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PLANT FIBER REINFORCED POLYMERIC COMPOSITES FOR ENGINEERING APPLICATIONS: A REVIEW

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ABSTRACT

Purpose: Scientists are looking for unconventional materials to achieve sustainable goals and reduce the consumption of non-renewable resources. This review focuses on polymeric composite materials with improved properties and low cost, synthesized from plant fibres and their potential fields of application.

Theoretical Framework: Natural fibers, which are globally accessible, play a crucial role in improving thermal and mechanical properties when incorporated into polymers. With remarkable stiffness-density, strength and lightness, fibers stand out as promising, low-cost composite materials for applications in various areas of engineering. The plant diversity of the Amazon makes Brazil one of the largest global producers of natural fibers, providing an opportunity to develop new sustainable technologies.

Method/Design/approach: Systematic literature review addressing potential applications of polymeric materials with plant fibers, fiber extraction methods, influence of fiber surface treatments and composite processing, and mechanical properties of polymeric composites with fibers.

Results: Polymer composites reinforced with natural fibers are emerging as sustainable alternatives to synthetic materials, driven by their ecological nature, easy availability, low cost and biodegradability. A systematic review of the literature revealed that the mechanical properties of these composites are intrinsically linked to various factors, such as fibre orientation and length, which require careful optimization. In addition, it was observed that surface treatments, such as chemical acetylation and alkaline treatments, play a crucial role in improving the properties of plant fiber reinforced materials. These processes are responsible for removing impurities present in the cell walls of the fibers, such as lignins, waxes and hemicellulose, among others. Given Brazil's significant potential in the production of natural fibers, their application in industrial contexts is promising, offering an

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environmentally friendly solution for waste management. Thus, it is believed that, in the future, plant fibers will gain even more prominence, possibly effectively replacing the synthetic fibers widely used in the market.

Research implications: This work contributes to the development of innovative, low-cost, sustainable materials, capable of minimizing the consumption of non-renewable resources and with potential applicability.

Originality/value: The results are promising for the development of environmentally sustainable polymer composites with plant fibers, with wide applications in engineering.

Keywords: Plant Fibers, Polymer Composites, Innovative Materials, Sustainability.

COMPÓSITOS POLIMÉRICOS REFORÇADOS COM FIBRAS VEGETAIS PARA APLICAÇÕES NA ENGENHARIA: UMA REVISÃO

RESUMO

Objetivo: Cientistas buscam materiais não convencionais para alcançar metas sustentáveis e reduzir o consumo de recursos não renováveis. Esta revisão tem como foco os materiais compósitos poliméricos, com propriedades aprimoradas e de baixo custo, sintetizados a partir de fibras vegetais e seus potenciais campos de aplicações.

Referencial Teórico: As fibras naturais, globalmente acessíveis, desempenham papel crucial ao aprimorar as propriedades térmicas e mecânicas quando incorporadas aos polímeros. Com notável rigidez-densidade, resistência e leveza, as fibras destacam-se como materiais compósitos promissores, de baixo custo para aplicações em diversas áreas da engenharia. A diversidade vegetal da Amazônia faz do Brasil um dos maiores produtores globais de fibras naturais, proporcionando o desenvolvimento de novas tecnologias sustentáveis.

Método: Revisão sistemática da literatura abordando potenciais aplicabilidades de materiais poliméricos com fibras vegetais, métodos de extração de fibras, influência dos tratamentos de superfície das fibras e do processamento dos compósitos e propriedades mecânicas de compósitos poliméricos com fibras.

Resultados: Os compósitos poliméricos reforçados com fibras naturais estão emergindo como alternativas sustentáveis aos materiais sintéticos, impulsionados por sua natureza ecológica, fácil disponibilidade, baixo custo e biodegradabilidade. Uma revisão sistemática da literatura revelou que as propriedades mecânicas desses compósitos estão intrinsecamente ligadas a diversos fatores, como orientação e comprimento das fibras, os quais demandam otimização cuidadosa. Além disso, observou-se que tratamentos de superfície, como acetilação química e tratamentos alcalinos, desempenham um papel crucial na melhoria das propriedades dos materiais reforçados com fibras vegetais. Esses processos são responsáveis pela remoção de impurezas presentes nas paredes celulares das fibras, tais como ligninas, ceras e hemicelulose, entre outras. Dado o expressivo potencial brasileiro na produção de fibras naturais, sua aplicação em contextos industriais se mostra promissora, oferecendo uma solução ambientalmente amigável para o gerenciamento de resíduos. Assim, acredita-se que, no futuro, as fibras vegetais ganharão ainda mais destaque, possivelmente substituindo de maneira eficaz as fibras sintéticas amplamente utilizadas no mercado.

Implicações da pesquisa: Este trabalho contribui para o desenvolvimento de materiais inovadores, de baixo custo, sustentáveis, capazes de minimizar o consumo de recursos não renováveis e com potenciais de aplicabilidade.

Originalidade/valor: Os resultados são promissores para o desenvolvimento de compósitos poliméricos com fibras vegetais, ambientalmente sustentáveis, com largas aplicações na engenharia.

Palavras-chave: Fibras Vegetais, Compósitos Poliméricos, Materiais Inovadores, Sustentabilidade.

1 INTRODUCTION

The discussion around sustainable and eco-friendly products has grown, researchers are examining the reasons for low adoption, and governments are striving for resource-efficient, low-carbon emission societies while sustainable technologies enable environmentally conscious investments and support sustainable development (Pandey and Rajeswari, 2023). Brazil is a forest production highlight out worldwide in forestry production due to its favorable environmental conditions and advanced management that has attracted attention in this discussion (Neto et al., 2023). Since activities such as deforestation, pollution of rivers and seas, mining, agriculture, forestry, energy generation, transportation, civil infrastructure development like roads and cities, population expansion, and the expansion of urban areas, alongside the operations of fundamental chemical and metallurgical industries, are not only jeopardizing the existence of various species but also threatening the survival of entire ecosystems and the preservation of biodiversity, creating a dire situation of unparalleled environmental devastation (Salgado and Franchi, 2023). Trying to meet the goals of the 2030 Agenda for sustainable development and reduce the consumption of non-renewable resources, scientists are increasingly seeking the use of non-conventional materials (Costa et al., 2024).

Natural fibers from renewable resources, such as pineapple, banana, bamboo, coconut, sisal and jute, have been widely investigated as reinforcement in polymeric matrices, as environmental issues and the use of renewable raw materials become increasingly relevant. In 2020, Brazil was responsible for 4.5% of global coconut production, reaching approximately 2.85 tons, therefore generating a high amount of waste. Several studies indicate that coconut waste has great potential in the construction industry (Morato et al., 2024). All natural lignocellulosic fibers consist of cellulose microfibrils in an amorphous matrix of lignin and hemicellulose. Microfibrils work along the length of the fiber and have a layered structure composed of a thin primary wall, involving a thicker secondary wall similar to wood fibero (Chattopadhyay et al., 2010). Cellulose, on the other hand, is the element present in natural fibers, which promotes high strength, rigidity and structural stability for the fiber. On the other hand, lignin is formed by a cellulose-hemicellulose chain, which improves the bond quality, which is responsible for the great resistance (Karthi et al., 2020).

Although the vegetable fiber classes have different characteristics, they have many common advantages, being recyclable, biodegradable (Daria et al., 2020), non-toxic, providing incentives for the agriculture sector by supporting employment generation and the development of rural communities and with low cost and energy consumption in production (Borges et al, 2019). These factors, combined with their good physical and mechanical properties, make them interesting for the use of reinforcement with polymeric materials, with a wide range of applications, in areas such as aerospace, automotive, sports, home appliances and construction (Latif et al., 2019).

