LOGO

Development of bioinspired structure with impact absorption capability: a study of case

Desenvolvimento de estrutura bioinspirada com capacidade de absorção de impacto: um estudo de caso

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ABSTRACT

The development of new materials is crucial for the advancement of engineering, architecture, and design fields. This is because new materials can offer significant benefits compared to traditional materials in terms of their structural, physical, and chemical properties. In architecture and design, new materials can be used to create more durable, sustainable, aesthetically pleasing, lightweight, and resilient products. Through biomimicry, this study conducted an analysis on the structures of four tropical fruits - orange, passion fruit, cocoa, and pomegranate - to generate a new structure with damping and energy dissipation properties, aided by scanning electron microscopy (SEM), computerized microtomography (Micro-CT), and computerized three-dimensional reconstruction. As a result, a bioinspired structure was developed based on the arrangements of cell walls found in the albedo (mesocarp) of the orange - Citrus sinensis. Using this developed structure, computational tests were performed and a resin prototype was created through digital fabrication. Therefore, the development of bioinspired materials for improved impact absorption and damping is important as it can enhance the safety and effectiveness of a wide range of products, from sports equipment to medical devices, while also contributing to sustainability and energy efficiency, which are significant interests in various fields of knowledge.

KEYWORDS

Biomimetics; Bioinspired; Hierarchical Structures; Fruits; Prototyping

RESUMO

O desenvolvimento de novos materiais é crucial para o avanço dos campos da engenharia, arquitetura e design. Isso ocorre porque novos materiais podem oferecer benefícios significativos em comparação aos materiais tradicionais em termos de suas propriedades estruturais, físicas e químicas. Na arquitetura e design, novos materiais podem ser usados para criar produtos mais duráveis, sustentáveis, esteticamente agradáveis, leves e resilientes. Através da biomimética, este estudo realizou uma análise das estruturas de quatro frutas tropicais - laranja, maracujá, cacau e romã - para gerar uma nova estrutura com propriedades de amortecimento e dissipação de energia, utilizando microscopia

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eletrônica de varredura (MEV), microtomografia computadorizada (Micro-CT) e reconstrução tridimensional computadorizada. Como resultado, uma estrutura bioinspirada foi desenvolvida com base nos arranjos das paredes celulares encontradas no albedo (mesocarpo) da laranja - Citrus sinensis. Utilizando essa estrutura desenvolvida, foram realizados testes computacionais e um protótipo de resina foi criado por meio de fabricação digital. Portanto, o desenvolvimento de materiais bioinspirados para melhor absorção de impacto e amortecimento é importante, pois pode melhorar a segurança e a eficácia de uma ampla gama de produtos, desde equipamentos esportivos até dispositivos médicos, ao mesmo tempo em que contribui para a sustentabilidade e eficiência energética, que são interesses significativos em diversos campos do conhecimento.

PALAVRAS-CHAVE

Biomimética; Bioinspirado; Estruturas Hierárquicas; Frutas; Prototipagem

1 INTRODUCTION

The development of bioinspired materials for improved impact absorption and damping is important because it can lead to the creation of safer, more durable, and effective products. Bioinspired materials are those that mimic the structure or properties of materials found in nature and can be found in various applications, ranging from the production of athletic footwear to the manufacturing of personal protective equipment. Nature provides a wide range of examples of materials that are highly effective in impact absorption and damping. For instance, the shells of snails, eggshells, the skin of certain animals, and fruit and seed husks possess structures that are highly resistant to impacts and can serve as inspiration for the development of new materials.

By imitating these natural structures, bioinspired materials can provide several benefits compared to conventional materials, such as increased impact resistance, improved shock absorption capacity, enhanced durability, and reduced weight. This can be especially important in applications where safety is a critical concern, such as in the manufacturing of personal protective equipment, sports equipment, or medical devices, as well as in the aerospace, automotive, and space industries. Therefore, the development of bioinspired materials for improved impact absorption and damping is important because it can help enhance the safety and effectiveness of a wide range of products.

