

Biomimetics as a strategy for the development of bio- inspired structures for energy absorption based on fruits

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Abstract: This review seeks to update our knowledge about fruits, their structures, their materials for development of bio-inspired products, and their respective applications involving energy absorption, and shock dissipation. In nature, we will find a multitude of biological structures that perform the function of protection and crashworthiness. This study focuses on one of the biologically most important functions found in the natural packaging—that consists of the direct or indirect protection against mechanical damage or other negative environmental influences that involving crashworthiness—as well as energy absorption. Through of the systematic literature review, which includes all peer-reviewed research, documents that are relevant to the objective to ensure a comprehensive search were selected 21 research studies. Three research databases were identified: (I) web of Science, (II) Scopus, and (III) Science Direct. Only primary empirical studies were included. The review identified several situations where Biomimetics and Bio-inspiration methodology are introduced for improvements and solving technological problems by analyzing, abstracting, adapting, and transposing biological principles, into the technical world. The results indicated that the structures based on fruits could improve the structure's efficiency that has the role of providing an effective bio-inspired absorber for a multitude of product designs. Although there are several studies, more research is needed for use of new technologies and new settings to ensure recommendations that can implement the improvement of the development of design bio-inspired.

Keywords: Biomimetics - Bio-inspired structures - Fruits - Natural packaging - Energy absorption - Crashworthiness

[Abstracts in spanish and portuguese at pages 205-206]

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1. Introduction

In recent years, Biomimetics has been increasingly used in the field of applied research for the development of new products and materials. With high potential for innovation and great possibility to offer new bio-inspired products and sustainable production chains (Speck *et al.*, 2018). Technological advancement brought enormous possibilities, mainly in the field of design, for the development of new techniques and devices that are linked to the potential of new materials, interaction, human factors, perception, cognition and user experience. This progress brought about profound consequences in the many fields of the sciences, be it on the intellectual field or the practical (Oliveira & Arruda, 2019).

Over millions of years, nature has been developing high performance materials and structures. As such, it provides valuable sources of inspiration for the design of structural materials for improvement or development of new products, given the variety of excellent properties found in nature. In order to improve traditional materials and structures for energy absorption, scientists, engineers and designers try to learn from biological organisms with resilient structures that have evolved optimally over generations (San Ha *et al.*, 2019).

Learning from concepts found in nature together with design principles is driving a paradigm shift in science, technology, and new materials. Thus, natural biology offers excellent structures with remarkable absorptive capacity, energy dissipation, and high impact resistance. However, we are not always able to faithfully develop the structures found in nature due to the limitations of traditional design and manufacturing technologies, thus impeding the progress of biomimetic study and advances in prototyping and testing of new models. However, according to (Yang *et al.*, 2018) advances in additive manufacturing have created new opportunities to manipulate and mimic nature's inherently multi-scale, multi-material, and multifunctional structures.

Biomimetics seeks to solve technological problems by observing, analyzing, adapting, and transposing biological principles to develop new bio-inspired materials that have evolved over 3.8 billion years and are employed as problem-solving strategies for the technical world (Benyus, 2002). These biological systems, found in nature, inspire studies and projects in diverse areas such as engineering and design. Among the various forms of collaboration between design and bioscience, Biomimetics is a discipline that proposes the transfer of biological quality and functionality to design artifacts. The study of these biological systems is an appropriate response to the respective challenges that present themselves as Design problems (Arruda *et al.*, 2019), (Langella, C., 2019).

Fruit shells, seed shells, as well as foams, lattices, usually perform a multitude of functions from storage to protection. The outer protective shells of nuts can have remarkable hardness and strength, which is usually achieved by a layered arrangement of cells and fibers with a polygonal shape, which perform a remarkable protective structure against impacts and bumps (Antreich *et al.*, 2019). The goal of Biomimetics is to analyze by exploiting the enormous reserve available in nature for the development of innovative solutions. However, there are several levels of abstractions and modifications that must be respected for a successful technical implementation of natural principles, encountering the question of how to produce these technical products (Bührig-Polaczek *et al.*, 2016).

These biological functions, which consist of direct or indirect protection against mechanical damage or other negative environmental influences, comprise principles, biological constructs, which will lead to the presentation of hierarchical structures as models for the development of new materials and components for protecting goods and/or people from damage caused, *for example*, by impacts due to improper handling or collisions. The functional study of these structures will allow the construction of new bio-inspired, lightweight, high-impact, puncture-resistant materials with a combination of high energy dissipation (Seidel *et al.*, 2010), (Sanchez *et al.*, 2015).

There are many biological organisms found in nature that perform a protective function or need to protect themselves against damage from mechanical loads. Biological mate-

rials such as found in the shells of fruits as well as in their seeds, such as pomelo, macadamia nuts, walnuts can exhibit high hardness and toughness as found in the Yucatan peninsula, Mexico, the fruit of the Cocoyol palm—*Acrocomia mexicana*. Coconuts perform excellent protection through their sophisticated hierarchical structure present in their fibers (Flores-Johnson, 2018). The structures of these composites generally have equivalent characteristics, as stated by (Zhao *et al.*, 2014), this combination of components and multi-scale arrangements provide valuable design principles for preparing inspiration for developing cushioning materials with broad applications in industry.

By observing nature, one can look for many structures with high energy absorption capacity, strength, low density that can inspire new designs with remarkable structures for impact absorption, as observed in the Pomelo fruit—*Citrus maxima* -which has a spongy mesocarp layer that can dissipate a large amount of energy- as shown in observed tests (Fisher *et al.*, 2010). Walnuts, like coconuts, also have a high impact resistance.

2. Research methods

2.1. Systematic Literature Review

The Systematic Literature Review (SLR) seeks to establish a rigorous procedure to bring about a revision of literature, to identify the available literature and analyze data as to obtain evidence of a certain phenomenon with a rigorous process in identification, evaluation, interpretation and relevance conducted in revision. It will be made according to the simplified model proposed by (Conforto *et al.*, 2011), which can be described in 15 steps and divided in 3 phases: Entry, Processing and Exit.

