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POTENTIAL APPLICATION OF AÇAÍ SEED WASTE IN BIODEGRADABLE POLYMERIC COMPOSITES SUCH AS PBAT: A REVIEW REGARDING THIS ISSUE

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Abstract: This review explores the potential application of açaí seed waste in biodegradable polymer composites, specifically PBAT (polybutylene adipate-co-terephthalate). The review covers the characterization of waste, composite processing methods and the resulting mechanical properties. The studies analyzed indicate that the incorporation of açaí seed waste can significantly improve the properties of composites, offering a sustainable solution for the materials industry. The review discusses characterization techniques, including visual inspection and Fourier transform infrared spectroscopy (FTIR), and highlights the potential industrial applications and environmental benefits of using agro-industrial waste in polymer composites. The findings suggest that açaí seed waste can be effectively used to improve the performance and sustainability of PBAT composites, offering a promising avenue for future research and industrial applications.

Keywords: PBAT, biodegradable composites, açaí seed, mechanical properties, sustainability.

INTRODUCTION

The development of sustainable materials has become a significant field of research, driven by the need to reduce environmental impacts associated with consumer products. Polymeric composites that incorporate agricultural waste, such as açaí seeds, emerge as promising alternatives, combining biodegradability and use of by-products of low economic value (WATAYA et al., 2016). Such composites offer a solution to the generation of waste, while enhancing the mechanical properties of the polymers used, such as PBAT and others (FERREIRA et al., 2019).

The use of fibers from açaí waste as reinforcement in polymer matrices not only contributes to the circular economy, but also enhances specific mechanical properties of the composite, such as strength and stiffness (ARAUJO et al., 2023). Açaí, present in the Atlantic Forest and Amazon regions, has great potential for use in composites, representing a valuable addition of value to a waste that would otherwise be discarded (GUEDES et al., 2022).

The use of açaí seeds as reinforcement in biodegradable polymer matrices, such as PBAT (Poly (butylene adipate-co-terephthalate)), presents significant potential for the production of composites with improved mechanical properties, while adding value to a hitherto underutilized waste. PBAT is a biodegradable polymer known for its flexibility and toughness, making it a suitable choice for applications that require these properties (JIAN; XIANGBIN; XIANBO, 2020).

Studies reveal that the addition of açaí fibers to polymer matrices such as PBAT and other polymers can result in composites with improved mechanical properties, making them suitable for a variety of applications, from packaging to automotive parts (ROSSETO et al., 2019). The appropriate choice of proportions of constituent materials and processing conditions is crucial to optimize the mechanical properties and biodegradability of composites (TOGLIATTI et al., 2021).

GENERAL ASPECTS

LIGNOCELLULOSIC WASTE

Lignocellulosic biomass (BL) constitutes a significant part of the waste generated globally, mainly from agriculture, forestry and food processing. These residues include straw, bark, bagasse, and other agricultural and forestry byproducts. Due to their carbon-rich composition and abundance, there is a growing interest in the valorization of these materials for the production of bioenergy, bioproducts and biochemicals. Lignocellulosic biomass, composed of cellulose, hemicellulose and lignin, stands out as the most abundant biological resource on the planet, with an estimated annual production of 181.5 billion tons. The current use of approximately 8.2 billion tons of this biomass highlights the vast underutilized potential, especially regarding conversion into chemical and energy products through lignocellulosic biorefineries (DAHMEN et al., 2019). However, according to Tišma, Bucić-Kojić and Planinić (2021), only a fraction of this biomass is currently used, highlighting its underutilized potential. The main sources of BL include crop residues such as straw and bark, food processing industry by-products such as sugarcane bagasse and cereal residues, and dedicated crops such as miscanthus and switchgrass. Açaí waste, specifically, is an example of BL from the food processing industry. After extraction of the açaí pulp, seeds and fibers remain that constitute a form of this biomass as shown in figure 1. The valorization of BL, including açaí residues, into high added value products requires the implementation of modular biorefinery concepts, such as discussed by Dahmen et al. (2019).