The study conducted by Wang et al. (2018) aimed to investigate the morphology and distribution of internal stresses in the peel of pomelo fruit. To achieve this, the researchers utilized X-ray computed tomography and digital volume correlation to map the internal stresses during the loading process. The results revealed that the pomelo peel possesses a highly porous cellular structure and a heterogeneous distribution of internal stresses, with higher stress concentrations observed in the junction regions between cells. Furthermore, a morphological evolution of the peel was observed during the loading process, with greater deformation occurring in regions where the cells are more elongated.

Zhang et al. (2016) aimed to develop a numerical model to analyze the damping response of bioinspired foams based on the structure of pomelo fruit. Through mechanical tests, the researchers determined the mechanical and damping properties of the bioinspired foams and compared them with pomelo fruit. The numerical model developed by the researchers considered the porous structure of the bioinspired foam, as well as the mechanical and damping properties of the constituent

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materials. The results indicated that the bioinspired foam exhibited a damping response similar to that of pomelo fruit, with a good energy dissipation capacity. The researchers concluded that the structure of pomelo fruit could serve as inspiration for the development of bioinspired materials with damping and energy dissipation properties. Additionally, the developed numerical model could be a useful tool for the design and optimization of bioinspired materials with these properties.

Thus, the study of the morphology and internal stresses in pomelo peel provided valuable insights for the development of a structure with damping and energy dissipation properties. Furthermore, the results highlight the importance of analyzing the morphology and internal stresses in porous materials for understanding their mechanical behavior.

2. METHODOLOGICAL PROCEDURES

Following in fig.01 is the developed framework and its respective methodological steps and tools for the development of this study. A literature review and grouping of results in the bioinspired structure highlights the potential of employing biological principles in industrial organization (OLIVEIRA, 2021). It also demonstrates that the present research mainly focuses on a qualitative description of biological entities and related biomimetic solution concepts, which can provide assistance for implementation in new product development scenarios.

The field of algorithms, where exact biological models have been constructed and applied in practice. Thus, the framework provides different possibilities for future research initiatives. Limitations may include the inability or inefficiency to bring any biomimetic technique to the level of application. However, there may be lessons to be learned from these biomimetic ideas for future case studies. Analyzing the tangible results of the framework, a major question for the future will be the use of biomimetic algorithms in everyday manufacturing, despite several studies already conducted in this field. Additionally, there are a number of production problems that have yet to be solved. As a result, seeking answers in biology would be a potential method.

The use of parametric design, in relation to transferring the structure to a new application, is still in its early stages, as the results generated by polygonal modeling software use a type of solution with generalized applications and indicate general characteristics for a specific application of a solution. For this reason, it can be a technique that defines a structured approach to achieve a certain goal or an algorithm that

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simulates a biological phenomenon to deal with engineering, architecture, and design cases. As mentioned earlier, one of the most predominant techniques is the implementation of algorithms, as they have the benefit of having a specific scope of application and capabilities, which assists in the transfer to other applications. However, they are generic abstractions derived from software or approximate abstractions generated from concept similarity. This research demonstrates the use and abstraction of biological inspiration and its exact replication using 7 steps for the replication and application of the bioinspired structure.

01- Input: The initial entry point of the unified biomimetic process model is the analysis of the problem. This can involve evaluating the situation and/or describing the problem, whether it is an unidentified problem or a specific problem to be solved.

02- Biological identification and understanding strategies principles: In this stage, a biological entity is identified. Identifying biological models can lead to a deeper understanding of the initial problem or, in the case of an already identified concrete problem, the description of the problem provides a suitable formalization of the biological entity to be studied.

03- Biological entity selection: This stage involves identifying and describing the biological entity. The goal is to formalize the use of biological fields during biomimetic practices, starting with biology-centered steps. By searching for biological models, professionals generate a generic request: Which organisms perform a function and what is its purpose? This leads them to identify functional solution spaces for potential problems.

04- Abstraction detachment from biological model: Morphology is abstracted from the biological form. The use of scanning techniques using Micro-CT, followed by material analysis for selecting the area of interest and 3D reconstruction. Transposing biological strategies allows designers to incorporate the outlined biological principles according to technical functionalities. Such transposition often requires the available technological knowledge to act as an interpreter for the biological solution(s) and enable their implementation in the technical world.