2.2. Research Question

The presented systematic literature review method was carried out by defining the following activities, according to (Roehrs *et al.*, 2017):

1. Research questions - introduce the research questions investigated
2. Search strategy - outline the strategy and libraries explored to collect data
3. Article selection - explain the criteria for selecting the studies
4. Distribution of studies - present how studies are distributed chronologically
5. Quality assessment - describe the quality assessment of the selected studies
6. Data extraction - compare the selected studies and research questions.

The following sections describe how this process of mapping the study was carried out. To better understand and structure the research, questions were developed to conduct this systematic review, which is one of the most important steps of the systematic review.

Therefore, it was sought to identify and classify the technology related to the object of study; the resources, problems, challenges, and solutions that are being considered; as well as the employed and emerging technologies. In this way it was defined in: General Question (GQ) and Specific Question (SQ).

(GQ1) How can the fruits contribute to development of new materials and structures for with better performance?

(GQ2) To which aspects found in the fruit have issues related to contributing to the development of bio-inspired design been attributed?

(SQ1) Which fruits have been studied for the development of structures to absorb impact?

(SQ2) Which structures were found in fruits that have characteristics to absorb impacts?

2.3. Method and Tools

Also, to definition inclusion and exclusion criteria was used to search string definition was defined using the terminology identified for PICOC framework (*See Table 1 and 2*) which stands for population, intervention, comparison, outcomes, and context can be useful to ensure that one decides on all key components prior to starting the review. During the planning phase, we used Parsifal tool to document the whole process, keywords and synonyms, and selecting the sources.

2.4. Eligibility Criteria

- Inclusion criteria:
 - IC 1: primary study presenting evidence of the use of structures found in fruits for bio-inspired products
 - IC 2: primary study that presents evidence of the contributions of Fruits for structures of absorption
 - IC 3: primary study that presents evidence of the use fruits to enhance the products design for crashworthiness
- Exclusion Criteria:
 - EC 1: Papers not written in English
 - EC 2: Papers that were published before 2010
 - EC 3: Papers that are duplicated within the search documents
 - EC4: Study that is not full paper
 - EC5: Papers that do not meet any of the inclusion criteria
 - EC6: Papers that are not primary research.
 - EC7: Primary study that not use fruits

Table 1
SLR search.

Database	Search string	Total	Rejected	Duplicated	Results
Scopus	ALL ("fruit" OR "fruit walls" OR "fruit peels" OR "seed shells" OR "fruit*") AND ALL ("bionic" OR "bio-inspired" OR "biomimicry" OR "biomimetic*" OR "bio-inspired" OR "bioinspiration") AND ALL ("foams" OR "lattices" OR "sandwich panels" OR "honeycomb" OR "Cellular material" OR "bio-inspired structures" OR "Structural hierarchy") AND ALL ("impact resistance" OR "energy absorption" OR "energy absorber" OR "crashworthiness" OR "shock dissipation"))	75	39	14	19
Science Direct	"bio-inspired" OR "biomimicry" OR "biomimetic*" OR "bio-inspired" OR "bioinspiration") AND ALL ("foams" OR "lattices" OR "sandwich panels" OR "honeycomb" OR "Cellular material" OR "bio-inspired structures" OR "Structural hierarchy") AND ALL ("impact resistance" OR "energy absorption" OR "energy absorber" OR "crashworthiness" OR "shock dissipation"))	8	4	3	1
Web of Science	OR "lattices" OR "sandwich panels" OR "honeycomb" OR "Cellular material" OR "bio-inspired structures" OR "Structural hierarchy") AND ALL ("impact resistance" OR "energy absorption" OR "energy absorber" OR "crashworthiness" OR "shock dissipation"))	4	0	3	1
Total results		91	43	24	21

Note. Search string delivery results classified by database.

Table 2
Research scope

Concept	Definition	SLR application
Population	The problem or situation the research is dealing with.	Fruits, fruit walls, fruit peels and seed shells for development and applications research: Biomimetics for energy absorber.
Intervention	Existing techniques utilised to address the problem identified.	Methods, tools and techniques for new technologies: Additive Technology Platforms.
Comparison	Techniques to contrast the intervention against.	Contrast between intervention techniques.
Outcome(s)	The measure to assess the effect of the techniques in the population.	Bio-inspired, Structural hierarchy.
Context	The particular settings or areas of the population.	Product Design.

Note. Obtained through the application of the PICOC framework.

3. Discussion and results

The aim of this paper is to discuss the state of the art as well as the energy absorbing characteristics found in fruits, as well as bio-inspired structures with different configurations. Through of the search string definition with the aid the PICOC framework our search the state of the art as well as the energy absorbing characteristics found in fruits, as well as bio-inspired structures with different configurations a set of 91 papers out of which 21 were selected as primary studies after qualitative assessment criteria, techniques, and improve safety (See Table 3).

Table 3*Empirical papers relating the fruits to Biomimetics studies for energy absorption.*

