolefins, with notable presence of biopolymers like polylactic acid and bio-based polyethylene (BioPE). BioPE, along with BioPAs, dominates the non-biodegradable bio-based plastic market due to its similarities with high density polyethylene (HDPE) and lower environmental footprint. Commercial composites typically employ glass fibers (GF) as reinforcements, despite their drawbacks such as fragility, health hazards, higher environmental impact of their production, and higher amount of more polluting base polymers, higher weight [18]. Natural fibers like abaca offer competitive alternatives, characterized by notable intrinsic properties, including mechanical strength, comparable to GF [19]. However, chemical treatments are often required to enhance interfacial bonding. Recent studies demonstrate significant improvements in tensile strengths of HDPE and BioPE-based composites reinforced with abaca fibers (AF) using coupling agents based on maleic acid functionalized polyethylene (MAPE) [20–23]. While studies on abaca-reinforced oil-based composites are prevalent, research on the stiffness of BioPE-based composites reinforced with abaca fibers is limited. Even though, industrial suitability assessments of these BioPE-based composites remain unreported, implying that comprehensive evaluations regarding the compatibility of these composites with industrial processes, their performance under various manufacturing conditions, their potential for large-scale production have not been documented or formally investigated. There is a notable gap in understanding regarding the feasibility and practicality of incorporating these BioPE-based composites reinforced with abaca into industrial applications.

In a study scenario, a specific material is implemented onto a specific component, which is modeled and exposed to various loads via simulation software to evaluate its competitive performance [24]. Throughout this process, modifications of the component's design may materialize to enhance dimensional stability, ergonomics, and other relevant factors. The simulation plays a crucial role as it significantly minimizes the necessity for the fabrication of numerous prototypes and its associated expenses.

In this case, a drawer fabricated from a high-density polypropylene was selected as the subject of examination. The drawer underwent measurement to establish a digital representation for finite element analysis, with load constraints and parameters derived from both empirical data and human factors tables. Mechanical evaluations were performed using the properties of both the original materials and proposed bio-based alternatives. The resultant data was then compared to ascertain which materials satisfy the design requirements under typical circumstances. Sets of BioPE-based composites were proposed as potential substitutes for polypropylene-based materials.

2.- METHODOLOGY

2.1.- MATERIALS

The primary composite materials were fabricated utilizing a bio-based polyethylene (BioPE) matrix, specifically SHA7260, sourced from Braskem (Sao Paulo, Brazil). These composites were reinforced with abaca fibers (AF) obtained from CELESA (Tortosa, Spain). Abaca strands were initially cut to a length of 700 mm, manually trimmed to 100 mm, and subsequently chopped to 5 mm using a mill. The chopped strands were further processed through a hammer mill fitted with a 6 mm screen. Fiber characterization in prior research revealed composition percentages of 72.7% cellulose, 14.6% hemicellulose, 8.9% lignin, 2.9% extractives, and 0.9% ashes. The densities of AF and BioPE were determined to be 1.45 g/cm³ and 0.95 g/cm³, respectively. A Fusabond® MB100D coupling agent, comprising 0.9% polyethylene functionalized with maleic acid (MAPE), sourced from DuPont (Wilmington, DE, USA), was employed to enhance compatibility between the matrix and AF, ensuring stronger interfaces.

2.2.- FIBERS CHEMICAL CHARACTERISATION

Raw abaca fibers were subjected to oven-drying at 105°C until a constant weight was achieved. Following drying, the fibers were milled and screened in accordance with TAPPI standard T257. Solvent extractives were determined following TAPPI standard T204. Subsequently, 5 g of the material underwent Soxhlet extraction for 5 hours using 150 mL of an ethanol-toluene mixture. The extract was then dried until it attained a constant weight. Klason lignin content was measured as per TAPPI standard T222, where 4 g of the sample was incrementally treated with 80 mL of 72% sulfuric acid. The beaker was maintained in a water bath at 20°C for two hours with continuous stirring, and then transferred to a flask containing 1000 mL of deionized water, followed by boiling for 4 hours. The flask was then inclined overnight to facilitate lignin precipitation.

Cellulose content was quantified using high-performance anion exchange chromatography (HPAEC). The samples were hydrolyzed in sulfuric acid and subsequently diluted with deionized water. Both samples and standard solutions were autoclaved for 60 minutes at 125°C, then filtered and washed. The resulting filtrate was used for chromatographic analysis. Hemicellulose content was determined by subtracting the sum of other components from 100%.

