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USE OF NATURAL FIBERS FOR SOUND ABSORPTION: A CHRONOLOGICAL LITERATURE REVIEW

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Abstract. *With the rapid increase in pollution, sustainability topics have become increasingly valued. Thus, studies exploring natural origin materials are widely esteemed, with sound-absorbing panels as an example. This paper examines relevant publications on natural fibers for sound-absorption purposes and evaluates their technical feasibility by analyzing their sound-absorption coefficients. This paper performs a chronological literature review, investigating natural fibers practicability in the sound-absorption area and summarizes a remarkable body of knowledge, in order to determine which natural fibers can achieve satisfactory results, to then tabulate their Noise Reduction Coefficient, which is a coefficient useful to compare the different materials that absorb sound. The articles gathered and scrutinized in this literature review were selected through databases such as Scopus, Engineering Village, Scholar Google, and ScienceDirect, with the following keywords (within the title, abstract, and keywords fields): natural fibers, acoustic, absorption panel, and sound absorption. For the selection of which natural fibers would be tabulated among the selected scientific articles, the following criteria were applied: (i) the sound absorption coefficient must be obtained experimentally for greater accuracy, (ii) be single-layered, (iii) must not present any added binder, and (iv) have tables or graphs of the sound absorption coefficient by frequencies of at least 250-2,000 Hz. The NRC results revealed low values for banana pseudostem (0.15), cotton (0.30), corn fiber (0.30), and cork (0.30), thus discouraging their use (individually) for sound absorption purposes, although they may be successful by adopting greater thicknesses and other techniques such as microperforated plating, multi-layer, and airspace layer. On the other hand, the NRC results obtained by the remaining absorbent fibers were higher than the previous ones mentioned in the paper, especially the sheep wool (0.70), kenaf (0.70), coconut fiber (0.50), and Betung bamboo (0.50), confirming that those natural fibers are viable options for sound absorption purposes.*

Keywords: *Natural fibers, Acoustic absorption, Sound absorption, Chronological literature review*

1. INTRODUCTION

Recent studies have taken an interest in the relationship between human development and the limits of planetary growth, connected with exploring environmental sustainability. As such, research and discussions on this topic have increased. Brazil's harvest of natural fibers provides a variety of materials. The 21st Ordinary Meeting of the Natural Fibers Sector Chamber CSFN/MAPA in 2019 reported that the 2018 harvest yielded 517 tons of silk, 400,000 tons of bamboo, 58,000 tons of sisal, 7,264 tons of jute, and 4,500 tons of coconut. However, this production process generates waste, presenting disposal challenges.

Additionally, latest research have considered the potential applications of natural-origin materials, with sound-absorbing panels as one example. Sound absorption' refers to a material's capacity to absorb sound wave energy and convert it into heat, which may prevent sound propagation (Zhu et al., 2014). However, some synthetic acoustic materials have been associated with energy consumption and greenhouse gas emissions (Dissanayake et al., 2021).

Given these observations, the current review explores publications discussing the use of natural fiber in sound absorption, including analyzing their sound absorption coefficients. This review is conducted chronologically and aims to collate studies on the potential applications of natural fibers in sound absorption and provide an overview of existing work in this field.

2. EXPERIMENTAL PROCEDURES

In this study, the aim is to determine which natural fibers exhibit high performance in sound absorption. Accordingly, research regarding the use of natural fibers as sound-absorbing materials is surveyed in a chronological manner and subsequently tabulated based on their sound absorption coefficient. This process is enhanced by using the Noise Reduction Coefficient which is defined by Berardi and Iannace, 2015 as the calculation of the arithmetic mean of the absorption coefficients in the octave band of 250 Hz, 500 Hz, 1,000 Hz, and 2,000 Hz, rounded to the nearest multiple of 0.05. This coefficient, also known as NRC, facilitates comparison between various sound-absorbing materials (Berardi and Iannace, 2015). The equation for this coefficient is presented in Eq. 1,

$$\mathrm{NRC} = \frac{\alpha 250Hz+\alpha 500Hz+\alpha 1000Hz+\alpha 2000Hz}{4}, \tag{1}$$

where α250Hz, α500Hz, α1,000Hz, and α2,000Hz denote the acoustic absorption coefficients at their respective frequencies. For this study, was compiled and reviewed literature from Scopus, Engineering Village, Google Scholar, and Science Direct databases. The following keywords were searched for in the title, abstract, and keywords fields: natural fibers, acoustics, absorption panel, and sound absorption.