05- Technical implementation and prototyping: Based on the known uses and benefits of prototypes in design practice, the goal of

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this phase was to explore recent digital fabrication techniques for 3D prototyping and current biomimetics, as well as the abstraction, transfer, and collaboration between digital tools. The aim is to describe current practices that provide general guidance on how to leverage the known benefits of prototyping associated with the research problem for product development in a biomimetic design context.

06- Workshop: With workshops, there is an approximation between researchers and participants regarding the methodological approaches, tools, and collaboration. A general introduction to the topic is provided, followed by explanatory case studies conducted by the facilitator, where the tools are presented individually and implemented sequentially according to the presented process.

07- Results: Although the workshop addressed the same research problem, concepts were generated by all teams, leading to a better understanding of the addressed problem.

3 METHOD

The Biomimicry Thinking process is divided into four distinct areas: scope definition, discovery, creation, and evaluation. Inspired by the Biology for Design method and its specific steps, this methodology successfully integrates with the strategies and principles of life in the field of bioinspired design. The diagram representing the Biomimicry Thinking process consists of four main fields, corresponding to the steps of the process, as shown in Figure 02 below.

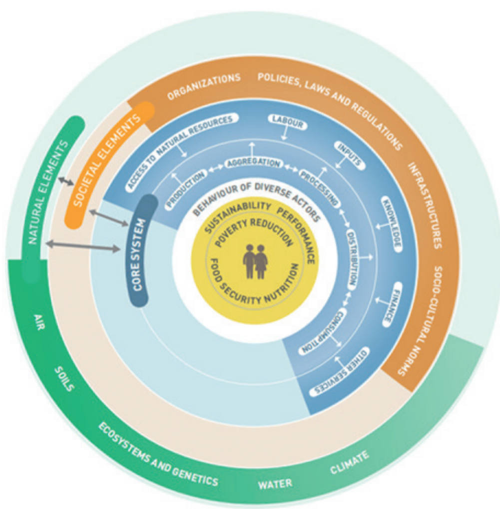

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Figure 1: Biomimicry thinking process. Source: (ROWLAND, 2017).

4 APPLICATIONS AND RESULTS

4.1 Input

Problem analysis, according to the product design methodology, is a systematic process of identifying and understanding the challenges, needs, and opportunities that users face when using a product or service. This analysis involves collecting relevant data, analyzing and interpreting that data, and defining a central problem to be solved. During problem analysis, it is common to use techniques such as user interviews, behavior observation, market research, and analysis of quantitative data to gather relevant information. This data is then analyzed and interpreted to identify patterns and insights that help define the central problem to be solved.

Action research is an exploratory research method in which the researcher/observer has direct involvement with the research object. Action research can be classified as collaborative, critical, and strategic.

ETAPAS	DESCRIÇÃO	OBJETIVO
1. 1. Systematic Literature Review (SLR)	Review of the main constructs and expanding the understanding of assumptions for the suitability of the action research method.	A literature review on fruits with natural characteristics for dissipation and absorption of mechanical shocks.
2. Exploratory Phase	The objective was to determine the research field, expectations, and the type of assistance that the group of experts could provide throughout the research process	An exploratory research characterized by direct involvement of the researcher with the research object.
3. Problem definition	Clear exposition of the problem, as well as its assumptions/premises.	To accurately define the problem to be addressed in a practical manner.

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ETAPAS	DESCRIÇÃO	OBJETIVO
4. Collaborative planning	Meeting with team members and interested researchers to define selection criteria. During this phase, the fruits with the observed characteristics were selected.	Selection of fruits for observation under optical microscopy.
5. Data collection protocol	Data collection tools protocol and application criteria.	Samples of the selected fruits were collected at the Center for Supply and Logistics of Pernambuco - CEASA/PE.
6. Data collection	Field research for direct observation of fruit structures.	Direct observation under optical microscopy conducted at the Plant Anatomy Laboratory (LAVeg - UFPE).
7. Reflection/ Results	The learning during the investigation process for categorizing, coding, and tabulating the data obtained in the action research.	Aprendizagem, discussão e resultados para norteamento da pesquisa e aferição das conclusões.