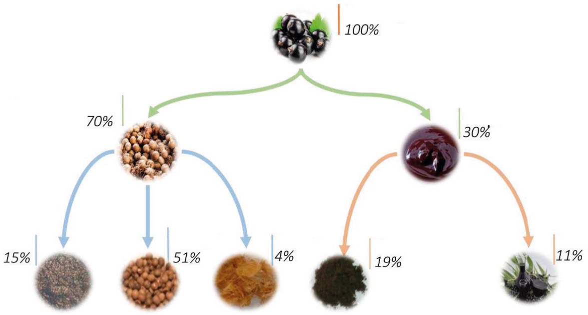

Fig. 1 - Açaí: waste and products generated. source: (LEMOS et al., 2021)

COMPOSITION AND PROPERTIES OF WASTE

Lignocellulosic biomass (BL) is an abundant and promising organic resource, essentially composed of three main components: cellulose, hemicellulose and lignin. Cellulose, a polysaccharide composed of glucose units linked by β-1,4-glycosidic bonds as shown in figure 2, is the most abundant organic component on earth, forming the primary skeletal structure of plant cell walls. As a fundamental element of lignocellulosic biomass, cellulose plays a crucial role in the bioenergy and bioproducts industry, serving as a substrate for the production of bioethanol and other biofuels. The robustness of cellulose arises from its crystalline organization and the formation of microfibrils, which provide resistance and stability to the plant structure. However, this same crystallinity and dense hydrogen network make cellulose resistant to hydrolysis, challenging its conversion into fermentable sugars (WOICIECHOWSKI et al., 2020).

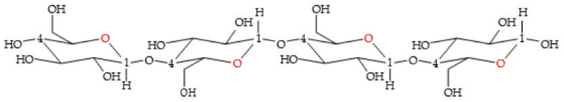

Fig. 2 - Repeated molecular structure of cellulose

Hemicellulose, a crucial component of lignocellulosic biomass, stands out for its heterogeneous and complex composition, consisting of a matrix of polysaccharides, including xylans, mannans and galactans. Unlike cellulose, hemicellulose has a branched structure and is not as crystalline (figure 3), which facilitates its hydrolysis. This polymer plays a fundamental role in the cellular matrix of plants, acting as a bridge between cellulose and lignin, and contributing to the structural integrity and flexibility of the cell wall (LUO et al., 2019).

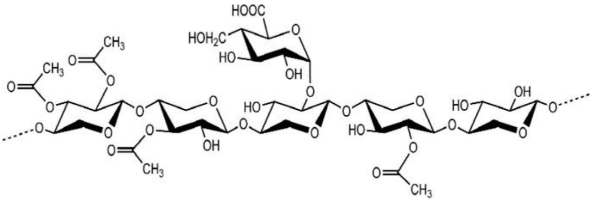

Fig. 3 -Molecular structure of hemicellulose

Lignin, an integral component of lignocellulosic biomass, is a complex and three-dimensional polymer composed of phenylpropane units as shown in figure 4, providing rigidity and structural resistance to plants. Characterized by its heterogeneity and recalcitrance, lignin plays a crucial role in protecting cellulose and hemicellulose against enzymatic degradation. This attribute, although essential for plant integrity, represents a significant challenge for the efficient conversion of biomass into biofuels and chemicals. Recently, advances in pretreatment strategies have focused on the selective modification or removal of lignin, aiming to reduce its recalcitrance and improve carbohydrate accessibility (YOO et al., 2020).

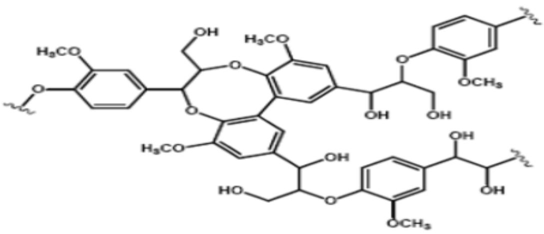

Fig. 4 - Molecular structure of lignin

AÇAÍ RESIDUES

In recent years, açaí has consolidated itself as one of the pillars of the Brazilian agroindustry, reflecting not only its nutritional and medicinal importance, but also its growing economic value. According to data from the Brazilian Institute of Geography and Statistics (IBGE), açaí production in Brazil has experienced a significant increase, from 1,091,667 tons in 2016 to an impressive 1,699,588 tons in 2022, accompanied by a substantial increase in the value of market, from approximately 2 billion reais to more than 6 billion reais in the same period.