In the future, vegetable fibers can stand out for being able to replace fibers already known on the market, such as glass, used as reinforcement agents since natural fibers' performance can be compared to synthetic's (Júnior et al., 2020). This is highlighted by the fact that natural fibers are considerably lighter than synthetic ones, with an average difference of approximately 0.8 g/cm^3. Jute, sisal, banana, coconut, kenaf and hemp fibers are one of the most selected to produce lightweight composites (Girijappa et al., 2019). Thus, vegetable fibers have numerous advantages over fiberglass, such as low density, high volume, better thermal resistance and better skin protection from radiation (Tonk, 2021).

Brazil is one of the largest producers of natural fibers in the world, due to the vast diversity of plant species found in the Amazon rainforest (Chawla, 2012). This is attested, for example, by the 258 native bamboo species existing in the country, of which 175 species in 12 generals are considered endemic and correspond to about 20% of the total number of bamboos in the world. Furthermore, Brazil is one of the largest producers of sisal fiber, corresponding to about 70% of the Brazilian commercial production of all hard fibers (Rusch et al., 2018).

As alternatives to the high cost of exploring non-renewable energy reserves and also of developing new technologies to replace wood, Brazil has great possibilities for commercial exploitation of its natural resources on the world stage. This must be done consonance with the pursuit of the sustainable production of these resources (Satyanarayana et al., 2007).

Brazil has an abundant variety of natural fibers with great potential for use, but the proper management of these residues, for each region, is a challenging issue and an environmental concern (Rocha et al., 2022; Sato et al., 2020)

Natural Fibers (NFs) are classified as: vegetable-based fibers, animal-based fibers and mineral-based fibers. Among vegetable fibers, bark, leaf and seed base fibers are mainly used to make commercial composites, while other fibers such as stalk, grass and wood base fibers are used to make research composites (Latif et al., 2019).[0] In addition, those from the stem or leaf are called hard fibers and are the most used for reinforcement in polymer composites (Júnior et al., 2020).There are eight main types of plant fibers: bast fibers (jute, ramie, flax, rattan, soybean, hemp, vine, banana, and kenaf), collected from the bark and fiber around the plant stem; leaf fibers (abaca, banana, sisal, and pineapple), collected from leaves; seed fibers (cotton, coir, and kapok), collected from seeds and seed boxes; grass fibers (corn, wheat, bamboo, barley, and rice); core fibers (corn and wheat stalk), collected from plant stems; wood pulp fibers; root fibers (luffa, swede, and cassava); and fruit fibers (tamarind, banana, and coir). These fibers can be primary sources, produced as by-products of other main products (e.g. food, raw material and fuel) for industrial use, or secondary plants, which are produced as by-products derived from manufacturing processes (Gholampour and Ozbakkaloglu, 2020).

Natural fibers, widely accessible across the globe, play a critically significant role in improving the thermal, mechanical, and acoustic attributes of polymers. Possessing an exceptional stiffness-to-density ratio, heightened strength, stability, corrosion resistance, and lightweight nature, they stand out as among the most prospective composite materials, they can be cultivated with minimal financial investment and maintenance, even in barren lands. These qualities make them suitable for many applications, such as aviation, automotive components, sports equipment and home appliances (Choudhary et al., 2023).

2 NATURAL AND SYNTHETIC FIBERS

Wood fiber is the most produced annually with 1,750,000,000 tons (Sanjay et al., 2019). After this, the fiber with highest production is Bagasse, equivalent to 75,000,000 tons per year, followed by Bamboo, with 30,000,000 tons, cotton, with 20,000,000 tons, and Jute, with 3450 tons (Fraxe and Ferreira, 2018). Brazil represents 40% of the annual production of Sisal, in addition to contributing to the production of fibers from Bagasse, Coir, Cotton, Ramie and Silk. Figure 1 shows some of the main natural fibers (Sanjay et al., 2018).

Figure 1. Biofibers.
Source: Hasan et al. (2020).

2.1 Fiber extraction methods

The extraction of NFs is a challenge in the processing of plant fibers. The most common methods for separating vegetable fibers are dew steeping and water steeping. However, these methods require 14 to 28 days, depending on the fiber type (Sanjay et al., 2019). Thus, in order to reduce processing time, mechanical extraction and chemical treatments are introduced.

During maceration, the action of bacteria and moisture in the plants dissolve or rot cell tissues and viscous substances, facilitating fiber separation. Maceration with water is the process where the fiber source is immersed in water or another fluid until the decomposition of non-fibrous constituents occurs (Manimaran et al., 2019; Khan et al., 2019). In this process, water can penetrate the central part of the stem and swell the inner cells, which results in the bursting of the outer layer of the plants, but it generates poor quality fibers (Sanjay et al., 2019). In dew maceration, the plant stalks are spread in fields, where the combined action of bacteria, sun, air and dew causes breakage of their cellular tissues and adhesive substances that involve the fibers (Sanjay et al., 2019).

Furthermore, decortication replaces the process of extracting fibers carried out in water, such as those that involve maceration. This process has not changed since the introduction of this activity in the state of Amazonas-Brazil, from the 1930s onwards, which is the cause of some health problems for workers, as it requires the operator to carry out the process with the whole body wet for several hours (Fraxe and Ferreira, 2018). Thus, mechanical shredding processes are more modern and more suitable.

According to researchers (Ferreira et al., 2018), the jute extraction process is described from maturation, followed by the other treatment steps for the extraction of this fiber: cutting, forming bundles, drowning and maceration, shredding and drying. Then, it highlights the main problems of activities carried out in water without proper tanks. In addition to being a tiring work process, it exposes workers to itching caused by direct contact with all the impurities accumulated over the days of drowning, in which the water is stagnant and exposed.

Fiber sources and extraction methods are outlined in Table 1.

Table 1. Fiber sources and extraction methods.

Fruit	Fiber source	Fiber extraction methods	References
Coconut	Mesocarp or epicarp	Maceration; Mechanical Defibration	(Vijay et al., 2021)
Bamboo	Bamboo pulp	Mechanical Defibration	(Gholampour and Ozbakkaloglu, 2020; Moura,

			2019)
Banana	Banana pseudostem	Mechanical Defibration	(Nery et al., 2018)
Açaí	Inner part of the seed	Decortication; Mechanical Defibration	(Tavres et al., 2020)
Curuará	Leaf	Decortication; Mechanical Defibration	(Spinacé et al., 2011; Hussain et al., 2021)
Sisal	Leaf	Maceration; Mechanical Defibration	(Sato et al., 2020; Spinacé et al., 2011)
Mallow	Woody part of the stalk	Decortication; Mechanical Defibration	(Latif et al., 2019; Fraxe and Ferreira, 2018; Ferreira et al., 2018)
Jute	Woody part of the stalk	Decortication; Maceration; Mechanical Defibration	(Latif et al., 2019; Fraxe and Ferreira, 2018; Ferreira et al., 2018)

Source: Own authorship.

2.2 Fiber properties

In general, the mechanical properties of composites reinforced with natural fibers are lower compared to synthetic fiber. However, these properties, shown in Table 2, can be improved through appropriate modifications (Gholampour and Ozbakkaloglu, 2020).

Natural fibers have advantages such as low density, low cost, high impact resistance, less abrasiveness to equipment and less environmental impact (Kerni et al., 2022). Recent works reveal that the specific properties of composites reinforced with natural fibers are very high (Sanjay et al., 2018).

Table 2. Mechanical properties of natural fibers.