The selection criteria for the natural fibers included exclusively in the tabulation were as follows:

1. The sound absorption coefficient should be derived from experimental results, specifically the impedance tube.
2. The material should be single-layered.
3. No added binder should be present.
4. Tables or graphs of the sound absorption coefficient by frequencies of at least 250-2,000 Hz should be provided.
5. The difference in thickness between the thinnest and thickest layer tabulated should be a maximum of 0.05 m.

All Noise Reduction Coefficients were calculated despite potential variations in density, porosity, fiber diameter, and airflow resistivity between samples within the same article. The best performers from each article were then presented.

The Noise Reduction Coefficient was extracted from the articles. It was gathered when directly quoted; if not directly presented, a proportionality method was applied using pixel counts taken from the graphs of the sound absorption coefficient by frequency using ImageJ software. This approach measures the pixel count in the vertical distance between a specific point on the curve and the abscissa axis at 250 Hz, 500 Hz, 1,000 Hz, and 2,000 Hz. This measurement was then used to calculate a value proportional to the pixel count on the ordinate axis of the sound absorption coefficient, α.

3. CHRONOLOGICAL LITERATURE REVIEW

Biot (1956a; 1956b) proposed one of the early mathematical models to predict sound absorption mechanisms. This work offered a conceptual and mathematical framework for analyzing elastic wave propagation in saturated porous media and mathematical equations to help describe this phenomenon. Delany and Bazley (1970) developed mathematical models to describe sound properties such as impedance and wave propagation in fibrous media. In order to utilize their model for predicting acoustic properties, a comprehensive understanding of the material's intrinsic properties, including porosity, tortuosity, and airflow resistance, is helpful. Dunn and Davern (1986) were inspired by the mathematical model of Delany and Bazley (1970) to devise a method for calculating the acoustic impedance of foamed multilayer sound absorbers. They then compared the results generated by their mathematical model to those obtained from the impedance tube, and the outcomes were satisfactory. Interestingly, they also evaluated the applicability of Delany and Bazley's (1970) equation forms for accurately determining parameters for the foamed materials.

Johnson *et al.* (1987) introduced significant improvements in describing viscous forces, defining Tortuosity and Viscous Dynamic Permeability. They described these as a structural factor dependent on the porous frame and a complex parameter relating the pressure gradient to fluid velocity in an isotropic porous medium, respectively. Drawing upon a large amount of experimental data, Qunli (1988) proposed empirical relationships between the characteristic impedance and propagation constant of porous plastic open-cell foams and the unit-depth flow resistivity. This same study compared the resulting data to those obtained from the Dunn-Davern (1986) and Delany-Bazley (1970) models, noting some findings.

Miki (1990) evaluated the Delany-Bazley mathematical model for the case of multiple layers and observed that the genuine part of the surface impedance tended towards negative values at low frequencies. He subsequently adapted this model to achieve positive values for higher frequency ranges. In response to Delany and Bazley's (1970) work, Allard and Champoux (1992) introduced new equations for sound propagation in fibrous materials. Drawing on Johnson *et al.* (1987) publication, they presented a subset of equations to predict fibrous materials' acoustic absorption properties. These were compared to Delany-Bazley's (1970) equations and indicated a higher accuracy for low frequencies.

Next, Allard (1993) delved into the critical theories underpinning sound absorption in porous materials, providing an in-depth discussion of mathematical models, including those of Johnson *et al.* (1987) and Biot (1956a; 1956b). Around the turn of the 21st century, paralleling the growing societal awareness of environmental degradation, interest in studying the acoustic insulation behavior of natural fibers began to increase. An early example is the work of Koizumi *et al.* (2002), which explored the acoustic insulation properties of bamboo fiber using an impedance tube. They observed correlations between the sound absorption coefficient and bamboo fibers' thickness, bulk density, and diameter. The study utilized samples with thicknesses of 25 mm, 50 mm, and 75 mm; fiber diameters ranging from 90 to 425 μm; and bamboo fibers with a bulk density of 80 kg/m³, 120 kg/m³, and 160 kg/m³. Through this experiment, they noted similarities between bamboo fiber's and glass wool's acoustic insulation properties, which had relative densities of 120 kg/m³ and 32 kg/m³, respectively (Koizumi *et al.*, 2002), confirming the potential of natural fiber as an effective acoustic insulation material.