Table 1. Source: developed by the authors.

4.2 Exploratory Phase

Optical Microscopy: The analysis of plant anatomy aims to prepare samples for studies under light microscopy. Typically, the examination is conducted using transmitted light, which requires the light to pass through the object being examined. For this purpose, it is necessary to obtain fragments of plant tissue that will be collected on very thin and transparent slides (RUZIN, 1999).

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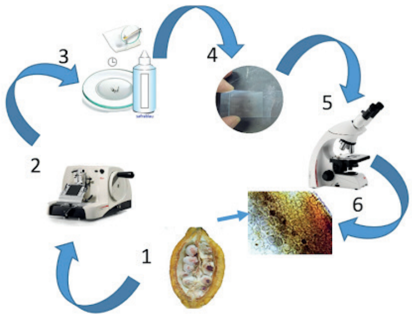


Figure 2: Stages of preparation for optical microscopy, LAVeg - UFPE. Source: Authors' own work.

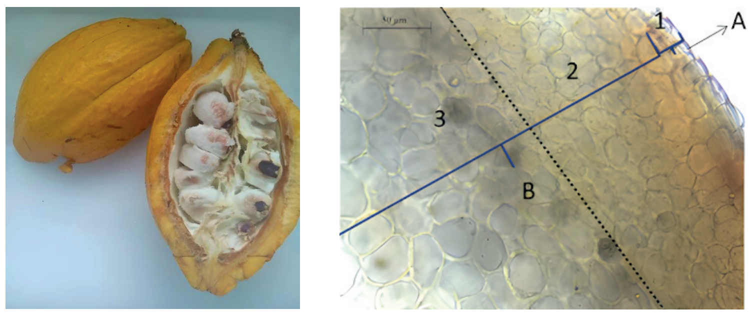
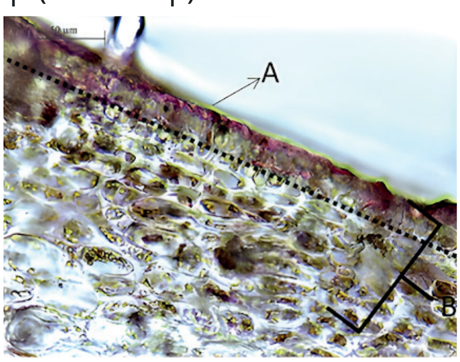


Figure 3: Anatomy of the cocoa pericarp, performed at LAVeg - UFPE. Source: Authors' own work.

The captions of the images represent: (A) Epicarp with a layer of cells. (B) Mesocarp with two cell layers: an outer collenchyma layer and an inner parenchyma layer. Cocoa is considered an Amphicarpic fruit - a fruit of placental origin, with a fleshy pericarp, a central cavity without individualized locules, and filled with seeds surrounded by succulent pulp (endocarp).



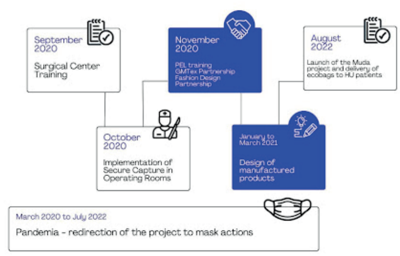


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Figure 4: Anatomy of the breadfruit pericarp, conducted at LAVeg - UFPE. Source: authors' own work.

Fonte: acervo do Projeto Muda (2020).

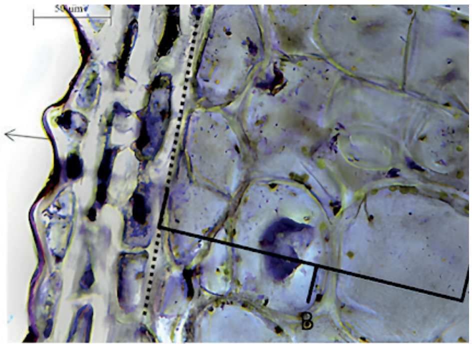

Figure 5: Anatomy of the dragon fruit pericarp, conducted at LAVeg - UFPE. Source: authors' own work.