2.3.- COMPOSITE MIXING

BioPE, abaca fibers, and MAPE were homogenized using an intensive G5S Gelimat kinetic mixer manufactured by Draiswerke (Mahaw, NJ, USA). The phases were subjected to mixing at 3000 rpm for 2 minutes until reaching a discharge temperature of 190°C. Subsequently, the blends were discharged from the mixer, cooled, and pelletized into 5 mm particles suitable for mold injection using a hammer mill. Composites with varying weight percentages of abaca fibers (30 wt.%) and MAPE contents (0, 2, 4, 6, 8, and 10 wt.%) were prepared to assess the influence of the coupling agent on the tensile properties. Previous research indicates that the optimum content of coupling agent yielding the highest tensile strength remains consistent across different reinforcement percentages. The authors opted for a 30 wt.% abaca fiber content, as it aligns with previous studies [25] and allows for application of coupling agent contents applicable to reinforcement percentages ranging from 10 to 50 wt.%. Upon determining that 8 wt.% of MAPE yielded the highest tensile strength, composites with this MAPE content and varying abaca fiber contents (20, 40, and 50 wt.%) were prepared.

2.4.- SPECIMEN OBTENTION

All residual moisture was removed from the pellets by subjecting them to a drying process in an oven at 80°C for 24 hours prior to mold injection. Subsequently, the dried pellets were molded using a steel mold designed to produce ASTM D638 tensile (dog bone) specimens. The molding process was carried out using a Meteor 40 machine manufactured by Mateu and Sole (Barcelona, Spain), with the nozzle temperature set to 190°C and the barrel temperature maintained between 175 and 180°C. Temperature levels were meticulously monitored to prevent overheating, which could potentially impact the structure of the lignocellulosic reinforcements. The filling pressure was maintained at 117.7 bar, with a holding pressure of 24.5 bar. At least ten specimens were produced for each composite formulation. The mold temperature was maintained at 70°C to promote matrix crystallization, and the cooling process within the mold lasted approximately 30 seconds. Following molding, the specimens were stored in a conditioning chamber set to 23°C and 50% relative humidity for 48 hours prior to undergoing tensile testing.

2.5.- TENSILE TEST

According to ASTM D638 standards, the specimens (Figure 1.b) were stored in a conditioning chamber at 23°C and 50% relative humidity for 48 hours before undergoing tensile testing. The specimens were then subjected to tensile testing using an Instron® 1122 Universal testing machine (Figure 1.c) sourced from Metrotec, S.A (Barcelona, Spain). This machine, equipped with a 5 kN load cell, conforms to the specifications outlined in ISO 527-1:2000 for tensile testing. Each composite formulation underwent tensile testing on a minimum of 5 specimens, with the experimental results representing the average values obtained from these tests. To assess the deformations necessary for calculating Young’s modulus, an extensometer was utilized.

2.6.- FLEXURAL TEST

Flexural strength assessment was conducted using a three-point bending flexural test in accordance with ASTM D790 standards. Sample preparation followed ASTM D760 guidelines, with a minimum of 5 samples (Figure 1.a) used for each composite formulation. Testing was performed using an Instron® 1122 Universal testing machine (Figure 1.c) equipped with a 5 kN load cell, supplied by Metrotec, S.A. (Barcelona, Spain), to determine flexural strength and deformation. The flexural stress experienced by the composite material results in some fibers being subjected to tensile stress while others experience compression stress. This phenomenon generates two flexural moments on both edges of the sample when force (F) is applied, with the combined moments counteracting the force. The force acts along the Y-axis, perpendicular to the neutral axis, which passes through the center of gravity of the Y-axis. This distribution leads to higher flexural strength compared to tensile strength, as fibers experience either compression or tensile stress. To ascertain the optimal flexural strength achievable with varying MAPE contents, a two-stage testing approach was adopted. Initially, uncoupled composites comprising 30 wt% abaca fibers and BioPE matrix were prepared and tested. Subsequently, composites containing MAPE coupling agent at concentrations ranging from 2 wt% to 10 wt% were prepared and evaluated. The MAPE content was calculated relative to the abaca fiber content. Additionally, a pristine BioPE sample was prepared and subjected to tensile testing for comparison with composites containing abaca fibers ranging from 20 to 50 wt% and a consistent MAPE content of 8 wt% across all samples.

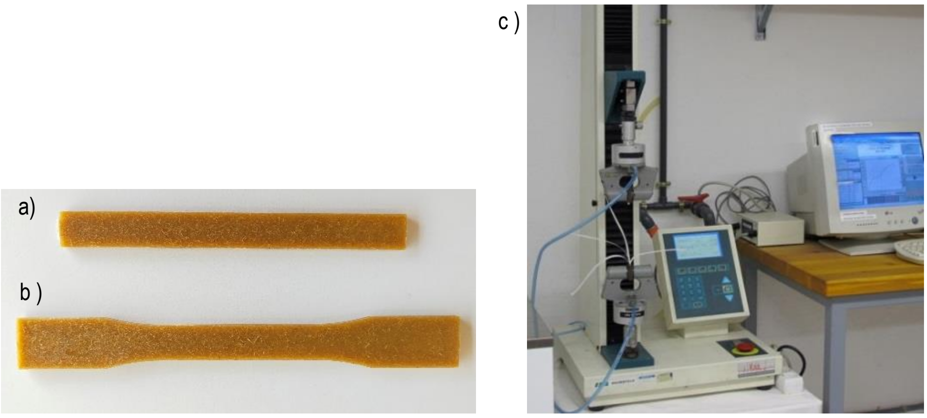


Fig. 1. Images of the a) flexural test specimen, b) tensile strength specimen c) Universal testing machine Instron® 1122 (Source: own work)