Fruits	Bio-inspired Structures	Result highlight	Authors
Natural Packaging		Energy absorption enhancement mechanisms	References
1. Pomelo (<i>Citrus maxima</i>)	<ul style="list-style-type: none"> • Foamy structure • Hierarchical structure 	<ul style="list-style-type: none"> • Foamy structure • Gradient foam • Hierarchical structure 	[1] (Fischer et al., 2010) [2] (Seidel et al., 2010) [3] (Fischer et al., 2013) [4] (Thielen et al., 2013) [4] (Looyrach et al., 2015) [6] (Ortiz et al., 2018) [7] (Wang et al., 2018) [8] (Wang et al., 2019) [9] (Li et al., 2019) [10] (Wen et al., 2019) [11] (Schäfer et al., 2020)
2. Coconut (<i>Cocos nucifera</i>)	<ul style="list-style-type: none"> • Macroscopically ordered • Microscopically disordered 	<ul style="list-style-type: none"> • Natural fiber orientation inspired artificial energy-absorption components of composite materials	[12] (Lu et al., 2019)
3. Cocoyol (<i>Acrocomia Mexicana</i>)	<ul style="list-style-type: none"> • Hierarchical cellular structure 	<ul style="list-style-type: none"> • High toughness and • high hardness • Mechanical performance 	[13] (Flores-Johnson et al., 2018)
4. Nuts and Seeds	<ul style="list-style-type: none"> • Polygonal form 	<ul style="list-style-type: none"> • A hard core • Soft outer layer with high impact strength 	
4.1 Walnut (<i>J. regia</i>)	<ul style="list-style-type: none"> • Sandwich layers 	<ul style="list-style-type: none"> • Some fibers oriented radially to the core 	[14] (Kaupp et al., 2011)
4.2 Pecan (<i>Illinoensis</i>)	<ul style="list-style-type: none"> • Hierarchical technical materials 	<ul style="list-style-type: none"> • Various kinds of fibrous 	[15] (Antreich et al., 2019)
4.3 Pistachio (<i>P. Fandoghi</i>)		<ul style="list-style-type: none"> • Lobed cell structure 	[16] (Bührig-Polaczek et al., 2016)
4.4 Beechnut (<i>sylvatica</i>)		<ul style="list-style-type: none"> • Interlocked walnut cell 	[17] (Sonego et al., 2016)
5. Macadamia (<i>M. ternifolia</i>)			
6. Brazil nut (<i>Bertholletia excelsa</i>)			
7. Durian (<i>Durio zibethinus</i>)	<ul style="list-style-type: none"> • Thorns structure 	<ul style="list-style-type: none"> • Total energy absorbed in the axial direction 	[18] (San Ha et al., 2019)
	<ul style="list-style-type: none"> • Spherical shape 	<ul style="list-style-type: none"> • absorption capacity of the thorns increased with the increase in the number of thorns 	
8. Formosan gum (<i>Liquidambar formosana</i>)	<ul style="list-style-type: none"> • Hierarchical structure • Spherical Fibonacci model 	<ul style="list-style-type: none"> • Designs of novel lightweight, anti-buckling composites, and bio-inspired architectures • micro-scale and the chambers distributed at the macro-scale 	[19] (Tung et al., 2020)
9. luffa sponge (<i>Luffa aegyptiaca</i>)	<ul style="list-style-type: none"> • Hierarchical structures 	<ul style="list-style-type: none"> • Natural cellular material • Mechanical properties 	[20] (Xie et al., 2020)
10. Babassu nut (<i>Orbignya speciosa</i>)	<ul style="list-style-type: none"> • Fibre composites • Biomimetic fibre reinforced composite structure 	<ul style="list-style-type: none"> • High requirements regarding hardness and impact 	[21] (Staufenberg et al., 2015)

Table 3. Empirical papers relating the fruits to Biomimetics studies for energy absorption.

3.1. Pomelo - *Citrus maxima*

Pomelo is the largest fruit of the genus *Citrus* with fruit weights up to 6 kg and with maximum height of the fruit trees reaching 15 m. These two factors combined, fruit weight and height, added together cause a large energy potential as they point out (Seidel *et al.*, 2010). The fruit when detaching from great heights, the static energy is converted into kinetic energy which has its maximum value reached before impact to the ground. The pomelo fruit has the largest number of publications involving energy absorption due to its mechanical properties, found in its peel.

According to (Fischer *et al.*, 2010), this resistance to impact is due to the hierarchical organization of the fruit skin, called pericarp, which is very pronounced, allowing the fruit to fall from 10m in height and not suffer severe external damage, thus preserving its structure, a remarkable example of resistance (See Figure 1).

Fischer *et al.* (2010) present as bio-inspired model a metal foam with improved impact resistance inspired by the structure of the pomelo bark.

Through mechanical evaluation and structural analysis of the biological model, the structural characteristics of the pomelo pericarp were transferred to the development of bio-inspired structures. In this way structures were developed and processed. The modified investment casting process and the Bi57Sn43 alloy model proved to be excellent candidates for making these bio-inspired structures (See Figure 2).

Wen *et al.* (2019) demonstrated that the structural hierarchy of Pomelo peel plays a critical role in optimizing crush resistance and energy absorption. The proposed study developed a new hierarchical structure based on hexagonal structure and investigated the crush resistance along with finite model study, energy absorption capabilities through an integrated analytical-numerical approach was developed. The results showed promise with the developed bio-inspired structure and may present a new perspective on providing superior mechanical properties of natural cellular materials and offer insights for applications of bio-inspired materials (See Figure 3).

3.2. Coconut - *Cocos nucifera*

Lu *et al.* (2019) revealed in their study the structure present in coconut fibers for shock resistance and energy absorption. Then a bio-inspired model was developed and validated by the numerical calculations for providing a functional compound. The structure of *Cocos nucifera* showed excellent shock resistance with multiscale presentation, including its macroscopically organized pericarp and microscopically disordered mesocarp, the latter possessing the thickest layer among the three pericarp layers. In the study, free-fall and quasi-static experiments were performed to describe the arrangement of coconut fiber. Computational numerical models were built for analysis. Through this study it was revealed that the fiber orientation of the coconut fruit bottom can increase the energy absorption capacity and the fiber arrangement can influence the stress wave propagation for protecting the fruit endocarp (See Figure 4).