The captions represent: (A) Epicarp with a layer of cells. (B) Mesocarp with two cell layers: an outer collenchyma layer and an inner parenchyma layer.

According to the study, it was possible to characterize the biological elements after identifying those with the best characteristics for the development of a bioinspired structure, which is part of the abstraction phase of biological strategies for design principles. This phase involved searching for an application area for energy dissipation structures. This scanning electron microscopy study was conducted on four fruits: cocoa (Theobroma cacao L.), passion fruit (Passiflora sp), orange (Citrus), and pomegranate (Punica granatum). The fruits were selected using the Delphi method after analyzing their anatomy through conventional optical microscopy. Two fruits (breadfruit and dragon fruit) were excluded from this research as they did not possess the required characteristics for this study. Consequently, two additional fruits, orange and pomegranate, were included, forming two groups. The first group consisted of orange and passion fruit, while the second group consisted of cocoa and pomegranate for this new analysis.

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Figure 6: Fruits selected for SEM. Source: authors' own work.

The sections of the plant samples were performed using the Leica CM 1850® cryostat for low-temperature preservation. The instrument is designed for rapid freezing and cutting of tissue samples. The fragments were sectioned at 50 micrometers with longitudinal cutting orientation. The sections were then placed on pre-labeled slides and stored in designated boxes in a freezer at -26°C for fixation.

SEM Sample 01 - Orange - Citrus sinensis

Figure 7: Exocarp and outer mesocarp of Citrus. Source: developed by the authors in collaboration with ESALQ.

Citrus is anatomically divided into three distinct layers. However, the endocarp or pulp, not represented in Figure 8, does not correspond to the area of interest in this study. The flavedo or exocarp (Ex) is highlighted in the outermost part, which includes the cuticle (Cu), epidermis, and hypodermis that contain the oil glands (OG), which vary in number and size according to the citrus species and variety. In the inner part of the peel, it is called albedo or mesocarp (M).

Sample SEM 02 - Passionfruit - Passiflora edulis

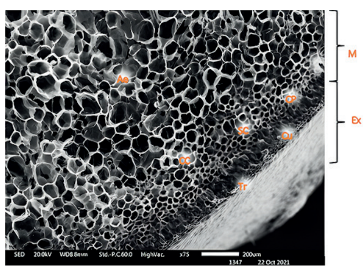

Figure 8: Exocarp and outer mesocarp of Passiflora edulis. Source: developed by the authors in collaboration with ESALQ.

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The sclerenchyma layer is located in the middle zone of the mesocarp. The pericarp has a peripheral sclerenchyma zone, while the inner zone of the mesocarp and endocarp are parenchymatous. (CM) mucilaginous cavity.

Sample SEM 04 - Pomegranate - Punica granatum

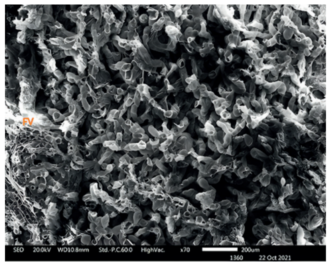

Figure 9: Exocarp and outer mesocarp of Punica granatum.
Source: authors' work in collaboration with ESALQ.

Microscopic observations in this study showed that there is a layer of cuticle (Cu) on the external surface (pericarps) of pomegranate fruit peel, followed by epidermal cells organized in a layer immediately below the cuticle. It was found that sclerenchyma cells and vascular bundles were present among the parenchyma cells located beneath the epidermal cells.

5. RESULTS ANALYSIS OR DISCUSSIONS

Scanning procedures were performed on the four fruits: cocoa, orange, passion fruit, and pomegranate. Through the scanning analyses, the research focus was narrowed down, and the orange (Citrus sinensis) was selected for analysis using specialized software for industrial computed tomography (CT) scanning. Specific modules were chosen for the study, resulting in the creation phase with 3D reconstruction, surface determination, and material analysis. Subsequently, in the evaluation phase, the structure was investigated using the 3D porosity analysis module.