2.7.- SPECIMEN 3D MODEL

The three-dimensional prototype product was designed using the CAD/CAE software Solidworks®, developed by Dassault Systems. The simulation analysis was conducted using Simulation Xpress software. The model has been parameterized using the provisions defined by the ASTM D638 standard. The finite element analysis (FEA) was performed using the SolidWorks® simulation analysis. The digital model was specifically designed for finite element analysis, necessitating the omission of certain details such as rounded edges [26]. The analysis was conducted under static conditions and utilized hexahedral elements for meshing. The initial mesh underwent refinement iterations until it was deemed satisfactory for analysis.

3.- RESULTATS AND DISCUSSION

3.1.- COMPOSITE MECHANICAL RESULTS

After studying the content of MAPE in the abaca-reinforced BioPE- based composite during the tensile and flexural tests, the 8 wt% content was established as the optimal content [20–23]. Table 1 and Table 2 shows the results of the tensile test and flexural test, respectively, with different percentages of abaca strands, ranging from 20 wt% to 50 wt%, and displaying the density (ρ), the tensile strength (σ_t^c), the Young's Modulus (E_t^c), the strain at breaking (ε_t^c), the flexural strength (σ_f^c), the flexural modulus (E_f^c) and the deformation at the maximum flexural strength value (ε_f^c).

Composite	ρ (g/cm$^{3)}$	σ_t^c (MPa)	E_t^c (GPa)	$_t^c\varepsilon$ (%)
BioPE20AF8MAPE	1.02 ± 0.04	26.64 ± 0.24	3.25 ± 0.03	6.10 ± 0.29
BioPE30AF8MAPE	1.06 ± 0.03	33.85 ± 0.77	3.76 ± 0.04	4.86 ± 0.20
BioPE40AF8MAPE	1.10 ± 0.05	42.51 ± 0.45	5.06 ± 0.01	3.82 ± 0.26
BioPE50AF8MAPE	1.15 ± 0.04	47.73 ± 0.27	6.44 ± 0.11	2.7 ± 0.13

Tabla 1. Results of the tensile test

Composite	σ_f^c (MPa)	E_f^c (GPa)	$^{fc}\varepsilon$ (%)
BioPE20AF8MAPE	41.74 ± 0.64	2.35 ± 0.109	5.0 ± 0.05
BioPE30AF8MAPE	50.28 ± 0.45	3.18 ± 0.165	4.3 ± 0.07
BioPE40AF8MAPE	59.62 ± 0.32	3.89 ± 0.091	2.8 ± 0.16
BioPE50AF8MAPE	64.23 ± 0.81	4.83 ± 0.130	2.1 ± 0.04

Tabla 2. Results of the flexural test

These values were introduced in the simulation analysis to obtain the results of stress, deformation, and safety factor.

3.2.- SUITABILITY OF THE MATERIAL TO THE DESIGN

Once the characteristics and properties of the composite material based on BioPE reinforced with abaca fibers have been analyzed, the next step is to determine a suitable application. To achieve this, methods and techniques commonly employed in product design and development are utilized [27].

For the development of a new product, two preliminary phases are considered:

- Idea generation, product design, and engineering
- Market research and marketing analysis

Considering the characterization of the studied composite material, a decision is made to search for an application that can replace the base polymer of the matrix. In this case, since BioPE is the material under consideration, an application made of high-density polyethylene (HDPE) is chosen for substitution.

Given that this is an initial study for potential application, a simple element capable of withstanding small forces and having an industrial application is selected. With these considerations in mind, a stackable plastic drawer is chosen (Figure 2).

Fig. 2. Caption of two kind of industrial drawer (Source: own work)

The iterative development process of a novel product necessitates the collaboration of multidisciplinary experts spanning design, product engineering, and materials science. In this study, professionals proficient in design, product engineering, and materials science were essential [28]. Engineers assimilated insights from materials science specialists, stylists, and product designers to conduct computer-aided engineering analyses. Throughout the procedure, there existed a continuous feedback loop among the experts to uphold the integrity of the design intent against alterations induced by modifications such as thickness adjustments and structural enhancements depicted in Figure 3.