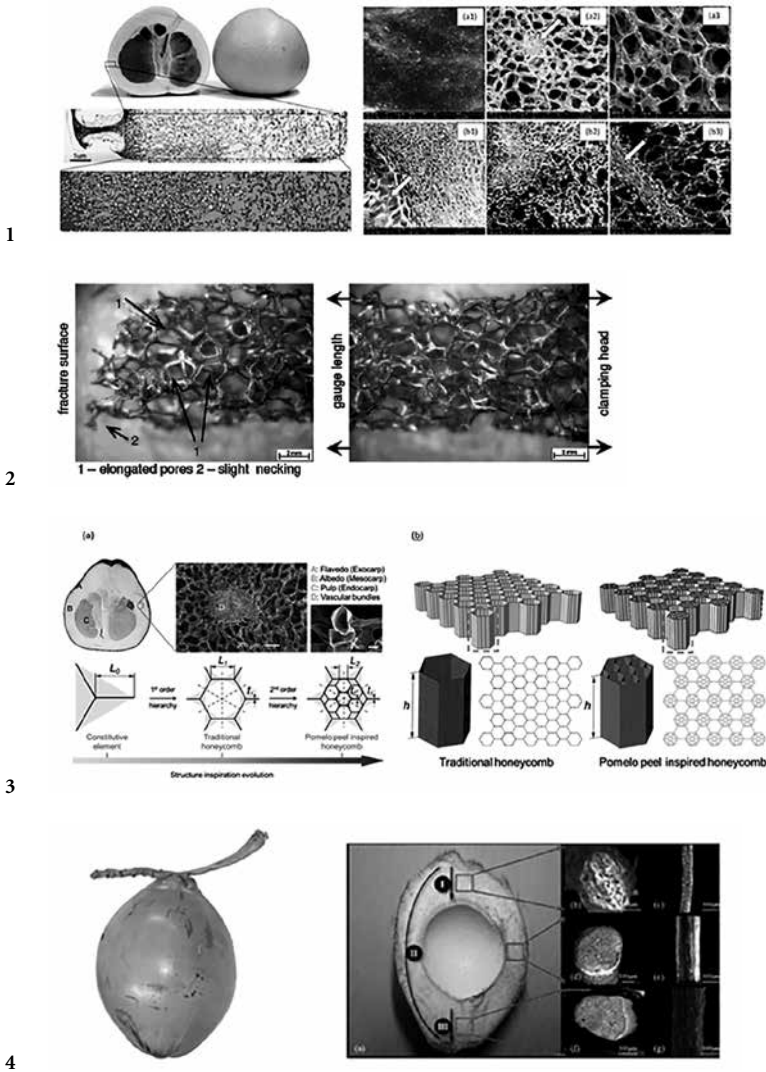


Figure 1. Analysis of the distribution of material within the fruit wall of *Citrus maxima* (Left. Font: adapted from (Seidel et al., 2010); Right. ESEM micrographs of (a) cross-section and (b) longitudinal-section: 1) exocarp (flavedo), 2) mesocarp (albedo) close to flavedo, and 3) mesocarp close to flesh. Source: Looyrach et al., 2015). **Figure 2.** Model developed by a metal foam bio-inspired (Microstructure near the fracture surface of a tension loaded specimen (left) as compared to undeformed area of the same specimen (transition from gauge length to clamping head; right). Source: Fischer et al., 2010). **Figure 3.** Bio-inspired model developed from pomelo fruit. (a) Multi-scale diagrams and SEM photographs for depicting detailed microstructures of typical pomelo peel (A, B, C and D represent flavedo, albedo, pulp and vascular bundles, respectively), along with configurations and geometric parameters of pomelo peel inspired hierarchical honeycomb. (b) Finite element models from different views for traditional honeycomb and pomelo peel inspired honeycomb. Source: Wen et al., 2019). **Figure 4.** The sectional view of the coconut fruit, the blue lines with arrows denote the fiber growing directions (b, d, f) the sectional view of the fiber, (c, e, g) the exterior view of the fiber. Source: Lu et al., 2019).

3.3. Cocoyol - *Acrocomia Mexicana*

The cocoyol palm fruit is commonly found on the Yucatán Peninsula in Mexico. Flores-Johnson *et al.* (2014), conducted a study of the mechanical properties and microstructure under different drying conditions of the endocarp of the Cocoyol fruit of the *Acrocomia Mexicana* palm tree with thirty-six fruits of similar sizes. Using optical and scanning electron microscopy of cross sections of the equatorial region revealed that the endocarp exhibits complex hierarchical structure. Micrographs showed that the structure is made of bundles of randomly oriented tubes and bubble-shaped cells, showing a tangled network of hollow microchannels, which are of the order of tens of microns. The results and microstructure presented here encourage future research for bio-inspired artificial materials.

Antreich *et al.* (2019), revealed a type of cell present in walnut shells. The result is an intricate arrangement that cannot be disassembled when conceived into what the authors term as a 3D puzzle. Mechanical tests were performed and higher strength of walnut compared to pine seed sclerenchyma tissue, this higher strength of walnut shell, is due to the interlocked cells with lobed cell structure. Comprising a structure identity in which its development will inspire in the concepts of biomimetic materials and bio-inspired products, as well as a valorization of food waste, since they are highly widespread throughout the world.

3.5. Macadâmia - *Macadamia integrifolia*

Bühlig-Polaczek *et al.* (2016), present several studies with Pomelo - *Citrus maxima* and Macadamia - *Macadamia integrifolia*, for developing bio-inspired structures for energy absorption. Macadamia seeds are known to be extremely difficult to break. By relating the fracture forces that are required to break the shells of different seeds, from nuts under uniaxial compression to their thickness, macadamia shells outperform all other shells. These strategies were they were abstracted and transferred into corresponding structural principles and thus hierarchically structured bio-inspired metal foams were designed. According to the authors technical materials with hierarchical levels have a great chance for diverse applications in various areas of knowledge and will in time fill some gaps in the current maps of properties of new materials. The results of the investigations presented above have shown that there are possibilities to achieve important material properties or new functions through knowledge of the hierarchical structuring present in fruits, peels and seeds for the development of new products and materials. As a result a pathway for the production of bio-inspired metal structures by casting has been successfully established (See Figure 5).