Fiber	**Density (kg/m^3)**	**Tensile Strength (MPa)**	**Elastic Modulus (Gpa)**	**Elongation (%)**	**References**
Abaca	1500.00	430.00-760.00	8.00-20.00	3.00-10.00	(Chattopadhyay et al., 2010; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Mahmud et al., 2021; Chandgude and Salunkhe, 2021)
Bagasse	1500.00	222.00-290.00	17.00-27.00	1.10	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Chandgude and Salunkhe, 2021)
Bamboo	910.00-1100.00	140.00-500.00	11.00-32.00	2.00-3.70	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021)
Banana	1350.00	600.00	12.00-17.00	1.50-9.00	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021;^{0} Mahmud et al., 2021; Chandgude and Salunkhe, 2021)
Coir	1150.00-1250.00	135.00-240.00	4.00-6.00	15.00-40.00	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021)
Cotton	1600.00	287.00-700.00	5.50-12.60	7.00-8.00	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021)
Curauá	1.40	87.00-1150.00	11.00-96.00	1.30-4.90	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018)

Flax	1400.00-1500.00	800.00-1500.00	27.00-103.00	1.20-3.20	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021; Hamidon et al., 2019)
Hemp	1480.00	550.00-900.00	55.00-70.00	2.00-4.00	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021; Hamidon et al., 2019)
Jute	1460.00	393.00-860.00	10.00-60.00	13.00-60.00	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021; Hamidon et al., 2019)
Kenaf	1200.00	200.00-900.00	53.00	53.00-66.00	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021; Hamidon et al., 2019)
Pineapple	1440.00	400.00-1000.00			(Sanjay et al., 2018; Mahmud et al., 2021; Chandgude and Salunkhe, 2021)
Ramie	1500.00	220.00-938.00	24.00-128.00	1.40-4.00	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021; Hamidon et al., 2019)
Sisal	1330.00-1450.00	468.00-640.00	9.00-38.00	2.00-7.00	(Karthi et al., 2020; Gholampour and Ozbakkaloglu, 2020; Sanjay et al., 2018; Vijay et al., 2021; Kerni et al., 2022; Mahmud et al., 2021; Chandgude and Salunkhe, 2021; Hamidon et al., 2019)
Sugarcane	-	290.00	17.00	-	(Mahmud et al., 2021)

Source: Own authorship.

2.3 Influence of surface treatments on fiber properties

This happens because, due to its hydrophilic characteristic, the fibers do not adhere well to common polymeric resins, due to the incompatibility between fiber and matrix. Interfacial adhesion is vital for the mechanical behavior of composites since weak bonding at the interface leads to a composite with poor mechanical properties (Gholampour and Ozbakkaloglu, 2020).

In addition, moisture retention can lead to the formation of voids at the fiber/matrix interface. These aspects can interfere in the transmission of tensions from the matrix to the fiber, which leads to a mechanical system with lower performance. Although moisture absorption mainly affects natural fibers, there are some resins that absorb a lot of moisture. Therefore, both the fiber surface and the matrix need to be modified to increase the adhesion of natural fibers to the matrix (Gholampour and Ozbakkaloglu, 2020). According to Ferreira (2018), the water absorption of natural fibers can represent about 300% of its own mass, which can cause a dimensional variation of its cross section of up to 47%.

To overcome these problems, surface treatments are required for a better fiber-matrix interaction since it improves the adhesion between natural fiber and polymer matrix by eliminating pectin and wax from natural fiber (Pokhriyal et al., 2023). These are extremely important for removing the impurities present on the fiber walls after mechanical extraction. In addition to removing lignins, waxes, hemicellulose, among others, exposing the cellulose and, consequently, increasing the roughness.

Chemical treatment is a key factor to improve the interaction between fiber-matrix and, consequently, the mechanical properties of composites since natural fibers have a certain incompatibility with thermoplastics. Some of the most common chemical treatments are: silane treatment, bleaching, acetylation treatment, peroxide treatment, benzoization treatment and alkali treatment. (Girijappa et al., 2019; Sanivada et al., 2020). In a study with ramie fiber, it was shown how the tensile strength improved after chemical treatment (Sanivada et al., 2020).

Furthermore, one of the most used methods is mercerization, due to its simplicity and high efficiency, in which there is modification of the fibrous structure by means of an aqueous solution, under different conditions of time, temperature and concentrations, of sodium hydroxide (NaOH), leading to an increase in mechanical properties (Girijappa et al., 2019).

In the alkaline treatment of *Pennisetum purpureum Schum* with NaOH (Vijay et al., 2021), a decrease in hemicellulose, lignin and wax is observed in relation to untreated fiber. Thus, alkaline treatments, when performed under optimal conditions, remove the amorphous content, which increases the surface roughness of the fiber. Therefore, it improves surface wettability, leading to better matrix bonding when used in composites (Vijay et al., 2021).

Finally, physical modifications on the surface of plant fibers can considerably contribute to the adhesion between fiber-matrix without altering the chemical properties of the fibers. Among these treatments are plasma, ultraviolet, fiber beating and heat treatment. Maleated coupling agents, for example, can provide sufficient interaction between the functional surface of the fibers and the matrix, which can lead to the formation of carbon-carbon chains with the polymer chains of the matrix (Gholampour and Ozbakkaloglu, 2020).

However, studies show that many variables influence the final results. The improvement of properties depends on the type of treatment used, the concentration, when the chemical method will be used and the duration of the treatments (Sanivada et al., 2020; Vijay et al., 2021).

2.4 Influence of processing on fiber composite properties

Natural fiber-reinforced polymer composites can be manufactured by several methods, such as manual lay-up, injection molding, compression molding and resin transfer molding. These include three steps: removing moisture from the natural fiber, blending fiber and matrix, and manufacturing parts (Karthi et al., 2020).

Manual lay-up is a simple open mold technology suitable for large components as it is a low volume and labor-intensive technique. Injection molding is used for the mass production of composites by manufacturers, so that the materials are injected into the mold, and it is used for thermosetting polymers and thermoplastics. On the other hand, compression molding is a method of producing lighter-scale thermoplastic composites, in which materials are placed in a preheated mold and subjected to pressure until cured. Furthermore, in the case of resin transfer molding, the fibers are placed in a mold and the resin mixture is injected into the mold cavity using pressure (Mahmud et al., 2021).

The reaction time in dew processing or fiber water retention must be carefully evaluated, as this presents a difficulty in separating the individual fibers and causes the weakening of their strength (Sanjay et al., 2019).

Table 3 shows the main advantages and disadvantages of some existing composite processing techniques.

Table 3. Advantages and disadvantages of different processing techniques.

Technique	**Advantages**	**Disadvantages**
Hand lay-up	- Low cost of tools - Flexibility in material design - Wide possibility of using different types of materials	- Laborious - The quality depends on the skill of the laminator - Lower production speed - Resin needs to have low viscosity due to manual

	- Suitable for large components	operation
Injection molding	- Low cost - Ideal for high production - Produces complex geometries - Little waste of materials - High precision	- High setup cost
Compression molding	- Quick setup time - Good cost-benefit - Produces complex composites - Little waste of materials - Uniform molding - Good cost-benefit - Produces complex composites	- Low production - Limited geometry – only flat or slightly curved composites
Resin transfer molding	- Low setup cost - Low maintenance cost - Quick setup time	- Resin needs to have low viscosity due to manual operation - Lower production speed

Source: Gholampour and Ozbakkaloglu (2020).

It is worth mentioning that parameters such as moisture, fiber type, fiber volume fraction and composite temperature must be observed, as they influence fiber processing. Therefore, fiber and matrix moisture must be controlled prior to processing and, if necessary, modifications to the control must be made (Gholampour and Ozbakkaloglu, 2020).