The characterization of pulped açaí seeds reveals an interesting potential for the valorization of these residues, mainly due to their chemical composition and physical properties. In the work of Tavares et al. (2020), açaí residues, particularly the fibers extracted from the seeds, exhibit an approximate composition of 40% cellulose, 12% hemicellulose and 40% lignin, in addition to a moisture content of 9% and 2% ash. The study by Queiroz et al. (2020) demonstrates that açaí seeds can be transformed into high-surface activated carbon, offering an innovative solution for removing metal ions from water, effectively taking advantage of the waste generated during açaí processing. The research by Monteiro et al. (2019) reveals that the seeds contain a high content of mannan, a component of hemicellulose present in various forms of lignocellulosic biomass, which represents around 50% of their dry weight, showing the feasibility of converting this polysaccharide into mannose, a sugar with commercial value, through enzymatic hydrolysis.

Furthermore, Melo et al. (2021) explore the açaí seed as a source of lipids, fibers and phenolic compounds with antioxidant activity, highlighting the high content of dietary fiber (86%) and an interesting profile of unsaturated and saturated fatty acids, indicating potential applications in the cosmetic and food. The study by Souto et al. (2021) highlights the importance of açaí waste as biomass for bioenergy, highlighting its effective thermal conductivity and how it affects the efficiency of the bioenergy process. Açaí waste, resulting from industrial processing, has physical and chemical characteristics that make it promising candidates for the production of thermal energy and the generation of compounds valued through thermochemical conversion processes. Additionally, the work of Buratto, Cocero and Martin (2021) on the microwave-assisted extraction of these residues indicates the presence of phenolic compounds and significant antioxidant capabilities, suggesting possible applications in cosmetic or food industries, in addition to the energy potential.

POLYMER MATRIX COMPOSITES

Composite materials represent a distinct class of engineered materials formed by the strategic combination of two or more materials with remarkably different physical and chemical properties (RAJAK et al., 2019). This combination is designed to produce a new material whose properties are superior to those of the individual components when operating in isolation. The main motivation behind the development of these materials lies in the search for optimized characteristics such as strength, stiffness, density, thermal and electrical resistance, essential to meet the requirements of specific applications (BIERMANN, 2018).

Composites are typically classified based on the type of matrix, which can be polymeric, metallic, ceramic or carbon - and the type of reinforcement used, which ranges from fibers (synthetic or natural) to particles or scales. The matrix acts as the continuous medium, holding together the reinforcing material, which is incorporated to improve the mechanical and physical properties of the composite (GEORGE, 2015).

As for its classification, it is typically based on the type and particularities of the reinforcement that makes up the matrix. This classification can be viewed schematically, as illustrated in figure 5, defined based on the type of reinforcement. This synergy between the components results in enhanced properties, which are carefully tuned to meet the specific needs of a wide range of applications. Composite manufacturing requires an in-depth understanding of the properties of the constituent materials as well as the manufacturing processes. These processes include techniques such as compression molding, extrusion, injection molding and lamination, each tailored to maximize the desired properties of the final composite, taking into consideration, factors such as reinforcement orientation, homogeneous distribution of materials and the minimization of structural defects. et al., 2021). Composites offer versatility and the ability to customize properties that make them attractive materials for sectors such as aerospace, automotive, construction, sports, electronics and biomedical. This diversity of applications highlights the continued importance of research and development in the area of composite materials, with the aim of improving their properties and exploring new application potentials (RAJAK et al., 2019; BIERMANN, 2018).

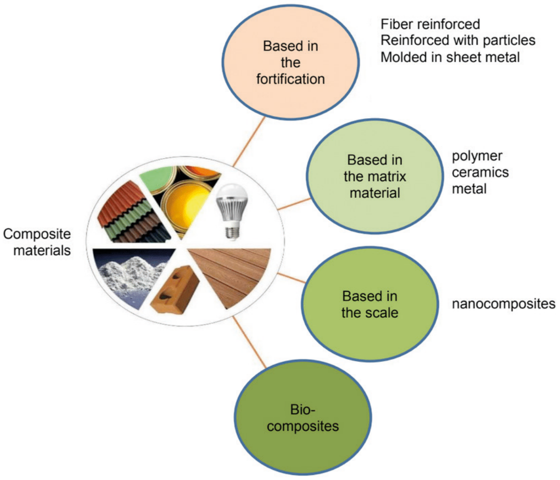

Fig. 5 - Classification of composites by type of reinforcement (adapted from Rajak et al. (2019)

Polymeric composites are materials that combine polymers with reinforcements (such as fibers or particles) to improve their mechanical, thermal, electrical properties, among others. These materials are made up of two main phases: the matrix and the disperse phase (reinforcement). The matrix, usually a polymer, serves as the continuous medium that holds the reinforcements together, while the dispersed phase is incorporated to improve certain properties of the composite material.