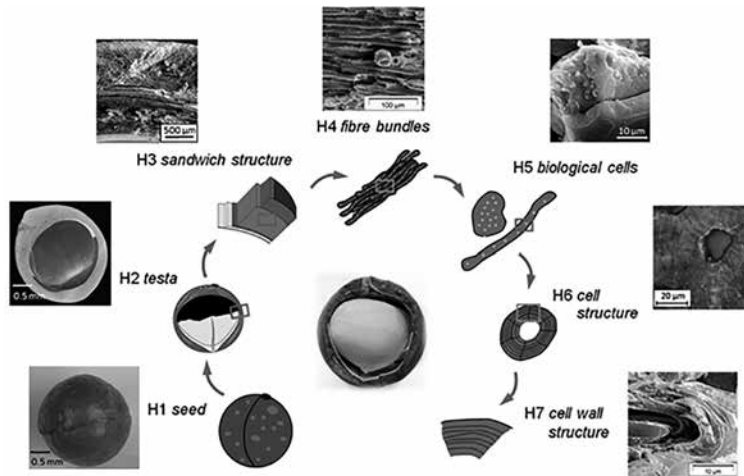


Figure 5. Schematic illustration of the hierarchical structure of Macadamia seeds containing seven levels of hierarchy ranging from the entire seed down to the cell walls' structure (The light (H1, H6) and scanning electron micrographs (H3, H4, H5, H7), and the virtual section through a 3D microtomography volume reconstruction (H2), arranged next to the schematics, show typical examples of structural features of the corresponding hierarchical levels. Source: Bührig-Polaczek et al., 2016).

3.6. Nut - *Bertholletia excelsa*

Sonego *et al.* (2016), they presented the hierarchical levels present in the Brazil nut (*Bertholletia excelsa*) mesocarp. Through optical microscopy, scanning electron microscopy (SEM), microtomography (MicroCT) and small angle X-ray scattering (SAXS) was used to deeply describe the levels of cellular and fibrillar organization. The fibers show different orientation in the three layers of the mesocarp. The mesocarp has several tubular channels and fractures on the surface that may act as sites of crack retention and increase its toughness. The presentation of these levels can inspire the development of products with better mechanical behavior.

The description and understanding of the hierarchical level of organization at the three levels of the mesocarp, present in the Brazil nut, can inspire several strategies to improve the impact and puncture resistance of materials. Focusing on the macro and cellular levels, a bioinspired composite is proposed. The voids in the mesocarp structure can be reproduced by 3D printing with a Teflon filament. Teflon has little adhesion to the surrounding material that can function in nothing like the voids in the mesocarp.

3.7. Fruit durian - *Durio zibethinus*

San Ha *et al.* (2019), presented the Mechanical properties and energy absorption characteristics present in the tropical Durian fruit found in West Malaysia. This is a primary study of the material properties and energy absorption capacity present *Durio zibethinus* as an attempt to use as an alternative sustainable material and reproduce its structural characteristics to design an inspired bio-structure for protective packaging applications. Quasi-static compression tests were performed to determine its energy absorption capacity.

Compression tests on the spines showed that an increase in the number of spines helped to absorb more energy. Specific energy absorption of the spines was almost twice as high as the mesocarp layer under axial loading. The results indicated that the spherical shape associated with the spines and mesocarp materials exhibited excellent energy absorption efficiency that can be mimicked to design an effective bio-inspired absorber for packaging applications.

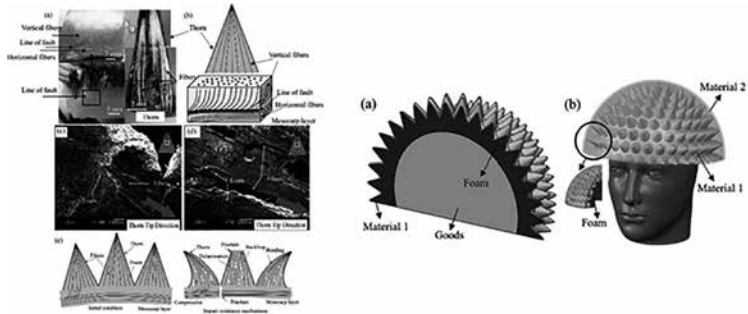
Like other fruit peels, the Durian peel consists of three distinct layers of structures: the exocarp (outer layer), mesocarp (middle layer), and endocarp (inner layer). The exocarp layer can easily identified by its hard, spiny outer shell. The mesocarp layer is identified as a thick white layer under the thorns. Finally, the endocarp is a thin layer that is in contact with the pulp (See Figure 6).

3.8. Formosan gum - *Liquidambar formosana*

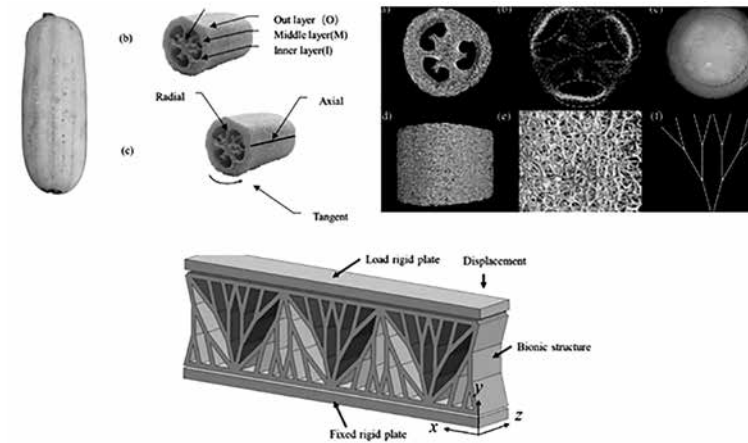
Tung *et al.* (2020), developed a study based on the cell structures of *Liquidambar formosana*-found in Hsinchu, Taiwan that have lightweight and compression-resistant structures inspired by Infructescence. Through micro-CT analysis to build the hierarchical structure three bio-inspired spherical structures were proposed: Thomson, Poisson and Fibonacci models. Compression tests and finite element method (FEM) were used for evaluation and characteristics of the structures.