2.5 Influence of fiber length and orientation on mechanical properties

The mechanical characteristics of a composite depend on some variables, such as length, fiber orientation, degree of dispersion and degree of crystallinity of the composite. The reinforcements can be in the form of particles, flakes, short fibers, continuous fibers or sheets. However, most of the reinforcements used in composites have a fibrous form, as in this geometry the materials are stronger and more rigid than in any other form, in addition to being very flexible (Chawla, 2012). There are two types of classification in relation to the length of the reinforcement: continuous or long fibers and short or discontinuous fibers.

In the composite reinforced with long fibers, the mechanical properties are highly anisotropic, that is, they depend on the direction in which they are measured. Short or discontinuous fibers, on the other hand, have lower strength compared to continuous fibers, but guarantee the isotropy of the material. It is easier to use short fibers, generating a higher production rate than continuous fibers. Furthermore, it is possible to develop complex shapes through compression, injection or extrusion molding (Gonçalves et al., 2019).

In this scenario, after performing mechanical tests with bamboo fiber, found that load transfer can occur effectively when the fiber is arranged parallel to the applied load. It was found that, in specimens with randomly oriented fibers, the longest fiber contributed to the appearance of voids (Sugiman et al., 2018).

2.6 Mechanical Properties of Composites

The use of composite has become increasingly relevant in several areas of engineering. This is observed due to its lightness and high performance (Boaretto et al., 2021).

As described, the mechanical properties of composites depend on many factors related to the choice of fiber and polymer matrix, fiber orientation and length, surface treatment, among others. In this scenario, it is necessary to evaluate the optimal configurations for the reinforcement, responsible for giving the material mechanical properties such as toughness and stiffness (Nascimento et al., 2019).

There are several studies that investigate the use of natural fibers in hybrid composites with synthetic fibers (Atmakuri et al., 2021; Mohanavel et al., 2022; Raja et al., 2021; Subramanian et al., 2021; Verma et al., 2021). Although natural fibers promote the reduction of the properties of synthetic composites and the difficult processing induced by hybridization, there is an improvement in tenacity and a modification of failure modes. This allows for greater energy absorption and damage tolerance, being interesting for mechanical properties and post-impact residual performance.

However, composites reinforced with natural fibers have benefits over composites reinforced with synthetic fibers, since there is an inherent damping property in these materials (Munde ET AL., 2019). The mechanical properties of plant fibers are dependent on cellulose and the angle that the microfibrils make with the plant axis, also known as microfibrillar angle (MFA). The increase in the cellulose content is proportional to the increase in the tensile strength of the material. On the other hand, the high content of MFA is responsible for increasing the ductility of the material. Lignin, on the other hand, is responsible for the elasticity of the fiber, as it is responsible for its binding. However, its presence with pectin is responsible for blocking the transfer of stress from the matrix to the fiber, which leads to a reduction in the mechanical properties of the composite (Chandgude and Salunkhe, 2021).

In this way, Jeyapragash et al. (2020) performed tests in order to measure the physical and mechanical properties of natural fibers. After carrying out the experiments, they found that the fibers of bast (skin) and sheet origin have the greatest ranges of tensile strength values. In the same study, the properties of the fibers mixed with the epoxy polymer were also measured, where it was observed that the composites based on bast and sheet fibers maintain the tendency of high tensile strength. Impact tests were also performed, where the linen composite (bast) presented the highest value, 191.71 Kj/m², while the coconut fiber-based composite presented the lowest value, 26.43 Kj/m² (Jeyapragash et al., 2020).

Table 4 presents the properties of some polymeric composites reinforced with natural fibers and their respective surface treatments.

Table 4. Mechanical properties of composites reinforced with natural fibers.

Fiber	**Matrix**	**Superficial treatment**	**Tensile strength (Mpa)**	**Yield Limit (Mpa)**	**Modulus of Elasticity (Mpa)**	**Impact Resistance (J/m)**	**Deformation at break (%)**
Açaí	PP	TAF/PpgMA (Chattopadhyay et al., 2010)	27.50 ± 1.00	-	887.00 ± 16.00	-	9.30 ± 1.20
Bamboo	Epoxy	Alkaline (6% NaOH (Zhang et al., 2018)	363.00 ± 103.00	-	11200.00 ± 2.40	-	3.30 ± 0.50
	PP	Maleic anhydride graft (Chattopadhyay et al., 2010)	50.26 ± 0.39	-	1633.00 ± 11.00	-	-
Banana	PP	Grafted with maleic anhydride (Becker et al., 2011)	34.30 ± 0.90	-	356.00 ± 5.30	5200.00 ± 500.00	-
		Alkaline treatment + MA-g-PP (Chattopadhyay et al., 2010)	32.65 ± 0.22	-	1020.00 ± 5.00	47.75 ± 0.35	-
Coconut	PP	Titanate grafted with polyethylene (Pisanu et al., 2019)	14.32 ± 0.57	16.95 ± 0.29	1608.00 ± 63.00	-	-
Jute	PLA	(Sanivada et al., 2020)	32.30	-	2110.00	-	-
	Epoxy	Sodium hydroxide (Pires et al., 2012)	52.00 ± 5.00	-	1700.00 ± 400.00	-	-
	PP	(Mahmud et al., 2021)	56.71	-	4.34	-	-

Source: Own authorship.

2.7 Applications of natural fibers

Natural fibers are used in various applications, such as in the manufacture of fabrics, yarns, ropes, non-wovens, carpets, reinforcements in land, among others. In the last decades, the use of natural fibers in different areas of engineering has become increasing and increasingly investigated, due to its application as reinforcement in composite materials. Table 5 presents some applications of plant fibers and their polymeric composites found in the literature.

Table 5. Applications of plant fibers and polymer matrix composites**.**

Fiber source	Composite application	References
Coconut	Bumper; Absorption of electromagnetic waves; storage tanks; wind turbine blades	(Mahmud et al., 2021; Wearn et a., 2020; Kangishwar et al., 2022; David et al., 2021; Yah et al., 2018)
Bamboo	Batteries; Automotive industry; Aerospace industry; Structural beams; Decking, Dielectric materials	(Gholampour and Ozbakkaloglu, 2020; Moura, 2019; Li et al., 2020; Han et al., 2017; Limper and Fischer, 2015)
Banana	Constructions; Dielectrics; Brick; Underfloor protection for cars	(Gholampour and Ozbakkaloglu, 2020; Kangishwar et al., 2022; Bolduc et al., 2018; Bhuvaneswari et al., 2017)
Açaí)	Cement Reinforcement	(Sato et al., 2020; Alves et al., 2010
Sisal	Cement reinforcement; Construction industry; Medicine; Wind turbine blades	(Li et al., 2020; Limper and Fischer, 2015; Lima et al., 2014; Ramzy et al., 2014; Arumugam et al., 2020)
Mallow	Automotive industry	(Fraxe and Ferreira, 2018; Margem et al., 2015; Devnani and Sinha, 2019)
Jute	Automotive components; Water pipes; Chip boards; Door panels; Building panels; Dielectric materials; Solar parabolic trough collector; Electromagnetic interference shields; Wind turbine blades	(Fraxe and Ferreira, 2018; Mahmud et al., 2021; Li et al., 2020; Alves et al., 2010; Devnani and Sinha, 2019)

Source: Gholampour et al. (2020).

In the aerospace sector, vegetable fibers are already widely used by European countries for making sidewalls. In this study, the popularity of plant fibers in the interior design sector is also cited, where many furniture and panels are manufactured using plant fibers (Khan et al., 2019).

In recent decades, an increasing number of car models have featured natural fiber-reinforced polymers in door panels, package trays, hat racks, instruments panels, internal engine covers, sun visors, boot liners and oil/air filters. Thus, applications have progressed to more structurally demanding components such as seat backs and exterior underfloor paneling (Pickering et al., 2016). These composites now account for around 4% of the European Union’s total composite output since legislation has been established in the European Union’s mandating the utilization of natural fibers in the production of automobile components (Pokhriyal et al., 2023).