Yang *et al.* (2003) conducted a study on rice straw's physical, mechanical, and acoustic properties intending to replace wood-based panels as building materials. Their acoustic behavior evaluation involved samples mixed with an adhesive resin hardener binder, which used an impedance tube to measure the sound absorption coefficient within a range of 0 to 8000 Hz. From the results they obtained, they concluded that rice straw makes a suitable sound-absorbing alternative to wood-based panels. Similarly, Nor *et al.* (2004) investigated the acoustic properties of coconut fiber theoretically, assessing the effectiveness of the air layers, known as airspace layers, between layers of insulating material and the influence of microperforated aluminum plates. They used the WinFLAG simulation program to calculate the sound absorption coefficient for different layers of materials. Their observations revealed that the air layer between the insulating material enhanced sound absorption effectiveness for low frequencies. While the microperforated aluminum plate also improved sound absorption for low frequencies, it had the opposite effect at high frequencies (Nor *et al.*, 2004).

Asdrubali (2007) emphasized the need to use sustainable materials and techniques for noise control in buildings. The environmental repercussions of applying conventional sound insulation materials were addressed, comparing Non-Renewable Energy, Global Warming Potential, and Acidification Power data between traditional and natural materials. An evaluation was carried out on several synthetic and natural materials categories by comparing their Noise Reduction

Coefficient (NRC) values, which are averages of the sound absorption coefficients at frequencies of 250, 500, 1,000, and 2,000 Hz. Based on the findings, Asdrubali (2007) suggested that natural materials offer numerous benefits, with a lower environmental impact and satisfactory sound absorption results among the key advantages.

Zulkifli *et al.* (2008) collected sound absorption data from two insulating panels made from coconut fiber; one was a regular panel, and the other was a coconut fiber panel sheathed in a microperforated outer layer of composite material. They gathered this information through experimental methods using a reverberation room compliant with ISO 354 and ISO 717-1 standards and theoretical methods using simulations based on the WinFLAG application, capable of calculating the sound absorption coefficient for different layers of materials. The similarity between simulation and experimental results indicated the potential for coconut fiber as a cheaper, lighter, and ecologically superior alternative to synthetic acoustic insulation (Zulkifli *et al.*, 2008).

In a separate study, Ayub *et al.* (2009) examined the sound absorption of natural coconut fibers using the Delany-Bazley theoretical model and an experimental method involving an impedance tube. This study investigated the sound absorption capacity of coconut fibers under various conditions, such as varying thicknesses between samples and the effects of the air gap on the sound absorption coefficient. The analysis found favorable sound absorption properties in coconut fibers, with the Delany-Bazley model demonstrating greater accuracy at low frequencies, except in cases of multiple layers, as previously highlighted by Miki (1990).

Fouladi *et al.* (2011) examined the sound absorption properties of coconut fiber, partitioned into two sets of 15 samples each. One set comprised ordinary coconut fiber, while the other consisted of coconut fiber treated with a binder to enhance fiber hardness, inhibit fungal growth, and improve flammability. To obtain results, the researchers applied three scientific methods - two theoretical (Delany-Bazley and Biot-Allard) and one practical (using an impedance tube). The binder was considered part of the fibers for the Biot-Allard method on samples with additives, and compensation was made. The study found that samples with a binder exhibited lower sound absorption as their peaks were flatter, and they demonstrated a lower sound absorption rate for low frequencies. The authors suggested techniques like airspace layers and microperforated plates to ease these issues.

Abdullah *et al.* (2011) investigated the potential of dried rice straw fibers as an acoustic-absorbing material, focusing on assessing these fibers' acoustic properties and sound absorption capacity. Their findings pointed towards the promising potential of dried rice straw fibers as acoustic absorptive materials. However, they also identified that using a methylcellulose binder impacted the sound absorption coefficient at lower frequencies. The authors proposed that this obstacle could be mitigated by increasing the sample's thickness or coupling it with a perforated panel.