3.9. Luffa sponge - *Luffa aegyptiaca*

Luffa aegyptiaca, a sponge exhibits excellent damping properties. This study presented a bio-inspired structure of the luffa sponge. The geometry of the bionic structure was built based on theory by Python programming language, along with additive manufacturing with 3D printing. quasi-static compression tests and finite element analysis were performed to determine the damping properties. The results demonstrate the great potential for designing hierarchical cellular structures and broad application prospects in the field of damping and energy absorption (Xie *et al.*, 2020) (See Figure 7).



6



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Figure 6. Study of Durian fruit conducted to develop bio-inspired structure (Left. (a) Fibres distribution on the mesocarp layer and thorn; (b) Schematic of fibre distribution in the mesocarp layer and thorn; (c) Microstructures of the thorn before compression test; (d) Delamination of the fibres in the thorn after the compression test; (e) energy absorption mechanisms of the durian shells. Right. (a) Spherical bio-inspired structure for goods packaging; (b) Bio-inspired helmet structure. Source: San Ha et al., 2019).

Figure 7. Study of luffa sponge conducted to develop bio-inspired structure (Left. The structure of luffa sponge: (a) Nature luffa; (b) Four main parts of luffa sponge; O (out layer), M (middle layer), I (inner layer) and C (core layer); (c) Three main directions of luffa sponge. Right. The micro-computed tomography (micro-CT) scan picture of luffa sponge: (a) Cross section of luffa sponge; (b) Three high-density areas of luffa sponge; (c) Cross section of nature luffa; (d) Vertical section of luffa sponge; (e) Texture of I layer; (f) Simplified structure of I layer. Below. Finite element (FE) model of 15 degrees bionic structure. Source: Xie et al., 2020).

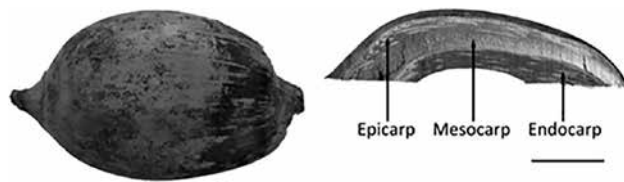


Figure 8. The structure of babassu nut (Left: overall view of the babassu nut. Right: layers of the babassu nut in longitudinal direction. Source: Staufenberg et al., 2015).

3.10. Babassu nut - *Orbignya speciosa*

Staufenberg *et al.* (2015), developed a study based on the *babassu nut* which is the fruit of the babassu palm *Orbignya speciosa*, native to the southern region of a Amazon Basin, mainly to the north and eastern north of Brazil. Scanning electron microscopy was used for mechanical and microscopic analysis of the pericarp. Four main principles were found for a biomimetic approach: a hard core

- (1) Endocarp: is embedded in a soft outer layer of high impact strength.
- (2) Epicarp: and is reinforced with varying fine fibers
- (3) Some of which are oriented radially to the core
- (4) Biomimetic fiber-reinforced composites were produced from mechanisms abstracted from the *babassu nut*. In the results there was a 60% increase in impact strength compared to a composite without layers of the same material composition.

As a result four biological principles that were abstracted from the *babassu nut* were transferred into a high performance biomimetic composite structure (See *Figure 8*).

4. Conclusion

Therefore, this study proves the efficiency in the production of complex and reliable structures, through the implementation, combination of different hierarchical structural elements found as generators of the biological concept and application for the improvement of structures for better efficiency in energy dissipation and resistance to collision and impact, according to the studies performed.

This work aimed to explore the recent literature related the fruits, Biomimetics methodology and energy absorption defining the strategies and identifying challenges, open questions and changes involving new Technology Platforms as 3D print for development of the

Products Bio-inspired. In addition, this study specifically sought to identify types of fruits, types of energy absorption, main authors, goals of studies, methods used, functions found on fruits as well as your structures and patters to involving inspiration for development of the new products or materials. In this study, the material properties and energy absorption capacity at different parts found in peels, shells was investigated through quasi-static compression tests and progressive cyclic tests. The main conclusions can be drawn as below:

- (A) The structural characteristics of the fruits can be mimicked to design a bio-inspired structure for development of product design bio-inspired
- (B) Biomimetics provides a key role for bio-inspired product development frameworks
- (C) The results showed that the types of structures can significantly improve efficiency in structures that perform protection against: shock, resistance and crashworthiness
- (D) More studies are needed for to establish Biomimetics as a design methodology that helps the development of problems for the technical world.