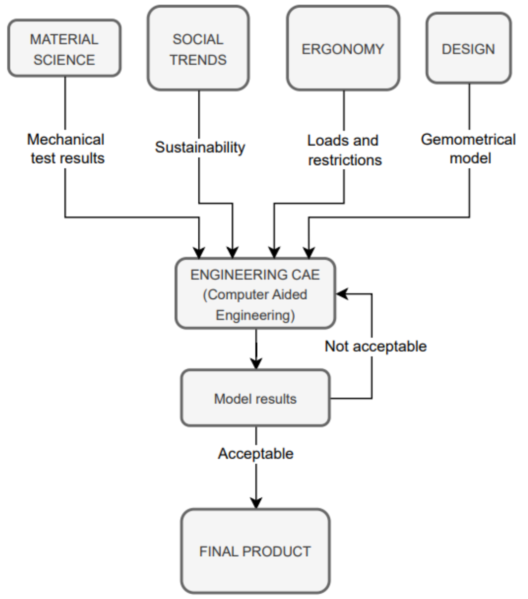


Fig. 3. Research framework of the development of a new product made of biodegradable material (Source: own work)

Designers skillfully discern market demands and transmute them into product concepts merging functional, aesthetic, and emotive dimensions [29]. Product engineers executed requisite computations to ascertain the technical viability of the product. The culmination was a virtual model capable of enduring requisite loads and deformations. Material science experts were tasked with formulating materials conforming to all technical specifications. Ultimately, the product's technical, economic, and market feasibility must be assured.

3.3.- DESIGN

In determining the market requirements for applicable drawers, the objectives, and trends to be achieved are defined. All of this is based on an existing industrial drawer.

Once the models found on the market have been analyzed, functionality, usage, and ergonomics parameters are established, all limited by technical requirements, and the foundations of the details and general form are specified.

To determine the shape, measurements of drawers already on the market are taken and defined based on them. A size of 300x200 mm and a height of 450 mm are determined. For technical requirements, necessary load values that the drawer must support are set, based on the items that will generally be placed in it. It must be considered that the objects placed on the drawer can have very different shapes and weights. Likewise, the material may vary. A maximum load to be supported of 3 kg is determined.

Once the objectives are defined, ideas are conceptualized in sketches. Several sketches are made until one is decided upon. From here, the details of the chosen design are sketched out, as shown in Figure 4.a, finalizing the initial idea.

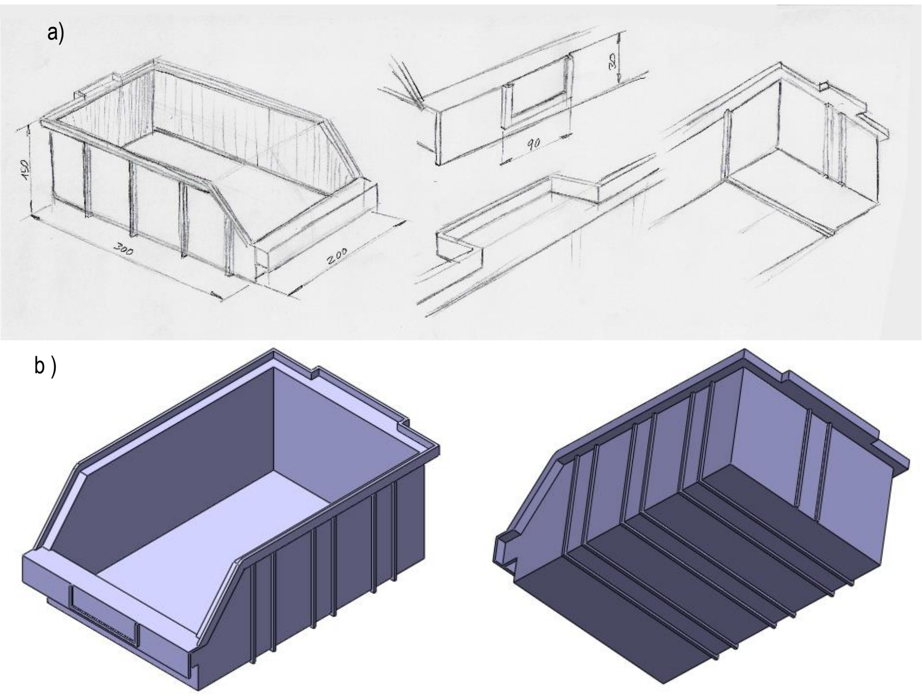


Fig. 4. a) Initial sketch phase of the drawer (all dimensions in millimeters), b) final proposal for a 3D model drawer (Source: own work)

From these sketches, a particular idea was selected and further refined utilizing Computer Aided Design (CAD) software, culminating in the creation of a three-dimensional model (Figure 4.b).

3.4.- TEST ANALYSIS

The utilization of stress-strain testing serves as a valuable tool for elucidating crucial mechanical properties including tensile strength, elastic and plastic limits, and Young’s modulus. These parameters play a pivotal role in predicting the mechanical response of materials. In the context of product design and development, understanding the geometric behavior under extreme conditions is imperative. Employing computer-aided engineering (CAE), notably finite element analysis (FEA), facilitates significant reductions in both time and cost associated with the design process [30].

CAE software enables engineers to assess virtual prototypes of the final product comprehensively. A standard CAE analysis typically encompasses geometric design, material characterization (e.g., tensile strength, Young's modulus), load application (forces, moments, pressures), constraints on model degrees of freedom, and iterative analysis review. The analysis output provides insights into how the product geometry reacts to applied loads and constraints, enabling engineers to make informed decisions regarding necessary modifications such as adjusting thickness, introducing ribs, or exploring alternative materials.