This research stage was developed in collaboration with DEN-UFPE (Department of Nuclear Energy) in January 2022. The XT H 225 ST was used for capturing X-ray Computed Microtomography (Micro-CT) images and detailed measurements of internal components necessary for 3D reconstruction, failure analysis, and materials research. The XT H 225

ST features a microfocus X-ray source, an inspection volume suitable for small to medium-sized parts, and high image resolution. X-rays are generated between a tungsten filament (cathode) and a tungsten target (anode) under applied voltage to the X-ray tube of up to 225kV and a maximum electrical current of 2 mA.

Figure 10: Left: Industrial CT Scanning - XT H 225 ST. Right: Internal view of XT H 225 ST with Citrus sample. Source: developed by the authors in collaboration with DEN.

Computed tomography is commonly used to visualize the internal structure of complex industrial parts. However, in this study, it was employed for non-invasive observation of plant samples. Micro-CT was used to quantify the internal and external dimensions of the plant samples in a smooth, fast, and non-destructive manner. Although the procedure was performed non-invasively, scanning had to be done in smaller pieces to obtain a more precise resolution of the internal structures of the fruits. The figure below shows X-ray images of both pieces and whole fruits of the samples.

Tension and current tests were conducted on some fruits to determine material densities and quantities of liquids present in the samples, as the scans were obtained with the fruits in their natural state. In some fruits, lower voltage provided better visualization for reconstruction. All scans were performed without the use of additional physical filters.

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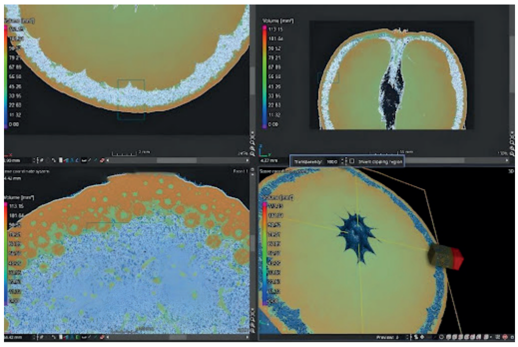

Figure 11: Surface and material determination. Source: developed by the authors in collaboration with DEN.

Surface and material determination was performed with the assistance of VGStudio Max software, in which a region of interest (RoI) was created based on the observed SEM images. The region is located in the middle mesocarp, which corresponds to the white part of the pericarp known as the albedo. Scanning was conducted on both the whole fruit and a 5x5 mm piece, as shown in Figure 5, to increase the pixel size and achieve higher resolution in the CT reconstruction through voxel size adjustment.

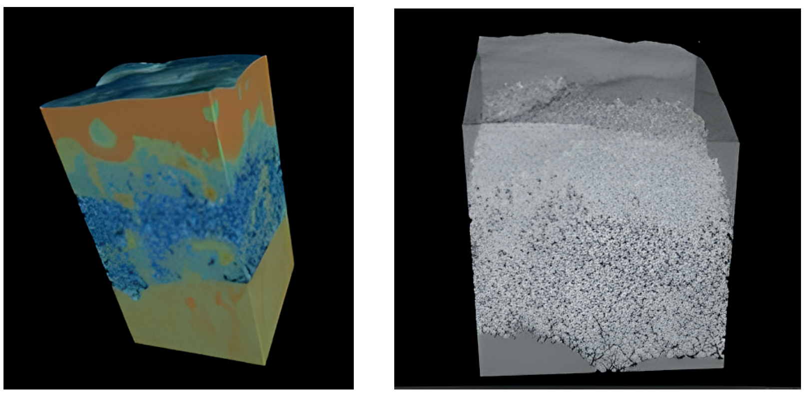

Figure 12: Left: Materials analysis. Right: Selection of the area of interest mesh. Source: Authors' own work.

Metrology based on computed tomography relies on precise surface determination in the voxel model. The better the surface determination, the lower the measurement uncertainty. Surface determination provides a multimaterial mode, allowing for the simultaneous determination of multiple material surfaces within a volume, resulting in a component per material.

Tetrahedral meshes can be exported for Finite Element Method (FEM) simulation in another software to create integration meshes. This allowed the conversion of a set of monomaterial volume data (2D images) of plant samples into a tetrahedral mesh.