References

- Antreich, S. J.; Xiao, N.; Huss, J. C.; Horbelt, N.; Eder, M.; Weinkamer, R., & Gierlinger, N. (2019). *The Puzzle of the Walnut Shell: A Novel Cell Type with Interlocked Packing*. *Advanced Science*, 1900644. <https://doi.org/10.1002/advs.201900644>
- Benyus, J. M. (2002). *Biomimicry: Innovation Inspired by Nature*. Harper Perennial.
- Bührig-Polaczek, A.; Fleck, C.; Speck, T.; Schüler, P.; Fischer, S. F.; Caliaro, M., & Thielen, M. (2016). *Biomimetic cellular metals—using hierarchical structuring for energy absorption*. *Bioinspiration & Biomimetics*, 11(4), 045002. <https://doi.org/10.1088/1748-3190/11/4/045002>
- Conforto, E. C.; Amaral, D. C.; Silva, S. L. (2011); *Roteiro para revisão bibliográfica sistemática: aplicação no desenvolvimento de produtos e gerenciamento de projetos*. In: 8º. Congresso Brasileiro de Gestão de Desenvolvimento de Produto - CBGDP 2011, Porto Alegre, RS, Brasil. Instituto de Gestão de Desenvolvimento do Produto – IGDP. Anais. Porto Alegre: IGDP. Website. <https://repositorio.usp.br/item/002833837>
- Fischer, S. F.; Thielen, M.; Loprang, R. R.; Seidel, R.; Fleck, C.; Speck, T., & Bührig-Polaczek, A. (2010). *Pummelos as Concept Generators for Biomimetically Inspired Low Weight Structures with Excellent Damping Properties*. *Advanced Engineering Materials*, 12(12), B658–B663. <https://doi.org/10.1002/adem.201080065>
- Fischer, S. F.; Thielen, M.; Weiß, P.; Seidel, R.; Speck, T.; Bührig-Polaczek, A., & Bünck, M. (2013). *Production and properties of a precision-cast bio-inspired composite*. *Journal of Materials Science*, 49(1), 43-51. <https://doi.org/10.1007/s10853-013-7878-4>
- Flores-Johnson, E. A.; Carrillo, J. G.; Zhai, C. *et al.* Microstructure and mechanical properties of hard *Acrocomia mexicana* fruit shell. *Sci Rep* 8, 9668 (2018). <https://doi.org/10.1038/s41598-018-27282-8>
- Kaupp, G., & Naimi-Jamal, M. R. (2011). *Nutshells' mechanical response: from nanoindentation and structure to bionics models*. *Journal of Materials Chemistry*, 21(23), 8389. <https://doi.org/10.1039/c0jm03713c>

- Langella, C. (2019). *Design & scienza*. List. ISBN 8832080079.
- Li, T. T.; Wang, H.; Huang, S.-Y.; Lou, C.W., & Lin, J.-H. (2019). *Bioinspired foam composites resembling pomelo peel: Structural design and compressive, bursting and cushioning properties*. *Composites Part B: Engineering*, 172, 290–298. <https://doi.org/10.1016/j.compositesb.2019.04.046>
- Looyrach, J.; Methacanon, P.; Gamonpilas, C.; Lekpittaya, P., & Lertworasirikul, A. (2015). *Pomelo (Citrus maxima) Peel-Inspired Property for Development of Eco-Friendly Loose-Fill Foam*. *Key Engineering Materials*, 659, 279–283. <https://doi.org/10.4028/www.scientific.net/kem.659.279>
- Lu, C.; Hou, S.; Zhang, Z.; Chen, J.; Li, Q., & Han, X. (2019). *The mystery of coconut overturns the crashworthiness design of composite materials*. *International Journal of Mechanical Sciences*, 105244. <https://doi.org/10.1016/j.ijmecsci.2019.105244>
- Oliveira, A. R. M. (2020). *Immersive virtual reality environment as a strategic tool to enhance the user experience*. *Cuadernos Del Centro De Estudios De Diseño Y Comunicación*, (87). <https://doi.org/10.18682/cdc.vi87.3770>
- Org. Arruda *et al*. *Tópicos em design: biomimética, sustentabilidade e novos materiais*. Curitiba, PR: Insight, 2019. ISBN 978-85-62241-65-9.
- Ortiz, J.; Zhang, G., & McAdams, D. A. (2018). *Modeling of a Pomelo Peel Bioinspired Foam*. *Journal of Mechanical Design*. <https://doi.org/10.1115/1.4040911>
- Roehrs, Alex & André da Costa, Cristiano & Righi, Rodrigo & Farias, Kleinner. (2017). *Personal Health Records: A Systematic Literature Review*. *Journal of Medical Internet Research*. 19. e13. <https://doi.org/10.2196/jmir.5876>.
- San Ha, N.; Lu, G.; Shu, D., & Yu, T. X. (2019). *Mechanical properties and energy absorption characteristics of tropical fruit durian (Durio zibethinus)*. *Journal of the Mechanical Behavior of Biomedical Materials*, 103603. <https://doi.org/10.1016/j.jmbbm.2019.103603>
- San Ha, N.; Lu, G.; Shu, D., & Yu, T. X. (2019). *Mechanical properties and energy absorption characteristics of tropical fruit durian (Durio zibethinus)*. *Journal of the Mechanical Behavior of Biomedical Materials*, 103603. <https://doi.org/10.1016/j.jmbbm.2019.103603>
- Sanchez, C.; Arribart, H., & Giraud Guille, M. M. (2005). *Biomimetism and bioinspiration as tools for the design of innovative materials and systems*. *Nature Materials*, 4(4), 277–288. <https://doi.org/10.1038/nmat1339>
- Schäfer, I.; Mlikota, M.; Schmauder, S., & Weber, U. (2020). *Modelling the damping response of biomimetic foams based on pomelo fruit*. *Computational Materials Science*, 183, 109801. <https://doi.org/10.1016/j.commatsci.2020.109801>
- Seidel, R.; Thielen, M.; Schmitt, C. A.; Bührig-Polaczek, C. Fleck & T. Speck. (2010). *Fruit Walls And Nut Shells As An Inspiration For The Design Of Bio-inspired Impact Resistant Hierarchically Structured Materials*. *Design and Nature V*. <https://doi.org/10.2495/DN100371>
- Sonego, M.; Fleck, C., & Pessan, L. A. (2020). *Hierarchical levels of organization of the Brazil nut mesocarp*. *Scientific Reports*, 10(1). <https://doi.org/10.1038/s41598-020-62245-y>
- Speck, T. *et al*. (2018). *Biomechanics and Functional Morphology of Plants - Inspiration for Biomimetic Materials and Structures*. Em: Geitmann A., Gril J. (eds) *Plant Biomechanics*. Springer, Cham. https://doi.org/10.1007/978-3-319-79099-2_18
- Thielen, M.; Schmitt, C. N. Z.; Eckert, S.; Speck, T., & Seidel, R. (2013). *Structure–function relationship of the foam-like pomelo peel (Citrus maxima) – an inspiration for the devel-*