Fatima and Mohanty (2011) explored jute composite materials' acoustic and fire-retardant properties. They set out to investigate these materials' acoustic performance and resistance to fire, conducting tests to measure the sound absorption coefficient of untreated and alkali-treated jute samples using an impedance tube. Their results indicated that jute composites displayed strong acoustic performance across various frequency ranges. The authors concluded that jute composite materials are promising candidates for acoustic insulation and fire protection with their favorable acoustic properties and fire resistance.

Karlinasari *et al.* (2012) investigated the acoustic properties of particle panels made from Betung bamboo (*Dendrocalamus asper*) as building materials. They aimed to gauge these bamboo panels' sound absorption performance. To this end, they conducted tests on Betung bamboo panels with particles of three different sizes (fine, medium, and wool or excelsior) and two different densities (0.5 g/cm³ and 0.8 g/cm³) to measure the sound absorption coefficient using an impedance tube. According to Karlinasari *et al.* (2012), particleboards crafted from Betung bamboo hold potential as building materials, particularly from the standpoint of acoustic absorption.

Fouladi et al. (2013) use an impedance tube to study the acoustic behavior of natural fibers found in Malaysia, such as Corn, Grass, Coir, and Sugarcane, all without added binders, and compare them with Synthetic Materials such as Carpet, Plywood, Drapery, and Fiberglass. The values found point to Fiberglass as an exception among the fibers, standing out among the others. Otherwise, the values found among the other fibers are close, making natural fibers great alternatives to replace existing synthetic materials.

In their study, ALRahman *et al.* (2013) carried out an experimental investigation on natural fibers as potential sustainable materials for sound absorption. Their examination centers on two types of fibers: Date Palm Fiber (DPF) and Coconut Coir Fiber (CCF). Using an impedance tube, the researchers assess these fibers for their sound absorption capabilities, considering characteristics such as thickness and density. The authors position these fibers as possible replacements for conventional synthetic fibrous materials, including glass wool, rock wool, and asbestos. Their findings indicate that fiber size significantly influences sound absorption efficiency, with smaller fiber diameters leading to more effective sound absorption.

Wang and Choy (2015) focus on improving the sound absorption efficiency of a perforated panel absorber composed of support cavities partially filled with polymeric materials. Three polymeric materials are considered: expandable polystyrene foam, polymethacrylimide foam, and polyester fiber. The paper simulates the acoustic behavior of a perforated panel absorber. Simulating the acoustic behavior of the composite sound absorber, the article uses numerical models of finite element simulations and experimental means using the impedance tube. A strong agreement was observed between the numerical predictions and the experimental results, which validates the use of the finite element modeling method for the polymer composite absorber. The author finally concludes that the addition of polymer foam can improve the sound absorption performance of the composite absorber, but the improvement is superficial.

Using an impedance tube, Berardi and Iannace (2015) investigate the sound insulation properties of various natural fibers, including kenaf, wood, hemp, coconut fiber, cork, reed, cardboard, and wool. These practical results are compared with values derived from theoretical models, specifically the model proposed by Delany and Bazley (1970). The authors notice that Delany and Bazley's model needs to be revised to predict sound absorption for high-thickness fibers accurately. This discrepancy arises as the original model is calibrated using fiber samples with diameters ranging from 1 to 10 μm. For example, hemp, which exhibits an average fiber diameter of 22 μm, exhibits many errors: 67%, 56%, 96%, and 59% at frequencies of 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz, respectively. The researchers also assess each material's Noise Reduction Coefficient (NRC). The NRC values generally prove high for the evaluated materials, affirming the viability of natural fibers as acoustic absorbers. Exceptionally high sound absorption efficiency emerges from the results for sheep's wool and coconut fiber (Berardi and Iannace, 2015).

Sambu *et al.* (2016) investigate the impact of physical properties on the acoustic performance of natural fibers derived from palm oil fronds. The research examines these fibers' physical properties and their relation to acoustic performance, particularly sound absorption. The study conducts experimental analyses of the density, porosity, tortuosity, and airflow resistivity of the material with binder compositions of 40%, 30%, 20%, and 0%. Sound absorption measurements are also performed at varying frequencies using an impedance tube. The findings suggest a significant influence of the fibers' physical properties on acoustic performance. The authors note that as the binder content in the material's composition increases, there tends to be a higher density and tortuosity and lower porosity. The palm oil frond fibers demonstrate effective sound absorption at specific frequencies, suggesting their potential use as acoustic absorption materials (Sambu *et al.*, 2016).