The matrix phase in polymer composites is essential for transmitting stress to reinforcements and protecting them against environmental and mechanical damage. Thermoplastic, thermoset polymers and elastomers are commonly used as matrices due to their versatility and ability to be molded into different shapes (GIBSON, 2016). The dispersed phase, or reinforcement, can be composed of fibers, particles, or even nanomaterials, and is responsible for providing the composite with improved properties, such as greater mechanical resistance, modulus of elasticity and impact resistance. Glass, carbon and aramid fibers, as well as silica particles and carbon nanotubes, are common examples of materials used as reinforcements in polymer composites (FRIEDRICH, 2018). The interface between the matrix and the dispersed phase is a critical region that significantly influences the properties of the composite. Adhesion at this interface determines the efficiency of load transfer from the matrix to the reinforcement and directly impacts the mechanical resistance, thermal and electrical conductivity of the composite material. Reinforcement surface treatment techniques and the addition of coupling agents are strategies used to improve the matrix-reinforcement interaction (KASHFIPOUR; MEHRA; ZHU, 2018).

Polymeric composites offer a unique combination of properties that cannot be achieved by constituent materials alone. Its properties depend on the nature of the components, the quantity and arrangement of the dispersed phase, as well as the quality of the interface between the matrix and the reinforcement. For example, the addition of carbon fibers to a polymer matrix can result in a composite material with high mechanical strength and low density, ideal for aerospace and automotive applications (HSISSOU et al., 2021).

BIODEGRADABLE POLYMERS

Biodegradable polymers have stood out as matrices for composites due to growing environmental concerns and the need to develop sustainable materials. Among the most used biodegradable polymers are Poly (butylene adipate-co-terephthalate) (PBAT) (figure 6), polylactide (PLA), polyhydroxy butyrate (PHB) and polyglycolic acid (PGA).

PBAT is known for its combination of flexibility, tensile strength and biodegradability. It is often used in applications that require high flexibility, such as plastic films and packaging. The incorporation of lignocellulosic fibers, such as açaí, into PBAT can improve its mechanical properties, making it suitable for a wider variety of industrial applications. Table 1 presents its main properties. Studies demonstrate that the addition of açaí fibers to PBAT results in composites with greater tensile strength and stiffness, without significantly compromising the flexibility and biodegradability of the material (ELVERS et al., 2016; COSTA et al., 2020).

In addition to PBAT, PLA is known for its high rigidity and clarity, and is widely used in packaging and disposable products. PHB has good mechanical properties and biodegradability, while PGA is known for its high mechanical strength and fast biodegradation rate. The combination of these polymers with açaí fibers can result in materials with superior mechanical properties and greater environmental sustainability (LIU et al., 2022; COSTA et al., 2020).

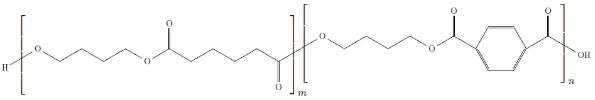

Fig. 6 - Structure of PBAT – Poly (butylene adipate-co-terephthalate)

Property	Value	Unit
Tensile strength	23	MPa
Stretching at break	720	%
Fusion Temperature (TM)	115-120	°C
Glass Transition Temperature (TG)	-35	°C
Fluidity index	2.7 - 4.9	g/10 min (2.16 kg, 190°C)
Density	1.25 - 1.27	g/cm3
Shore Hardness D	32	—

Table 1: Properties of Polybutylene Adipate Terephthalate (PBAT) with additional information adapted from BASF's ecoflex® F Blend C1200 product.

STATE OF THE ART

In reviewing the literature, it is evident that lignocellulosic waste and biodegradable polymers are topics of great interest in scientific research. The Web of Science database reveals significant scientific production in recent decades, with an increasing focus on sustainability and materials innovation. Research into lignocellulosic waste, such as açaí fibers, has intensified since the early 2000s. The Web of Science database features a collection of 39,256 documents related to biodegradable polymers, of which 8,997 are specifically focused on polymer composites biodegradable. Between 2020 and 2023, 10052 articles were published on biodegradable polymers, with a notable growth in interest in the application of agricultural waste in composite materials (Web of Science, 2023).