In the realm of the automotive industry, natural fiber composites exhibit superior performance compared to their synthetic fiber reinforced counterparts, owing to their cost-effectiveness, reduced weight, and sustainable nature (Choudhary et al., 2023). In this scenario, many researchers are increasingly developing renewable substitutes in automobiles (Kim and Chalivendra, 2020; Roy et al., 2019). The use of vegetable composites is relevant in this sector due to the need to reduce weight in automobiles, which provides lower fuel consumption and reduction in the emission of gasses into the atmosphere, in addition to raw materials derived from petroleum. For example, hemp and flax fibers are strong candidates for replacing fiberglass in many components, especially in the German automotive sector (Jeyapragash et al., 2020).

Furthermore, for decades natural fibers have been evolving in the civil industry in many forms due to their characteristics. In this sense, several studies investigate the use of natural fibers as reinforcement in concrete, in order to develop an ecologically correct material with better physicochemical properties (Azevedo et al., 2021; Hu et al., 2018).^{0}

In this scenario, the fibers extracted from the rod tape by the maceration process have a moderately high tensile strength and stiffness. Such fibers stand out when the combination of strength, lightness and noise absorption is required, which makes them great options for the automotive and construction industry (Gholampour and Ozbakkaloglu, 2020).

3 CONCLUSION

Polymer composites reinforced with natural fibers are replacing synthetic materials due to their ecological, non-toxic, easily obtainable, low cost and biodegradable nature. However, research into these fibers needs to be carried out to improve their properties and workability.

Through a systematic review of the literature, it was noticed that the mechanical properties of composites depend on several factors, such as fiber orientation and length, which must be optimized. In addition, the properties of vegetable fiber reinforced materials can be improved with surface treatments, such as chemical acetylation and alkali treatments. This process is responsible for the removal of impurities found in the cell walls of fibers such as lignins, waxes, hemicellulose, among others.

The use of plant fibers as reinforcement in polymeric matrices must still be explored, as there are few reports in the literature. In addition, given the high Brazilian potential in the production of natural fibers, the use of vegetable fibers in industrial applications is promising, solving the problem of waste in disposal and presenting low cost, thus reinforcing the economic viability in several applications. Thus, it is believed that in the future plant fibers will have even more prominence for being able to effectively replace the synthetic fibers already used in the market.

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REFERENCES

ALVES, C.; FERRAO, P. M. C.; SILVA, A. J.; REIS, L. G.; FREITAS, M.; RODRIGUES, L. B.; ALVES, D. E. Ecodesign of automotive components making use of natural jute fiber composites. **J Clean Prod,** Amsterdam, v. 18, p. 313-327, 2010. DOI 10.1016/j.jclepro.2009.10.022.

ARUMUGAM, S.; ANDASAMY, J.; SHAH, A. U.; SULTAN, M. T. H.; SAFRI, S. N. A.; MAJID, M. S. A.; BASRI, A. A.; MUSTAPHA, F. Investigations on the Mechanical Properties of Glass Fiber/Sisal Fiber/Chitosan Reinforced Hybrid Polymer Sandwich Composite Scaffolds for Bone Fracture Fixation Applications. **Polymers,** Basel; v. 12, n. 7, p. 1501, Jul 2020. DOI 10.3390/polym12071501.

ATMAKURI, A.; PALEVICIUS, A.; KOLLI, L.; VILKAUSKAS, A.; JANUSAS, G. Development and Analysis of Mechanical Properties of Caryota and Sisal Natural Fibers Reinforced Epoxy Hybrid Composites. **Polymers**, Basel, v. 13, n. 6, p. 864, Mar 2021. DOI 10.3390/polym13060864.

AZEVEDO, A. R. G.; MATOS, P. R.; MARVILA, M. T.; SAKATA, R. D.; SILVESTRO, L.; GLEIZE, P. J. P.; BRITO, J. Rheology, Hydration, and Microstructure of Portland Cement Pastes Produced with Ground Açaí Fibers. **Appl Sci,** Basel, v. 11, n. 7, p. 3036, Mar 2021. DOI 10.3390/app11073036.

BECKER, D.; KLEINSCHMIDT, A. C.; BALZER, P. S.; SOLDI, V. Influência da sequência de mistura do PP-MA nas propriedades dos compósitos de PP and fibra de bananeira. **Polímeros,** São Carlos, v. 21, n. 1, p. 7-12, 2011. DOI 10.1590/S0104-14282011005000012.

BHUVANESWARI, H.; VINAYAKA, D.; ILANGOVAN, M.; REDDY, N. Completely biodegradable banana fiber-wheat gluten composites for dielectric applications**. J Mater Sci Mater Electron**, New York, v. 28, n. 23, p. 12383–12390, Sep 2017. DOI 10.1007/s10854-017-7058-4

BOARETTO, J.; FOTOUHI, M.; TENDE, E.; AVER, G. F.; MARCON, V. R. R.; CORDEIRO, G. L.; BERGMANN, C. P.; CAMARGO, F. V. Biomimetics and Composite Materials toward Efficient Mobility: A Review. **J Compos Sci**, Basel, v. 5, n. 1, p. 22, Jan 2021. DOI 10.3390/jcs5010022.

BOLDUC, S.; JUNG, K.; VENKATA, P.; ASHAKCLINE, M.; JAYASINGHE, R.; BAILLIE, C.; LESSARD, L. Banana fiber/low-density polyethylene recycled composites for third world eco-friendly construction applications – Waste for life project Sri Lanka. **J Reinf Plast**, Los Angeles, v. 37, n. 21, p.1322-1331, Sep 2018. DOI 10.1177/0731684418791756.

BORGES, A.; MOTTA, L.; PINTO, E. B. Study of Concrete Properties with Vegetal and polypropylene fibers for use in structural walls. **Matéria**, Rio de Janeiro, v. 24, n. 2, e-12364, Jan. 2019. DOI 10.1590/S1517-707620190002.0679. (In portuguese)

BRESSIANI JÚNIOR, I.; BELINI, U. L.; ELLENBERGER, A.; KEINERT, A. C. Fibras Naturais and Compósitos nas Indústrias de Mobilidade. **MIX Sustentável**, Florianópolis, v. 6, n. 4, p. 129-138, Aug. 2020.

CHANDGUDE, S.; SALUNKHE, S. In state of art: Mechanical behavior of natural fiber-based hybrid polymeric composites for application of automobile components. **Polymer Composites**, Wetteren, v. 42, n. 6 p. 2678-2703, Mar 2021. DOI 10.1002/pc.26045.

CHATTOPADHYAY, S. K.; KHANDAL, R. K.; UPPALURI, R.; GHOSHAL, A. K. Bamboo fiber reinforced polypropylene composites and their mechanical, thermal, and morphological properties. **J Appl Pol Sci**, Hoboken, v. 119, n. 3, p. 1-8, Aug. 2010; 9: 1-8. DOI 10.1002/app.32826.

CHATTOPADHYAY, S. K.; KHANDAL, R.; UPPALURI, R.; GHOSHAL, A. K. Bamboo fiber reinforced polypropylene composites and their mechanical, thermal, and morphological properties. **J Appl Polym Sci**, Hoboken, v. 119, n. 3, p. 1619-1626, Feb 2011. DOI 10.1002/app.32826.

CHAWLA, K. K. **Metal Matrix Composites**. *In*: CHAWLA, K. K. et al. Composite Materials: Science and Engineering. 3rd ed. New York: Springer New York, 2012, p. 197-248.