In this phase of development, geometry data, manufacturing technology, and legal specifications are introduced. Geometry is defined using a 3D model via CAD (Solidworks®), manufacturing technology is determined to be injection molding, and no specific regulations apply as this product does not have specific legislation.

To define the tensile mechanical properties of the composite material, experimental results obtained from tests conducted are utilized. The most restrictive requirements are defined by the results of finite element analysis conducted using Solidworks® 3D design software.

Load assumptions (3 kg) and model constraints (supported by the side wings) are input into the program. It is estimated that the most unfavorable scenario occurs when the drawer is supported on top of another, containing items inside with a 3 kg load. The consideration regarding constraints is that it behaves like a beam simply supported at both ends by the side wings of the drawer.

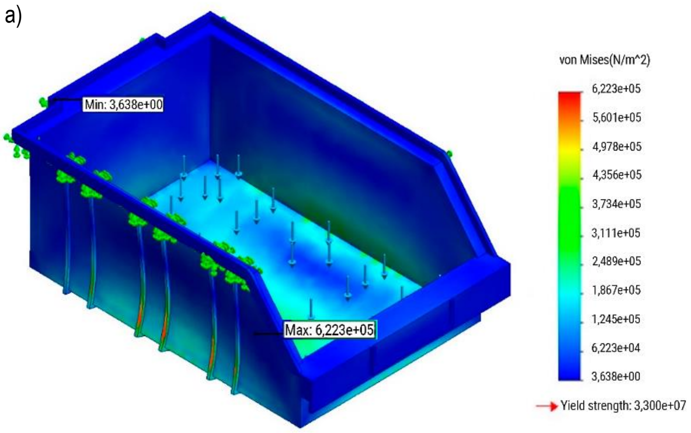
Mesh geometry is accomplished using solid tetrahedral elements, with uniform size throughout the geometry, requiring no adjustment.

With all this information introduced, is performed the obtaining results of the Von Misses stress distribution (Figure 5.a), deformations (Figure 5.b), and safety factors (Figure 5.c) from the static mechanical study. The authors selected Von Mises model due to its suitability for non-brittle materials. Considering that the interface of the composite material is primarily subjected to shear stress, and recognizing that the matrix, which is less resistant to shear, is a non-brittle material, this model was deemed the most appropriate.

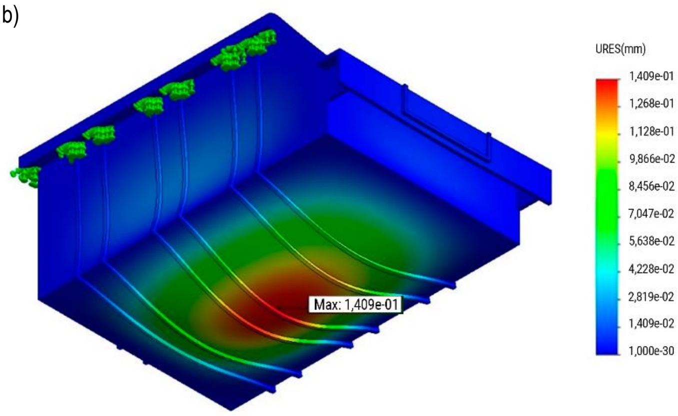
In the specific case under study, a comparison is made between HDPE and BioPE compounds reinforced with abaca with different load percentages.

Once these results are obtained, they must be analyzed to determine if the model is correct or if some geometries need to be modified to address any mechanical deficiencies observed.

a)



b)



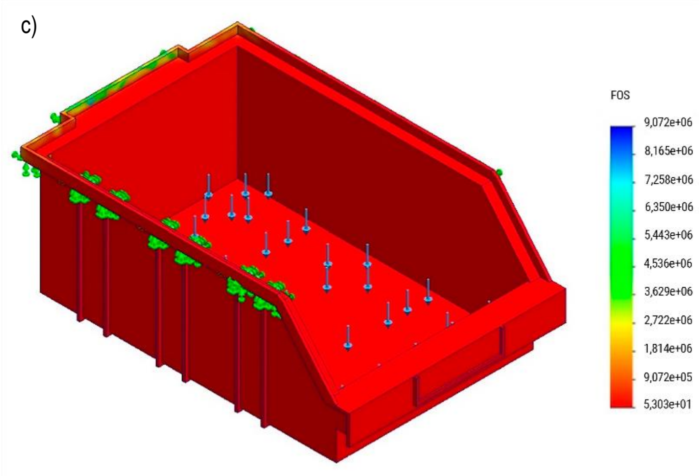


Fig. 5. Examples of the a) stress distribution, b) deformations and c) safety factor results obtained from the design software after performing the FEA analysis to the many models of different drawer materials (Source: own work)