The incorporation of lignocellulosic residues into polymeric matrices is a promising approach for improving the mechanical and environmental properties of composites. Research indicates that the addition of açaí fibers, for example, can significantly increase the strength and stiffness of composites, offering sustainable solutions for various industrial applications. The use of natural fibers in polymer composites is a growing area of research due to the environmental benefits and improved mechanical properties. The Web of Science database reveals that there are 3258 specific articles on composites reinforced with natural fibers published between 2020 and 2023 (Web of Science, 2023).

Biodegradable polymers, such as Poly (butylene adipate-co-terephthalate) (PBAT), have been widely studied due to their combination of biodegradability and good mechanical properties. The bibliographic analysis reveals that, between 2020 and 2023, there was a substantial production of articles focused on biodegradable composites, with 3252 documents categorized as articles in the area of Polymer Science (Web of Science, 2023). Over the past five years, research on PBAT composites reinforced with lignocellulosic fibers, such as açaí, has gained prominence, with approximately 75% of articles focusing on materials science.

INNOVATIVE APPLICATIONS OF WASTE IN COMPOSITES

The research by Barbosa et al. (2022b) highlights that the introduction of açaí seed residues as reinforcement in polymer composites increases the mechanical resistance and thermal stability of the final material, offering a sustainable and low-cost alternative to traditional reinforcements. Furthermore, the use of açaí fibers in natural rubber composites has shown promising results, with improvements in impact resistance and thermal stability. These discoveries pave the way for innovative applications of açaí waste in sectors such as automotive and construction, where there is a growing demand for sustainable and high-performance materials (Martins et al., 2008). In the area of cementitious composites, Silva et al. (2023b) observe that the alkaline treatment of açaí fibers significantly improves their adhesion to the cement matrix, resulting in composites with superior mechanical properties. This advance suggests a valuable new application for açaí leaves, usually discarded as waste, contributing to the development of more sustainable and efficient construction materials.

The study by Tavares et al. (2020) breaks new ground in the use of açaí fibers (*Euterpe oleracea*) to reinforce polymer composites, highlighting an innovative method through the heat treatment of these fibers in an autoclave. This process modifies the physical, chemical and morphological properties of the fibers, optimizing their interaction with polypropylene (PP) matrices. To achieve this, polypropylene grafted with maleic anhydride (PPgMA) is used as a coupling agent, improving fiber-matrix adhesion. These advance highlights the potential of açaí fibers as a valuable reinforcement for polymer composites and proposes a sustainable alternative for using this waste. Silva et al. (2023a) reinforce this view by exploring açaí fibers as reinforcement in High Impact Polystyrene (HIPS) ecocomposites. The investigation focuses on the effect of alkaline treatment with NaOH on the structural, thermal and mechanical properties of composites, revealing new possibilities for the use of these natural fibers in advanced materials engineering applications.

Nogueira et al. (2022) explore the production of active biodegradable films from red bean flour and açaí seed extract, intended for extra virgin olive oil packaging. The incorporation of 0.5% to 10% açaí seed extract resulted in a significant increase in the tensile strength of the films, in addition to reducing solubility and transparency, increasing relative crystallinity and antioxidant activity. These improvements depend on the concentration of the added extract, extending the shelf life and preserving the quality of sensitive food products. Lima et al. (2022) point out a growing interest in the use of these fibers in civil construction to reinforce cementitious composites, offering a comprehensive view of the potential of natural fibers from the Amazon. The diversity and abundance of fibers in the region open doors for the development of more sustainable and ecological construction solutions.

Studies demonstrate that hydrothermal treatment and chemical modification of lignocellulosic fibers with silanizing agents can significantly improve compatibility with the polymer matrix, resulting in composites with better mechanical and thermal performance (Dahy, 2019). The incorporation of lignocellulosic reinforcements into polymeric matrices, both biodegradable and synthetic, represents an innovative approach to improving the properties of composites and contributing to sustainability. Agricultural residues such as rice husks and sugarcane bagasse provide rich sources of lignocellulosic material that, when treated properly, can be used as effective reinforcements (Yap et al., 2020).

Research into composite materials has seen a growing interest in the use of lignocellulosic materials as reinforcement. Materials such as rice husk, sugarcane bagasse, and jute fibers have traditionally been valued for their reinforcing properties and contribution to reducing the carbon footprint of composites (Nechita & Ionescu, 2018; Chong, Law & Chan, 2021). Furthermore, agricultural and industrial residues, such as nut shells and banana fibers, are being investigated for their potential applications in composite materials (Stanciu, Savin & Nastac, 2018; Dahy, 2019). With appropriate surface treatments and the correct choice of polymer matrix, these materials can offer significant improvements in the properties of composites, contributing to a more circular economy and reducing the environmental impact associated with the disposal of this waste.