Berardi *et al.* (2017) investigate the acoustic insulating properties of Broom fiber, a plant native to Europe and Asia. The study uses an experimental method with an impedance tube on samples with diameters ranging from 1.5 to 4 mm and thicknesses of 60 mm, 80 mm, and 120 mm. According to the authors, this plant, widely available in Mediterranean countries, demonstrated promising acoustic absorption results, thus encouraging the use of such sustainable materials (Berardi *et al.*, 2017).

Lim *et al.* (2018) examine the sound absorption performance of natural kenaf fibers. Experiments were carried out to evaluate the sound absorption coefficient using an impedance tube and to measure kenaf fibers' random-incidence sound absorption coefficient at various frequencies in a reverberation chamber. The findings suggest that kenaf fibers excel in sound absorption. The study also investigates the effects of air gaps and bulk density on the sound absorption coefficient, revealing that adding air gaps significantly enhances absorption for frequencies below 1500 Hz while increasing the bulk density improves sound absorption overall. As per the authors, kenaf fiber's performance in sound absorption is comparable to that of synthetic fiber Rock Wool (Lim *et al.*, 2018).

Zhu et al. (2018) explore innovations in sound absorption technology, which is mainly focused on broadening the sound absorption bandwidth of a perforated panel using a membrane-type resonator. The authors explore how incorporating a membrane resonator can improve the perforated panel's performance as an acoustic absorber. The author uses a numerical model in which the performance of the perforated panel as a sound absorber is obtained analytically by combining the vibration equation of the membrane-type resonator with the acoustic impedance equation of the perforated panel and then validates the results found through the impedance tube. Finally, the author concludes that the membrane-type resonator can widen the perforated panel's sound absorption band.

Silva *et al.* (2019) investigate the sound insulation characteristics of sisal, coconut, and sugarcane fibers at low frequencies, utilizing the Delany and Bazley (1970) and Allard and Champoux (1992) models and experimentally through an impedance tube. The transfer function technique assessed the sound absorption coefficient per ASTM 1050-12 standard. With ten samples of each material having thicknesses of 20 mm, 30 mm, and 40 mm, they evaluated sound absorption coefficients within a frequency range of 200 to 1600 Hz. The authors found that the Allard and Champoux (1992) equations yielded more accurate values for low and medium frequencies, particularly notable when the samples had small thicknesses and airflow resistivity. The theoretical methods exhibited greater accuracy with high airflow resistivity values. The authors also demonstrated that sugarcane fiber displays a higher sound absorption quality when compared to coconut fiber and sisal (Silva *et al.*, 2019).

Liu *et al.* (2021) researched the airflow resistivity measurement and sound absorption performance analysis of sound-absorbing cotton. The study aimed to assess cotton's acoustic properties using airflow resistivity measurement as a significant parameter. Three experiments were performed: two theoretical and one experimental to measure the sound absorption coefficient for different thicknesses of cotton samples. The theoretical methods employed were the Delany and Bazley (1970) – Miki (1990) and Johnson *et al.* (1987) – Allard and Champoux (1992) mathematical models, whereas the experimental method utilized the impedance tube. The authors concluded that the Johnson-Champoux-Allard model aligns more accurately with the measured sound absorption coefficient, thus showcasing its capability to predict and design the sound absorption performance of new fibrous materials (Liu *et al.*, 2021).

Mendes and Nunes (2022) examined the acoustic properties of banana pseudostem fibers using a sound impedance tube, assessing frequencies from 100 to 6300 Hz. They employed the transfer function technique described in ISO 10534:2 to verify the sound absorption coefficient. The researchers divided the samples into groups A, B, and C, each consisting of eight samples. Group A featured fibers grouped without additional substances; Group B had fibers bound by a natural glue derived from cassava starch and water; and Group C contained fibers bound with the same natural glue but sandwiched between two plaster plates. They observed that Group C showed the highest Noise Reduction Coefficient values, reaching a sound absorption coefficient of 0.89 at 6300 Hz. However, Mendes and Nunes (2022) noted that adding natural glue did not influence sound absorption, as Groups A and B exhibited similar NRCs.