CHOUDHARY, S.; SAIN, M. K.; KUMAR, V.; SARASWAT, P.; JINDAL, M. S. Advantages and applications of sisal fiber reinforced hybrid polymer composites in automobiles: A literature review. **Mater Today: Proc**, Amsterdam, Feb 2023. DOI 10.1016/j.matpr.2023.02.072.

COSTA, T.L; GUEDES, V.S.; RIBEIRO, C.C.; OLIVEIRA, D.M.; HENRIQUES, A.B.; LIBÂNIO, M.; AYRES, E.; ALMEIDA, M.L.B.A. Sustainable concrete produced with petroleum catalyst waste and polyethylene glycol as a self-healing agent. **Rev. Gest. Soc. Ambient**, Miami, v.18, p.1-15, Jan 2024. DOI 10.24857/rgsa. v18n1-015.

DARIA, M.; KRZYSZTOF, L.; JAKUB, M. Characteristics of biodegradable textiles used in environmental engineering: A comprehensive review. **J of Clean Produc**, Amsterdam, v. 268, p. 122-129, Sep. 2020. DOI 10.1016/j.jclepro.2020.122129.

DAVID, A. O.; CHUKWUEMEKA, I. S.; OSTHER, E. E.; SALIHU, G. N. Development and characterization of hybrid coconut/glass fibers reinforced low density polyethylene composites for bumper application. **Metall Mater Eng**, Amsterdam, v. 27, n. 1, p. 89-104, Aug 2020. DOI 10.30544/453

DEVNANI, G.; SINHA, S. Extraction, characterization and thermal degradation kinetics with activation energy of untreated and alkali treated Saccharum spontaneum (Kans grass) fiber. **Compos B Eng**, Amsterdam, v. 166, p. 436-445, Jun 2019. DOI 10.1016/j.compositesb.2019.02.042.

FERREIRA, A. D. S.; MATOS, M. The building of the authoritative discourse: agronomic knowledge, reasearches and controversoes on jute in São Paulo. **Rev Hist,** São Paulo, v. 177, 2018. DOI 10.11606/issn.2316-9141.rh.2018.131697. (in Portuguese)

FRAXE, T. J. P.; FERREIRA, A. S. Nova técnica para extração de fibras de juta and malva em processo a seco no Estado do Amazonas: o resgate da utopia. **Inclusão Social**, Brasília, v. 12, n. 1, p.161-171, Dec. 2018. (In portuguese).

GHOLAMPOUR, T.; OZBAKKALOGLU, A. A review of natural fiber composites: properties, modification and processing techniques, characterization, applications**. J Mater Sci**, New York, v. 55, p. 829–892, Jan 2020. DOI 10.1007/s10853-019-03990-y

GIRIJAPPA, Y. G. T.; RANGAPPA, S. M.; PARAMESWARANPILLAI, J.; SIGCHIN, S. Natural fibers as sustainable and renewable resource for development of eco-friendly composites: a comprehensive review. **Front in Mate**, v. 6, n. 226, p. 1-14, Sep. 2019. DOI 10.3389/fmats.2019.00226.

GONÇALVES, F. C. P.; JÚNIOR, M. Q. D. S.; FONTE, K. E. S.; LIMA, R. N.; PEREIRA, K. R. A.; ALMADA, L. F. A. Análise da caracterização mecânica de compósito composto por fibra de coco and resina acrílica. *In:* ANDRADE, D. F. et al. **Engenharia no Século XXI Volume 3**. 1st ed. Belo Horizonte: Poisson, 2019, cap. 6, p. 81-88.

HAMIDON, M. H.; SULTAN, M. T.; HAMDAN, A.; SHAH, A. U. M. Effects of fibre treatment on mechanical properties of kenaf fibre reinforced composites: A review. **J Mater Res Technol**, Amsterdam, v. 8, n. 3, p. 3327–3337, May 2019. DOI 10.1016/j.jmrt.2019.04.012.

HAN, Q.; YI, Z.; WANG, F.; . WU, Y.; WANG, L. Preparation of bamboo carbon fiber and sandwich-like bamboo carbon fiber@SnO2@carbon composites and their potential application in structural lithium-ion battery anodes. **J Alloys Compd**, Amsterdam, v. 709, p. 227-233, Jun 2017. DOI 10.1016/j.jallcom.2017.03.141.

HU, B.; ZHANG, N.; LIAO, Y.; PAN, Z.; LIU, Y.; ZHOU, L.; LIU, Z.; JIANG, Z. Enhanced Flexural Performance of Epoxy Polymer Concrete with Short Natural Fibers. **Sci China Technol Sci**, New York, v. 61, n. 8, p.1107 – 1113, Jul 2018. DOI 10.1007/s11431-017-9272-4.

HUSSAIN, M. K.; ABBAS, S. H.; YOUNIS, Y. M.; JAMEL, T. Fabrication of Epoxy Composite Mater. Reinforced with Bamboo Fibers**. J Appl Sci Eng**, v. 19, n. 1, p. 1-7, Dec 2020. DOI 10.5937/jaes0-26549.

JEYAPRAGASH, R.; SRINIVASAN, V.; SATHIYAMURTHY, S. Properties of Natural Fiber/Particulate Reinforced Epoxy Composites: A Review of the Literature. **Mater Today: Proc**, Amsterdam, v. 22, p. 1223-1227, 2020. DOI 10.1016/j.matpr.2019.12.146.

JOSSO, B.; BURTON, D. R.; LALOR, M. J. Frequency normalised wavelet transform for surface roughness analysis and characterisation. **Wear,** Amsterdam, v. 252: p. 491-500, Mar 2002. DOI 10.1016/S0043-1648(02)00006-6.

KANGISHWAR, S..; RADHIKA, N.; SHEIK, A. A.; CHAVALI, A.; HARIHARAN, S. A comprehensive Review on Polymer Matrix Composites: Material Selection, Fabrication, and Application. **Polym Bull**, New York, v. 80, p. 47-87, Jan 2022. DOI 10.1007/s00289-022-04087-4.

KARTHI, N.; KUMARESAN, K.; SATHISH, S.; GOKULKUMAR, S.; PRABHU, L.; VIGNESHKUMAR, N. An overview: Natural fiber reinforced hybrid composites, chemical treatments and application areas. **Mater. today: proceeding**, Amsterdam, v. 27, n. 3, p. 2828-2834, Jan. 2020. DOI 10.1016/j.matpr.2020.01.011.

KHAN, A.; VIJAY, R.; SINGARAVELU, D. L.; SANJAY, M. R.; SIENGCHIN, S.; VERPOORT, F.; ALAMRY, K. A.; ASIRI, A. M. Extraction and Characterization of Natural Fiber from Eleusine Indica Grass as Reinforcement of Sustainable Fiber-Reinforced Polymer Composites. **J Nat Fibers,** Los Angeles, v. 18, p. 1-9, Nov 2019. DOI 10.1080/15440478.2019.1697993.

KIM, Y. K.; CHALIVENDRA, V. Natural fibre composites (NFCs) for construction and automotive industries. *In:* KOZLOWSKI; MACKIEWICZ-TALARCZYK, M. **Handbook of Natural Fibres**. 2nd ed. North Dartmouth: Elsevier, 2012, p. 469-498. DOI 10.1533/9780857095510.2.254

LATIF, R.; WAKEEL, S.; KHAN, N. Z.; SIDDIQUEE, A. N.; VERMA, S. L.; KHAN, Z. A. Surface treatments of plant fibers and their effects on mechanical properties of fiber-reinforced composites: A review. **J of Reinforc Plast and Comp**, Los Angeles, v. 38, n. 1, p. 15-30, Jan. 2019. DOI 10.1177/0731684418802022.