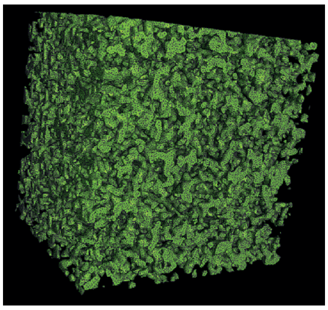

Figure 13: Volume mesh generated in VGstudio max. Source: elaborated by the authors.

PHASE 4 - Evaluating

Computed tomography allows for non-destructive testing of parts. The study of simple cross-sectional views allows for the detection of existing pores and inclusions of other materials. Below, in Fig. 14, a spatial cutout in a cubic shape is observed to delimit the area of interest, which exhibits a hierarchical structure and spaces between cells that serve as an energy absorption strategy. In Fig. 14, there is an analysis of the structure's porosity, obtained from the mesh, which corresponds to approximately 44% porosity through 3D Porosity Analysis, recognizing and characterizing porosity in three dimensions.

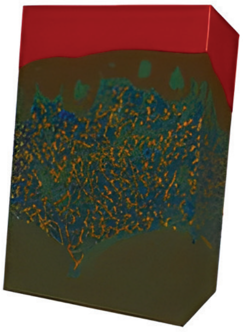

Figure 14: Porosity analysis. Source: elaborated by the authors.

Prototyping of the bioinspired structure through digital fabrication:

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In this stage, alternative structures based on the studied fruits are generated. These structures are derived from the biological entity studied to optimize the material used (volumetrics) and energy absorption of the generated structure. They will be evaluated using physical simulation software through mathematical calculations in the next phase of the research.

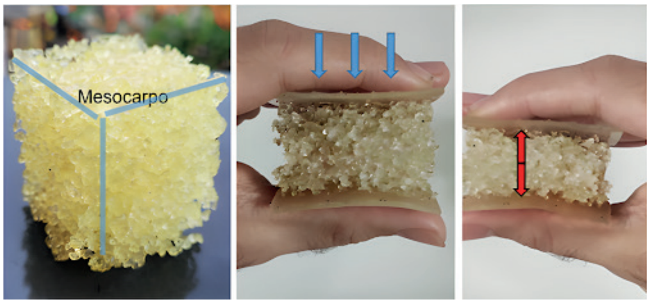

Figure 15: (a) Bioinspired structure, (b) Compression stress, (c) Displacement. Source: Authors' own work.

In this study, combining X-ray microtomography imaging technique and digital fabrication enabled the prototyping of a structure abstracted through the observation and implications of its structure in the natural world. After printing the structure with the physical model, a better compacting relationship of the structure for energy absorption under tension was observed in the axial direction (from exocarp to mesocarp), as shown in Figure 16. The presence of elastic energy in the structure was also verified when it was subjected to tension through empirical investigation by the authors.

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6 CONCLUSION

Nature is incredibly diverse and offers an seemingly “infinite” range of possibilities for the development of innovative products and materials. This statement applies to biomimetic materials that span from micro and nanoscale dimensions to molecular-level studies. By exploring nature, it is possible to identify principles that can be systematically interpreted and applied in the development of bioinspired projects. These principles can be creatively and innovatively applied to solve design problems. The observation of cellular microstructures serves as a source of inspiration for creating innovative materials and forms in the development of new products. The characterization of these cellular-level structures, along with the mechanical properties found in these natural materials, can help understand the morphology-related characteristics and guide structural optimization in industrial design projects.

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Curriculum Summary: She holds a bachelor's degree in Biological Sciences from the Federal University of Pernambuco (2003), a master's degree (2005), and a Ph.D. (2010) in Biological Sciences (Botany) from the University of São Paulo. She currently holds the position of Associate Professor 2 in the Department of Botany at the Federal University of Pernambuco. She has experience in the field of plant anatomy and morphology, including topics such as: Anatomical studies and areolar development and their taxonomic and phylogenetic implications for the Cactaceae family (Caryophyllales); Ecological anatomy of species in the Caatinga and Mangrove ecosystems; Environmental impact assessment through species occurring in impacted environments (terrestrial and aquatic); Pollution effects on plants; Secretory structures.

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