Figure 5.a indicates the highest values of the Von Misses stress are concentrated on the lateral ribs, particularly in their lower regions. These rips are incorporated to increase the thickness in this area, thereby reinforcing the lateral walls. The application of loads at the bottom of the drawer subjects this region to flexural stress, resembling the behavior of a simply supported beam under distributed load.
Figure 5.b shows the internal stress, were usually coincide with the Von Misses stresses. The figure facilitates the identification of areas susceptible to collapse. The higher strains are located at the center of the bottom of the drawer. Nevertheless, none of the regions are anticipated to undergo collapse or exhibit fractures.
Figure 5.c depicts the safety factor, defined as the ratio of tensile strength to the applied load. The component exhibits a nearly uniform coloration, indicative of a well-balanced design.

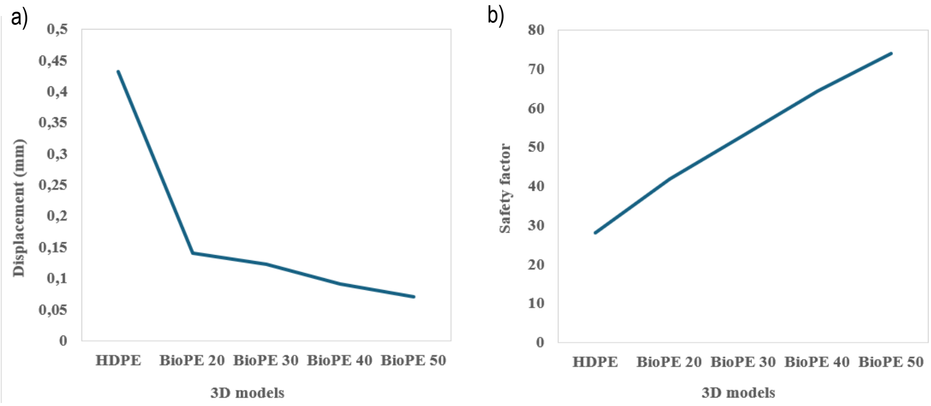


Fig. 6.a) Evolution of the maximum displacement and b) the safety factor withstood by the different 3D models of drawer made of HDPE and BioPE-based reinforced of abaca composite ranging different contents of Abaca (Source: own work)

The HDPE drawer model showed a displacement of 0.432 mm. In the case of the BioPE-based composites reinforced with abaca, displacements at the center of the drawer ranged from 0.141 to 0.071 mm, with abaca content ranging from 20 wt% to 50 wt%, respectively.
Figure 6.a shows a discernible trend of decreasing displacement with increasing the abaca content in the composite, emphasizing a reduction in deformation compared to the drawer made of HDPE.
The HDPE drawer model showed a safety factor of 28.1. The safety coefficient, representing the ratio of applied load to maximum load capacity, of the BioPE-based composites reinforced with abaca varied from 41.8 to 73.9.
Figure 6.b illustrates a shift in the safety factor when comparing HDPE and bio-composite drawers, with varying abaca fiber contents. It indicates the enhancement of the safety factor regarding an HDPE drawer. The safety factor reaches its maximum value with the highest content of abaca.

The design and development procedure of a drawer constructed from the bio-composite materials emphasizes the increased value and practical feasibility of such materials, while also highlighting the extent to which they can vary in terms of application potential. The authors consider that this application of a drawer could be extended to other elements subjected to similar stresses, such as trays for stationary, shelves, tables, and more.

4.- CONCLUSIONS

Composite materials consisting of a BioPE matrix reinforced with abaca strands were formulated, fabricated, and subjected to testing with variations in composition.

A case study involving the analysis of an industrial drawer was conducted. The study focused on an original part fabricated using HDPE. The part underwent testing under normal conditions. Finite Element Analysis was employed for this investigation. The analysis revealed that BioPE-based matrix reinforced with abaca strands, with different contents of fiber ranging from 20 wt% to 50 wt%, provided safety factors and maximum deformations higher to those of the original component.

From a mechanical point of view the bio-based composites showed fitted to replace an HDPE industrial application as the studied case.

Future analysis should include production costs and potential market pricing in order to compare the product being studied with existing commercial products, as well as a comprehensive Life Cycle Analysis.

REFERENCES

[1] A. K. Mohanty, M. Misra, and L. T. Drzal, “Sustainable Bio-composites from Renewable Resources: Opportunities and Challenges in the Green Materials World,” in *Renewable Energy*, 1st ed., B. Sørensen, M. A. Green, P. Lund, A. Luque, I. MacGill, P. Meibom, N. I. Meyer, W. Patterson, S. L. Pedersen, A. Rabl, H. Tsuchiya, and G. Watt, Eds., Routledge, 2018, pp. 396–409. doi: 10.4324/9781315793245-107.

[2] S. Richter, K. Stromann, and J. Müssig, “Abacá (Musa textilis) grades and their properties—A study of reproducible fibre characterization and a critical evaluation of existing grading systems,” *Industrial Crops and Products*, vol. 42, pp. 601–612, Mar. 2013, doi: 10.1016/j.indcrop.2012.06.025.