LI, M.; PU, Y.; THOMAS, V. M.; YOO, C. G.; OZCAN, S.; DENG, Y.; NELSON, K.; RAGAUSKAS, A. J. Recent Advancements of Plant-based Natural Fiber-reinforced Composites and their Applications. **Compos B Eng,** Amsterdam, v. 200, p. 108254, Nov 2020. DOI 10.1016/j.compositesb.2020.108254.

LIMA, P. R.; SANTOS, R. J.; FERREIRA, S. R.; FILHO, R. D. T. Characterization and treatment of sisal fiber residues for cement-based composite application. **Engenharia Agrícola,** v. 34, n. 5, p. 812, Sep 2014. DOI 10.1590/s0100-69162014000500002.

LIMPER, A.; FISCHER, K. Processing of Natural Fibres in An Internal Mixer Opens up New Perspectives for Thermoplastic Lightweight Materials in the Automotive Industry. **Int Polym Sci,** Los Angeles**,** v. 42, n. 2, p. 1-4, Feb 2015. DOI 10.1177/0307174X1504200201.

MAHMUD, S.; HASAN, K.; JAHID, M.; MAHIUDDIN, K.; ZHANG, R.; ZHU, J. Comprehensive review on plant-fiber reinforced polymeric biocomposites. **J of Mater Sci**, Amsterdam, v. 56, p. 7231–7264, Apr 2021. DOI 10.1007/s10853-021-05774-9.

MANIMARAN, P.; SARAVANAN, S.; SANJAY, M.; JAWAID, M.; SIENGCHIN, S.; FIORE, V. New Lignocellulosic Aristida Adscensionis Fibers as Novel Reinforcement for Composite Mater.s: Extraction, Characterization and Weibull Distribution Analysis**. J Polym Environ,** New York, v. 28, p. 803-811, Mar 2020. DOI 10.1007/s10924-019-01640-7.

MARGEM, J. I.; GOMES, V. A.; MARGEM, F. M.; IBEIRO, C. G. D.; BRAGA, F. O.; MONTEIRO, S. N. Flexural Behavior of Epoxy Matrix Composites Reinforced with Malva Fiber. **Mater Research**, South Brisbane, v. 18, p. 114-120, Dec 2015. DOI 10.1590/1516-1439.359514.

MISHRA, T.; MANDAL, P.; ROUT, A. K.; SAHOO, D. A state-of-the-art review on potential applications of natural fiber-reinforced polymer composite filled with inorganic nanoparticle. **Compos C: Open Access,** Amsterdam, v. 9, p. 100298, Oct 2022. DOI 10.1016/j.jcomc.2022.100298.

MOHANAVEL, V.; KUMAR, S. S.; VAIRAMUTHU, J.; GANESHAN, P.; NAGARAJAGANESH, B. Influence of Stacking Sequence and Fiber Content on the Mechanical Properties of Natural and Synthetic Fibers Reinforced Penta-Layered Hybrid Composites. **J Nat Fibers**, Milton Park, v. 19, n. 4, p. 5258-5270, Feb 2021. DOI 10.1080/15440478.2021.1875368.

MORATO, B.N.; GUEDES, V.S.; BARBOSA, R.A.; BRANCO, L.A.M.N.; RIBEIRO, S.E.C.; FLOR, J.M.; OLIVEIRA, D.M.; ALMEIDA, M.L.B.A. Influence of Coconut Fiber Waste and Rice Husk Ash on Green Concrete. **Rev. Gest. Soc. Ambient.** Miami, v.18, p.1-18, Jan 2024. DOI 10.24857/rgsa.v18n3-033.

MOURA, C. R. Aplicações and tratamentos da fibra de bamboo and similares: uma revisão**. J Eng Exact Sci,** v. 5, n. 5, p. 46, 2019. DOI 10.18540/jcecvl5iss5pp0460-0468.

MUNDE, Y. S.; INGLE, R. B.; IRULAPPASAMY, S. A comprehensive review on the vibration and damping characteristics of vegetable fiber-reinforced composites. **J of Reinforc Plast and Comp**, Los Angeles, v. 38, n. 17, p. 822–832, May 2019. DOI 10.1177/0731684419838340.

NASCIMENTO, G. M.; FUJIYAMA, R. T.; SILVA, S. S. C.; DIAS, R. S.; MAGALHÃES, I. S. Estudo and comparação entre compóstios reforçados com fibras naturais, fibras de vidro and híbridos. *In:* XIII Congresso Brasileiro de Engenharia Química em Iniciação Científica, Uberlândia, Brazil, 21 May- 24 Apr. 2019. **Anais** [...]. São Paulo: Blucher, 2019. Paper no. 1. (in Portuguese)

NERY, T. B. R.; SANTOS, Z. I. G. D.; JOSÉ, N. M. Development and Characterization of Polyhydroxybutyrate and Banana Fiber biocomposites. **Matéria**, Rio de Janeiro, v. 23, n. 4, e-12257, Apr 2018. DOI 10.1590/S1517-707620180004.0591.

NETO, E. M. C.; ARAUJO, E. C. G.; VERAS, H. F. P.; PELISSARI, A. L.; SILVA, T. C.; CORTE, A. P.; SANQUETTA, C. R. A categorical modelling approach to site and growth of eucalyptus stands in brazilian eastern amazon. **Rev Gest Soc Ambient,** Miami, v.17, n.9, p.1-19, e04115, Aug 2023. DOI 10.24857/rgsa.v17n9-003.

NETO, J. S. S.; LIMA, R. A. A.; CAVALCANTI, D. K. K.; SOUZA, J. P. B.; AGUIAR, R. A. A.; BANEA, M. D. Effect of chemical treatment on the thermal properties of hybrid natural fiber-reinforced composites. **J Appl Polym Sci**, Hoboken, v. 136, n. 1, p. 47154, Oct 2018. DOI 10.1002/app.47154.

PANDEY, R.; RAJESWARI, M. Sustainable technologies and sustainable products. **Rev Gest Soc Ambient,** Miami, v.17, n. 4, p. 1-13, e03377, Jun 2023. DOI 10.24857/rgsa.v17n4-006.

PICKERING, K. L.; EFENDY, M. A.; LE, T. M. A review of recent developments in natural fibre composites and their mechanical performance. **Compos Part A Appl Sci**, Amsterdam, v. 83, p. 98-112, Apr 2016. DOI 10.1016/j.compositesa.2015.08.038.

PIRES, E. N.; MERLINI, C.; AL-QURESHI, H. A.; SALMORIA, G. V.; BARRA, G. The influence of alkaline treatment on jute fiber-reinforced epoxy resin composite. **Polímeros,** São Carlos, v. 22, n. 4, p. 339-344, Dec 2011. DOI 10.1590/S0104-14282012005000053. (in Portuguese)

PISANU, L.; BARBOSA, J.; SOUZA, R.; NASCIMENTO, M. Evaluating the influence of coupling agents in the structural properties of polypropylene coconut fiber composites. **Mater Res Express,** Bristol, v. 6, p. 115320, Oct 2019. DOI 10.1088/2053-1591/ab4626.

POKHRIYAL, M.; RAKESH, P.; SANJAY, M. R.; SIENGCHIN, S. Effect of alkali treatment on novel natural fiber extracted from Himalayacalamus falconeri culms for polymer composite applications. **Biomass Convers Biorefi**, New York, Feb 2023.DOI 10.1007/s13399-023-03843-4.

RAMZY, A.; BEERMANN, D.; STEUERNAGEL, L.; MEINERS, D.; G. ZIEGMANN, G. Developing a new generation of sisal composite fibres for use in industrial applications. **Compos B Eng,** New York, v. 66, p. 287-298, Nov 2014. DOI 10.1016/j.compositesb.2014.05.016.