4. RESULTS AND DISCUSSION

The data presented in Table 1 was filtered from the chronological review according to the 5 criteria presented above, which provides data for each type of natural fiber selected and their respective Noise Reduction Coefficient (NRC).

Table 1. Noise Reduction Coefficient of each sample analyzed among filtered articles

Material	Thickness (m)	∝250Hz	∝500Hz	∝1000Hz	∝2000Hz	NRC
Betung Bamboo	0.01	0.2354	0.2483	0.5903	0.8483	**0.50**
Shredded Broom	0.06	0.081	0.159	0.647	0.929	0.45
Banana Pseudostem	0.01	0.07	0.1033	0.1566	0.2533	0.15
Kenaf	0.06	0.3	0.61	0.99	0.95	**0.70**
Wood	0.06	0.4	0.5	0.65	0.91	0.60
Hemp	0.03	0.15	0.25	0.51	0.7	0.40
Coconut	0.05	0.20	0.34	0.67	0.79	**0.50**
Cork	0.03	0.02	0.1	0.3	0.86	0.30
Sheep wool	0.06	0.28	0.66	0.95	0.94	**0.70**
Reed	0.04	0.12	0.38	0.64	0.62	0.45
Cotton	0.0151	0.038	0.0952	0.2761	0.7666	0.30
Oil palm frond	0.05	0.1157	0.2912	0.7052	0.7473	0.45
Jute fibre	0.0254	0.1587	0.438	0.8825	0.8031	**0.60**
Sugar cane	0.02	0.05	0.13	0.88	0.63	0.40
Corn fiber	0.02	0.06	0.16	0.28	0.81	0.30
Grass	0.02	0.08	0.14	0.45	0.98	0.40

The NRC results found respectively by Mendes and Nunes (2022), Liu et al. (2021), Fouladi et al. (2013), and Berardi and Iannace (2015) reported low values for banana pseudostem (0.15), cotton (0.30), corn fiber (0.30), and cork (0.30), suggesting these materials may not be ideal for sound absorption if used individually. However, increasing thickness and utilizing techniques like microperforated plating, increasing bulk density, multi-layering, and airspace layering may enhance their performance, as already researched by Lim et al. (2018), Nor et al. (2004), Zulkifli et al. (2008), Mendes and Nunes (2022), and suggested by Fouladi et al. (2011) and Abdullah et al. (2011).

Contrastingly, other absorbent fibers yielded high-performance NRC results, as reported by the authors Berardi and Iannace (2015), Fatima and Mohanty (2011), Karlinasari et al. (2012), notably sheep wool (0.70), kenaf (0.70), jute fiber (0.60), coconut fiber (0.50), and betung bamboo (0.50). Among these, kenaf and sheep wool (both 0.6 m) were the thickest, followed by coconut fiber (0.05 m), jute fiber (0.0254 m), and betung bamboo (0.01 m), despite being the thinnest, betung bamboo still exhibited a relatively high Noise Reduction Coefficient.

Compared to synthetic fibers, natural fiber's shorter decomposition time contributes to their environmental sustainability. However, this benefit also implies less durability, requiring consideration of material exchange or maintenance ease. For instance, using natural fibers in building construction for soundproofing may not be advantageous if the insulating panels are located between walls with difficult access.

5. CONCLUSION

This study aimed to investigate the viability of natural fibers for sound absorption and to summarize significant research in this field chronologically. Researchers may consider incorporating binders or additives to improve their shape retention and flammability resistance when using natural fibers as absorbent materials. Such modifications could enable the placement of absorbent panels in locations with easy access, simplify their exchange and maintenance, and make them suitable for framed, exposed, and lined applications.

Sustainable development remains a prominent focus in today's society. Concurrently, scientific research considers natural fibers as potential materials for sound wave absorption. The hypothesis that natural fibers could substitute synthetic fibers in sound absorption applications originates from mathematical models and the inherent properties of natural fibers. These fibers exhibit promising potential for sound wave absorption. Additionally, they could provide environmental benefits, such as repurposing agricultural waste, offering biodegradability, boosting widespread availability, and enhancing accessibility and cost-effectiveness. Further research may consider the assessment of those natural fibers in more industrial applications, for instance, civil construction, household appliances, and the automotive industry.

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