[3] W. Shahri, I. Tahir, and B. Ahad, “Abaca fiber: a renewable bio-resource for industrial uses and other applications,” *Biomass and Bioenergy: Processing and Properties*, pp. 47–61, 2014.

[4] B. J. D. Barba, J. F. Madrid, and D. P. Penaloza Jr., “A REVIEW OF ABACA FIBER-REINFORCED POLYMER COMPOSITES: DIFFERENT MODES OF PREPARATION AND THEIR APPLICATIONS,” *J. Chil. Chem. Soc.*, vol. 65, no. 3, pp. 4919–4924, Sep. 2020, doi: 10.4067/s0717-97072020000204919.

[5] R. A. Kurien *et al.*, “A comprehensive review on the mechanical, physical, and thermal properties of abaca fibre for their introduction into structural polymer composites,” *Cellulose*, vol. 30, no. 14, pp. 8643–8664, Sep. 2023, doi: 10.1007/s10570-023-05441-z.

[6] K. Van De Velde and P. Kiekens, “Biopolymers: overview of several properties and consequences on their applications,” *Polymer Testing*, vol. 21, no. 4, pp. 433–442, 2002, doi: 10.1016/S0142-9418(01)00107-6.

[7] S. S. Ali *et al.*, “Bioplastic production in terms of life cycle assessment: A state-of-the-art review,” *Environmental Science and Ecotechnology*, vol. 15, p. 100254, Jul. 2023, doi: 10.1016/j.ese.2023.100254.

[8] V. Siracusa and I. Blanco, “Bio-Polyethylene (Bio-PE), Bio-Polypropylene (Bio-PP) and Bio-Poly(ethylene terephthalate) (Bio-PET): Recent Developments in Bio-Based Polymers Analogous to Petroleum-Derived Ones for Packaging and Engineering Applications,” *Polymers*, vol. 12, no. 8, p. 1641, Jul. 2020, doi: 10.3390/polym12081641.

[9] I. Ansola Arizmendiarrieta *et al.*, “A NEW MANUFACTURING PROCESS OF STRUCTURAL AERONAUTICAL STRINGERS FROM STRAIGHT STRINGERS USING AN ADAPTATIVE MOULD,” *DYNAII*, vol. 95, no. 1, pp. 144–148, Mar. 2020, doi: 10.6036/9386.

[10] P. Villanueva Llaurado, A. Cortez Flores, and J. Fernandez Gomez, “EFECTIVENESS OF ANCHORS FOR STRUCTURAL RETROFITTING WITH COMPOSITE MATERIALS OF POLYMERIC AND CEMENTITIOUS MATRICES,” *DYNAII*, vol. 95, no. 1, pp. 187–191, Mar. 2020, doi: 10.6036/9242.

[11] U. Nirmal, J. Hashim, and M. M. H. Megat Ahmad, “A review on tribological performance of natural fibre polymeric composites,” *Tribology International*, vol. 83, pp. 77–104, Mar. 2015, doi: 10.1016/j.triboint.2014.11.003.

[12] C. E. Okafor, “Review of natural fiber composite design for sustainable infrastructural development,” *University-Led Knowledge and Innovation for Sustainable Development*, vol. 64, 2021.

[13] M. R. Mansor, M. S. Salit, E. S. Zainudin, N. A. Aziz, and H. Ariff, “Life Cycle Assessment of Natural Fiber Polymer Composites,” in *Agricultural Biomass Based Potential Materials*, K. R. Hakeem, M. Jawaid, and O. Y. Alothman, Eds., Cham: Springer International Publishing, 2015, pp. 121–141. doi: 10.1007/978-3-319-13847-3_6.

[14] C. Zhou, S. Q. Shi, Z. Chen, L. Cai, and L. Smith, “Comparative environmental life cycle assessment of fiber reinforced cement panel between kenaf and glass fibers,” *Journal of Cleaner Production*, vol. 200, pp. 196–204, Nov. 2018, doi: 10.1016/j.jclepro.2018.07.200.

[15] T. Corbière-Nicollier, B. Gfeller Laban, L. Lundquist, Y. Leterrier, J.-A. E. Månson, and O. Jolliet, “Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics,” *Resources, Conservation and Recycling*, vol. 33, no. 4, pp. 267–287, Nov. 2001, doi: 10.1016/S0921-3449(01)00089-1.

[16] L. J. Rodríguez, C. E. Orrego, I. Ribeiro, and P. Peças, “Life-Cycle Assessment and Life-Cycle Cost study of Banana (Musa sapientum) fiber Biocomposite materials,” *Procedia CIRP*, vol. 69, pp. 585–590, 2018, doi: 10.1016/j.procir.2017.11.145.