- opment of biomimetic damping materials with high energy dissipation. *Bioinspiration & Biomimetics*, 8(2), 025001. <https://doi:10.1088/1748-3182/8/2/025001>
- Tung, C.-C.; Wang, H.-J., & Chen, P.-Y. (2020). *Lightweight, compression-resistant cellular structures inspired from the infructescence of Liquidambar formosana*. *Journal of the Mechanical Behavior of Biomedical Materials*, 103961. <https://doi:10.1016/j.jmbbm.2020.103961>
- Van Opendbosch, D.; Thielen, M.; Seidel, R.; Fritz-Popovski, G.; Fey, T.; Paris, O. & Zollfrank, C. (2012). *The pomelo peel and derived nanoscale-precision gradient silica foams*. *Bioinspired, Biomimetic and Nanobiomaterials*, 1(2), 117-122. <https://doi:10.1680/bbn.11.00013>
- Wang, B.; Pan, B., & Lubineau, G. (2018). *Morphological evolution and internal strain mapping of pomelo peel using X-ray computed tomography and digital volume correlation*. *Materials & Design*, 137, 305-315. <https://doi:10.1016/j.matdes.2017.10.038>
- Wang, H.; Li, T.-T.; Ren, H.; Peng, H.; Huang, S.-Y.; Lin, Q. & Lou, C.-W. (2019). *Expanded Vermiculite-Filled Polyurethane Foam-Core Bionic Composites: Preparation and Thermal, Compression, and Dynamic Cushion Properties*. *Polymers*, 11(6), 1028. <https://doi:10.3390/polym11061028>
- Yang, Y.; Song, X.; Li, X.; Chen, Z.; Zhou, C.; Zhou, Q., & Chen, Y. (2018). *Recent Progress in Biomimetic Additive Manufacturing Technology: From Materials to Functional Structures*. *Advanced Materials*, 1706539. <https://doi:10.1002/adma.201706539>
- Zhang, W.; Yin, S.; Yu, T. X., & Xu, J. (2019). *Crushing resistance and energy absorption of pomelo peel inspired hierarchical honeycomb*. *International Journal of Impact Engineering*, 125, 163-172. <https://doi:10.1016/j.ijimpeng.2018.11.014>
- Zhao, N.; Wang, Z.; Cai, C.; Shen, H.; Liang, F.; Wang, D. & Xu, J. (2014). *Bioinspired Materials: from Low to High Dimensional Structure*. *Advanced Materials*, 26(41), 6994-7017. <https://doi:10.1002/adma.201401718>

Resumen: Esta revisión busca actualizar nuestro conocimiento sobre frutas, sus estructuras, sus materiales para el desarrollo de productos bioinspirados y sus respectivas aplicaciones relacionadas con la absorción de energía y la disipación de impactos. En la naturaleza, encontraremos multitud de estructuras biológicas que cumplen la función de protección y resistencia a los choques. Este estudio se centra en una de las funciones biológicamente más importantes que se encuentran en el embalaje natural, que consiste en la protección directa o indirecta contra daños mecánicos u otras influencias ambientales negativas que involucran la resistencia a los choques, así como la absorción de energía. A través de la revisión sistemática de la literatura, que incluye toda la investigación revisada por pares, se seleccionaron 21 estudios de investigación documentos que son relevantes para el objetivo de asegurar una búsqueda integral. Se identificaron tres bases de datos de investigación: (I) web of Science, (II) Scopus y (III) Science Direct. Solo se incluyeron estudios empíricos primarios. La revisión identificó varias situaciones en las que se introduce la metodología Biomimética y Bioinspiración para mejorar y resolver problemas tec-

nológicos mediante el análisis, la abstracción, la adaptación y la transposición de principios biológicos al mundo técnico. Los resultados indicaron que las estructuras basadas en frutas podrían mejorar la eficiencia de la estructura que tiene la función de proporcionar un absorbente bioinspirado eficaz para una multitud de diseños de productos. Aunque existen varios estudios, se necesita más investigación para el uso de nuevas tecnologías y nuevos escenarios para asegurar recomendaciones que puedan implementar la mejora del desarrollo de diseño bioinspirado.

Palabras clave: Biomiméticos - Estructuras bioinspiradas - Frutas - Envases naturales - Absorción de energía - Resistencia al impacto

Resumo: Esta revisão busca atualizar nosso conhecimento sobre frutas, suas estruturas, seus materiais para o desenvolvimento de produtos bioinspirados e suas respectivas aplicações envolvendo absorção de energia e dissipação de choque. Na natureza, encontraremos uma infinidade de estruturas biológicas que desempenham a função de proteção e resistência a choques. Este estudo enfoca uma das funções biologicamente mais importantes encontradas nas embalagens naturais - que consiste na proteção direta ou indireta contra danos mecânicos ou outras influências ambientais negativas que envolvam resistência ao choque - bem como a absorção de energia. Por meio da revisão sistemática da literatura, que inclui todas as pesquisas revisadas por pares, foram selecionados 21 trabalhos de pesquisa que são relevantes ao objetivo de garantir uma busca abrangente. Três bancos de dados de pesquisa foram identificados: (I) web of Science, (II) Scopus e (III) Science Direct. Apenas estudos empíricos primários foram incluídos. A revisão identificou várias situações onde a Biomimética e a metodologia de Bioinspiração são introduzidas para melhorias e solução de problemas tecnológicos por meio da análise, abstração, adaptação e transposição de princípios biológicos para o mundo técnico. Os resultados indicaram que as estruturas baseadas em frutas podem melhorar a eficiência da estrutura que tem o papel de fornecer um absorvedor bioinspirado eficaz para uma infinidade de designs de produtos. Embora existam diversos estudos, mais pesquisas são necessárias para utilização de novas tecnologias e novos ambientes para garantir recomendações que possam implementar a melhoria do desenvolvimento de projetos bioinspirados.

Palavras chave: Biomimética - Estructuras bioinspiradas - Frutas - Embalagem natural - Absorción de energía - Resistência ao choque