Table 2 illustrates the primary properties and the impact on composite properties of various lignocellulosic wastes. For example, açaí seed waste is emerging as a valuable addition to the group of lignocellulosic materials used to reinforce polymer composites. With a high content of cellulose, hemicellulose, lignin, mannan, as well as lipids and antioxidant phenolic compounds, açaí fibers have shown significant potential to improve the mechanical and thermal properties of composites, offering a sustainable solution for the use of agro-industrial by-products. Like other lignocellulosic waste, açaí requires specific treatments to optimize compatibility with the polymeric matrix. Other materials such as corn waste fibers improve the mechanical properties of composites, but require surface treatment for better compatibility between fiber and matrix. Rice husk, rich in silica and low in density, increases thermal insulation properties, although it can reduce mechanical properties without adequate treatment. Sugarcane bagasse reinforces the mechanical strength and rigidity of composites, but can absorb water if not treated correctly. Wood flour offers good mechanical reinforcement, depending on particle size and water resistance treatments. Jute and mallow fibers also stand out: jute for its high tensile strength and good flexibility, and mallow for its low density and moderate mechanical properties, requiring treatment to improve hydrophobicity (Nechita & Ionescu, 2018; Chong, Law & Chan, 2021; Stanciu, Savin & Nastac, 2018.

CONCLUSION

Analysis of studies on the incorporation of açaí seed waste into PBAT composites reveals significant improvements in the mechanical properties of the materials. The incorporation of these fibers can increase the tensile strength of composites by up to 20% compared to pure PBAT composites and stiffness by up to 15%, without compromising biodegradability. Furthermore, the use of açaí waste can reduce production costs by up to 25%, promoting a sustainable solution for the materials industry.

Studies demonstrate that the use of açaí waste can provide a sustainable and low-cost alternative to traditional materials, contributing to the circular economy by valuing agro-industrial by-products. The addition of açaí fibers to PBAT matrices resulted in composites with superior mechanical properties and greater thermal stability, indicating high potential for diverse industrial applications.

Furthermore, the literature indicates that fiber surface treatments can optimize matrix-reinforcement adhesion, further improving the performance of composites. The characterization of waste through techniques such as FTIR and visual inspection proved to be effective in identifying the improvements provided by the treatments.

Despite advances, there are challenges to be addressed, such as optimizing processing conditions and scalability of production methods. Future work must focus on standardizing characterization techniques and exploring new applications of açaí seed residues in other types of polymeric matrices. In summary, the incorporation of açaí seed waste into PBAT composites represents an innovative and promising approach, offering environmental benefits and improvements in material properties. Continued advancement in this area of research is essential for the development of more sustainable,

Lignocellulosic Waste Material	Primary properties	Impact on Composite Properties
Açaí Seed Fibers	Significant cellulose, lignin and high mannan content	Increased tensile strength and stiffness, improved thermal stability, may require surface treatment for better matrix-reinforcement adhesion
Corn Waste Fibers	High cellulose content, variable lignin	Improvement of mechanical properties, need for surface treatment for better fiber-matrix compatibility
Rice Husk	High silica content, low density	Increased thermal insulation properties, reduced mechanical properties without adequate treatment
Bagaço de Cana-de-açúcar	High content of cellulose, hemicellulose	Reinforcement of mechanical strength and rigidity, potential for water absorption if not treated correctly
Wood Flour	Variable lignin and cellulose content	Good mechanical reinforcement, dependent on particle size and treatment for water resistance
Olive Kernel Flour	High lignin content, robust structure	It provides rigidity and thermal stability; surface modification may be necessary to improve composite properties
Jute Fibers	High tensile strength, good flexibility	Significant improvement in tensile and flexural strength, good compatibility with various matrices
Mallow Fibers	Low density, moderate mechanical properties	It can increase matrix modulus, requires treatment to improve hydrophobicity

Table 2: Properties of Lignocellulosic Waste Materials as Reinforcement in Composites

Source: Adapted from Chong, Law and Chan (2021), Nechita and Ionescu (2018), Stanciu, Savin and Nastac (2018) and Silva et al. (2023a).

high-performance materials, contributing significantly to materials science and industrial sustainability.

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