ROCHA, L. D.; JÚNIOR, L. U. D. T.; MARVILA, M. T.; PEREIRA, E. C.; SOUZA, D.; AZEVEDO, A. R. G. A Review of the Use of Natural Fibers in Cement Composites: Concepts, Applications and Brazilian History. **Polymers**, Basel, v. 14, n. 10, p. 2043, May 2022. DOI 10.3390/polym14102043.

ROY, P.; TADELE, D.; DEFERSHA, F.; MISRA, M.; MOHANTY, A. A comparative life-cycle assessment of talc- and biochar-reinforced composites for lightweight automotive parts. **Clean Technol Environ Policy,** New York, v. 21, n. 8, p. 1535–1548, Apr 2020. DOI 10.1007/s10098-019-01807-9.

RUSCH, F.; HILLIG, E.; CEOLIN, G. B. Anatomia de hastes adultas de bambu: uma revisão. **Pesquisa Florestal Brasileira**, Colombo, v. 39, p. 1-10, Sep. 2018. DOI 10.4336/2018.pfb.38e201701530. (In portuguese)

SALGADO, E. G.; FRANCHI, R. A. S. Green technologies: the role of green patents for innovation, preservation and sustainable development. **Gest Soc Ambient,** Miami, v.17, n. 8, p. 1-17, e03331, Aug 2023. DOI 10.24857/rgsa.v17n8-023.

SANIVADA, U. K.; MÁRMOL, G.; BRITO, F.; FANGUEIRO, R. PLA Composites Reinforced with Flax and Jute Fibers - a Review of Recent Trends, Processing Parameters and Mechanical Properties. **Polymers**, Basel, v. 12, n. 10, p. 2373, Oct 2020. DOI 10.3390/polym12102373.

SANJAY, M.; MADHU, P.; JAWAID, M.; SENTHAMARAIKANNAN, P.; SENTHIL, S.; PRADEEP, S. Characterization and Properties of Natural Fiber Polymer Composites: A Comprehensive Review. **J Clean Prod**, Amsterdam, v. 172, p. 566-581, Jan 2018. DOI 10.1016/j.jclepro.2017.10.10.

SANJAY, M.; MADHU, P.; JAWAID, M.; SENTHAMARAIKANNAN, P.; SENTHIL, S. PRADEEP, S. Characterization and Properties of Natural Fiber Polymer Composites: A Comprehensive Review**. J Clean Prod,** Amsterdam, v. 172, p. 566-581, Oct 2017. DOI 10.1016/j.jclepro.2017.10.101.

SANJAY, M.; SIENGCHIN, S.; PARAMESWARANPILLAI, J.; JAWAID, M.; PRUNCU, C. I.; KHAN, A. A comprehensive Review of Techniques for Natural Fibers as Reinforcement in,- Composites: Preparation, Processing and Characterization. **Carbohydrate polymers**, Amsterdam, v. 20, p. 108-121, Mar. 2019. DOI 10.1016/j.carbpol.2018.11.083.

SATO, M. K.; LIMA, H. V. D.; COSTA, A. N.; RODRIGUES, S.; MOONEY, S. J.; CLARKE, M.; PEDROSO, A.; MAIA, C. M. B. F. Biochar as a sustainable alternative to açaí waste disposal in Amazon, Brazil. **Process Saf Environ Prot**, Amsterdam, v. 139, n. 9, p. 36-46, Apr. 2020. DOI 10.1016/j.psep.2020.04.001.

SATYANARAYANA, K.; GUIMARÃES, J.; WYPYCH, F. Studies on Lignocellulosic Fibers of Brazil. Part I: Source, Production, Morphology, Properties and Applications. **Compos. Part A Appl Sci**, Amsterdam, v. 38, n. 7, p. 1694–1709, Jul. 2007. DOI 10.1016/j.compositesa.2007.02.006.

SPINACÉ, M. A.; JANEIRO, L. G.; BERNARDINO, F. C.; GROSSI, T. A.; PAOLI, M. Poliolefinas reforçadas com fibras vegetais curtas: sisal× curauá. **Polímeros**, São Carlos, v. 21, n. 3, p. 168-174, 2011. DOI 10.1590/S0104-14282011005000036.

SUBRAMANIAN, M.; ARUNKUMAR, N.; RETHNAM, G. S. N.; THANIGAIARASU, B. Exploration of the Damping Characteristics of Basalt Hybrid Composites Reinforced with Natural Fibers and Epoxy Resin. **Fibers and Polymers**, New York, v. 22, n. 6, p. 1684-1692, Mar 2021. DOI 10.1007/s12221-021-0761-z

SUGIMAN, S.; SETYAWAN, P.; ANSHARI, B. Effect of fiber length on the mechanical properties and water absorption of bamboo fiber/polystyrene-modified unsaturated polyester composites. *In*: The 4th International Conference on Science, Technology and

Interdisciplinary Research (IC-STAR 2018), Bangka-Belitung Province, Indonesia, 29–30 August 2018. **Anais** […]. Bristol: IOP, 2018. Paper no. 532. DOI 10.1088/1757-899X/532/1/012008.

TONK, R. Natural fibers for sustainable additive manufacturing: A state of the art review. **Mater. Today: Proc**, Amsterdam, v. 37, n. 4, p. 3087-3090, Seop. 2020; DOI 10.1016/j.matpr.2020.09.017.

VERMA, A. R.; DAGALE, M. D.; MAHAJAN, R. M.; BHOLE, K. S. Hybrid Natural Fibers Composites with Jute and Banana Fibers: A Review. *In:* 4th Biennial International Conference on Nascent Technologies in Engineering (ICNTE), Navi Mumbai, India, 15-16 January 2021. **Anais** [...]. Manhattan: IEEE, 2021. Paper no. 20995389. DOI 10.1109/ICNTE51185.2021.9487714.

VIJAY, R.; VINOD, A.; SINGARAVELU, D. L.; SANJAY, M. R.; SIENGCHIN, S. Characterization of chemical treated and untreated natural fibers from Pennisetum orientale grass-A potential reinforcement for lightweight polymeric applications. **Int J Lightweight Mater Manuf**, v. 4, n. 1, p. 43-49, Jul 2021. DOI 10.1016/j.ijlmm.2020.06.008.

WEARN, Y. N.; MONTAGNA, L. S.; PASSADOR, F. R. Compósitos de fibra de coco/LDPE: efeito do tratamento superficial das fibras de coco em compósitos verdes. **Matéria,** Rio de Janeiro, v. 25, n. 1, Jun 2020. DOI 10.1590/S1517-707620200001.0873. (in Portuguese)

YAH, N. F. N.; RAHIM, H. A.; LEE, Y. S.; WEE, F. H.; ZAINAL, H. Electromagnetic Wave Absorption Properties of Novel Green Composites Coconut Fiber Coir and Charcoal Powder over X-band Frequency for Electromagnetic Wave Absorbing Applications. **Ad Electromagn**, France, v. 7, n. 1, p. 13-18, Jan 2018. DOI 10.7716/aem.v7i1.598.

ZHANG, K.; WANG, F.; LIANG, W.; WANG, Z.; DUAN, Z.; YANG, B. Thermal and Mechanical Properties of Bamboo Fiber Reinforced Epoxy Composites. **Polymers**, Basel, v. 10, n. 6, p. 1–18, Jun 2018. DOI 10.3390/polym10060608.

ZULKARNAIN, N. A.; YOUSIF, B. F.; MANALO. A.; KARUNASENA, W. M. A Review on the Degradability of Polymeric Composites Based on Natural Fibres. **Mater & Design**, Amsterdam, v. 47, p. 424-442, May 2013. DOI 10.1016/j.matdes.2012.11.025.