[17] D. Ferrandez Vega, P. Saiz Martinez, C. Moron Fernandez, and E. Atanes Sanchez, “COMPARATIVE ANALYSIS OF FIBRE-REINFORCED PLASTERS FOR THE PRODUCTION OF PRECAST ELEMENTS,” *DYNAII*, vol. 95, no. 1, pp. 333–338, May 2020, doi: 10.6036/9576.

[18] S. V. Joshi, L. T. Drzal, A. K. Mohanty, and S. Arora, “Are natural fiber composites environmentally superior to glass fiber reinforced composites?,” *Composites Part A: Applied Science and Manufacturing*, vol. 35, no. 3, pp. 371–376, Mar. 2004, doi: 10.1016/j.compositesa.2003.09.016.

[19] A. Gholampour and T. Ozbakkaloglu, “A review of natural fiber composites: properties, modification and processing techniques, characterization, applications,” *J Mater Sci*, vol. 55, no. 3, pp. 829–892, Jan. 2020, doi: 10.1007/s10853-019-03990-y.

[20] F. Seculi, F. X. Espinach, F. Julián, M. Delgado-Aguilar, P. Mutjé, and Q. Tarrés, “Evaluation of the Strength of the Interface for Abaca Fiber Reinforced Hdpe and Biope Composite Materials, and Its Influence over Tensile Properties,” *Polymers*, vol. 14, no. 24, p. 5412, Dec. 2022, doi: 10.3390/polym14245412.

[21] F. Seculi, F. X. Espinach, F. Julián, M. Delgado-Aguilar, P. Mutjé, and Q. Tarrés, “Comparative Evaluation of the Stiffness of Abaca-Fiber-Reinforced Bio-Polyethylene and High Density Polyethylene Composites,” *Polymers*, vol. 15, no. 5, p. 1096, Feb. 2023, doi: 10.3390/polym15051096.

[22] F. Seculi, F. X. Espinach, F. Julián, M. Delgado-Aguilar, P. Mutjé, and Q. Tarrés, “Evaluation of the Interface Strength in the Abaca-Fiber-Reinforced Bio-Polyethylene Composites,” *Polymers*, vol. 15, no. 12, p. 2686, Jun. 2023, doi: 10.3390/polym15122686.

[23] F. Seculi, F. Julián, J. Llorens, F. X. Espinach, P. Mutjé, and Q. Tarrés, “Methodologies to Evaluate the Micromechanics Flexural Strength Properties of Natural-Fiber-Reinforced Composites: The Case of Abaca-Fiber-Reinforced Bio Polyethylene Composites,” *Polymers*, vol. 15, no. 14, p. 3137, Jul. 2023, doi: 10.3390/polym15143137.

[24] F. Julián, F. X. Espinach, N. Verdaguer, M. A. Pèlach, and F. Vilaseca, “Design and Development of Fully Biodegradable Products from Starch Biopolymer and Corn Stalk Fibres,” *J Biobased Mat Bioenergy*, vol. 6, no. 4, pp. 410–417, Aug. 2012, doi: 10.1166/jbmb.2012.1228.

[25] D. Romanzini, A. Lavoratti, H. L. Ornaghi, S. C. Amico, and A. J. Zattera, “Influence of fiber content on the mechanical and dynamic mechanical properties of glass/ramie polymer composites,” *Materials & Design*, vol. 47, pp. 9–15, May 2013, doi: 10.1016/j.matdes.2012.12.029.

[26] A. Serrano, F. X. Espinach, J. Tresserras, N. Pellicer, M. Alcala, and P. Mutje, “Study on the technical feasibility of replacing glass fibers by old newspaper recycled fibers as polypropylene reinforcement,” *Journal of Cleaner Production*, vol. 65, pp. 489–496, Feb. 2014, doi: 10.1016/j.jclepro.2013.10.003.

[27] M. R. M. Asyraf *et al.*, “Product Development of Natural Fibre-Composites for Various Applications: Design for Sustainability,” *Polymers*, vol. 14, no. 5, p. 920, Feb. 2022, doi: 10.3390/polym14050920.

[28] R. Blok, J. Smits, R. Gkaidatzis, and P. Teuffel, “Bio-Based Composite Footbridge: Design, Production and *In Situ* Monitoring,” *Structural Engineering International*, vol. 29, no. 3, pp. 453–465, Jul. 2019, doi: 10.1080/10168664.2019.1608137.

[29] C. Zechmeister, M. Gil Pérez, N. Dambrosio, J. Knippers, and A. Menges, “Extension of Computational Co-Design Methods for Modular, Prefabricated Composite Building Components Using Bio-Based Material Systems,” *Sustainability*, vol. 15, no. 16, p. 12189, Aug. 2023, doi: 10.3390/su151612189.

[30] M. Alhijazi, Q. Zeeshan, Z. Qin, B. Safaei, and M. Asmael, “Finite element analysis of natural fibers composites: A review,” *Nanotechnology Reviews*, vol. 9, no. 1, pp. 853–875, Sep. 2020, doi: 10.1515/ntrev-2020-0069.